Case Study: Multicriteria Assessment of Drought Mitigation Measures

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Case Study: Multicriteria Assessment of Drought Mitigation Measures

Giuseppe Rossi[1]; Antonino Cancelliere[2]; and Giuseppe Giuliano[3]

Abstract: The proactive approach to drought management is based on measures devised and implemented before, during, and after the drought event, according to a planning strategy rather than within an emergency framework. The measures taken before the initiation of a drought event consist of *long-term measures* oriented to improve the reliability of the water supply system to meet future demands under drought conditions. The measures taken after a drought is forecasted or starts are *short-term measures* that try to mitigate the impacts of the particular drought on the basis of a contingency plan. Selection of the preferable mix of long-term and short-term measures can be accomplished through multicriteria decision analysis (MCDA), which enables the comparison of alternatives on the basis of appropriate quantitative and/or qualitative assessment criteria. In this paper, a methodology for the assessment of drought mitigation measures based on a combined use of simulation models and MCDA is applied to a water supply system located in eastern Sicily, Italy. The system comprises two reservoirs and several diversion dams and hydropower plants, and its main uses are irrigation and municipal water supply. First, a simulation model is applied to evaluate the effects of several drought mitigation alternatives consisting of a mix of long- and short-term measures. Then, MCDA is applied to rank the different alternatives on the basis of economic, environmental, and social criteria, taking into account the process of coalition formation among stakeholders on the basis of their different point of view. The results confirm the applicability of the proposed multicriteria methodology for a transparent comparison of drought mitigation measures to be adopted as a support for the decision making process.

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Introduction

Drought is a complex hydrometeorological phenomenon, originated by meteorological anomalies which reduce precipitation, but whose consequences are strongly affected by the state of the various components of the hydrologic cycle (Wilhite 2000). In spite of its basic nature as a natural hazard, drought encompasses significant anthropic dimensions (Rossi 2000). Its most severe impacts can be mitigated by appropriate measures considered and implemented during the planning, design, and operation of water systems.

Although in the past such drought mitigation measures have generally been selected according to a conventional engineering approach, among those exhibiting technical feasibility on the basis of an economical comparison, the application of general principles of sustainability, as suggested by the Bruntland Commission (World commission on Environment and Development 1987), to the water sector requires a significant broadening of the criteria adopted in the decision-making process (Simonovic, 1996). Indeed, the goals of water resources development should include the new concepts of environmental integrity and social equity along with technical performance and economic efficiency, which are already accounted for within an integrated water resources management. Moreover, the time horizon for assessing consequences of the projects should be chosen taking the needs of future generations into account, and the procedure for implementation of measures should be revised in order to promote stakeholders' participation in the decision-making process, balancing market mechanisms with democratic control. A broader approach in water resources management emphasizes the need to use methodologies such as multicriteria decision analysis (MCDA), which is able to assist the decision process in comparing and ranking different alternatives exhibiting complex multidimensional impacts by considering the different levels of preference of the various groups of interest (Goicoechea et al. 1982). Indeed, by showing how each alternative performs with respect to the others, MCDA enables the decision makers to obtain a better understanding of the available choices, providing information about the trade-offs among different alternatives.

The importance of MCDA in water resource planning is largely recognized, and several applications arise from a literature review. They include preliminary investigations for planning and/or an environmental impact statement (e.g., Nijkamp and Vos 1977; Gershon et al. 1982), with particular regard to river basin planning (Raju and Pillai 1999; Stewart and Scott 1995). Some authors (e.g., Goicoechea et al. 1992; Hobbs et al. 1992) carried out experimental evaluation of MCDA models

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taking into account feedback from the end users of the MCDA tools. Several applications of MCDA are also oriented to assisting the decision-making process in the water system operation sector. In particular, some authors analyzed and ranked different water operation policies (Flug et al. 2000; Yin et al. 1999).

Within the framework of a proactive approach to drought mitigation, selection of the preferable mix of long-term and short-term measures against water shortage can be performed by means of traditional economics-based methods, such as the cost-benefit analysis approach (Dziegielewski 2003). However, MCDA techniques are more appropriate tools to select the preferable alternatives for coping with drought, as a pioneering work undertaken by Duckstein (1983) suggested. In particular, Duckstein (1983) proposed a methodology to rank alternatives based on an alternatives versus criteria matrix; alternatives included several combinations of supply-oriented, demand-oriented, and impact minimization-oriented measures, and their consequences were assessed in terms of economic, hydrologic (water deficits), social, and environmental criteria. More recently, Munda et al. (1998) applied the relatively new MCDA technique NAIADE (Novel Approach to Imprecise Assessment and Decision Environments) (Munda 1995) to select the most suitable drought mitigation alternatives in the context of integrated water management. The proposed technique is particularly suited to deal with uncertainty-affected qualitative criteria, also enabling the MCDA analysts to pay particular attention to the potential conflicts that may arise among stakeholders.

This paper presents an application of MCDA to the comparative assessment of drought mitigation measures considering economic, environmental, and social criteria. After introducing a general framework for coping with drought within a proactive approach, a procedure aimed at evaluating drought vulnerability of water supply systems and assessing different courses of action is presented. A set of alternatives for drought mitigation is identified, based on a mix of long- and short-term drought mitigation measures. Such alternatives are then compared and ranked on the basis of selected criteria, involving economic, environmental, and social aspects. The complete ranking provided by the MCDA method enables the decision maker to identify alternatives that dominate others and thus should be preferred, at least on the basis of the adopted criteria. Such a ranking is later refined by taking into account the preferences of the different stakeholders towards alternatives. Based on the similarity in judgment of the stakeholders with respect to the alternatives, the coalition formation process is analyzed. This allows identification of the alternatives, that are reasonably characterized by a higher level of agreement and are therefore more suitable for later implementation than alternatives vetoed by coalitions. Special focus is placed on the application of the proposed methodology to a case study located in Italy (eastern Sicily).

Multicriteria Assessment of Drought Mitigation Measures

The measures to be implemented to improve drought preparedness and mitigate drought impacts can be classified in several ways. The *proactive approach* consists of measures conceived and prepared according to a planning strategy rather than within an emergency framework. Proactive measures are devised and implemented before, during, and after the drought event. Measures taken before the forecasting or initiation of a drought event aim to reduce the vulnerability to drought or improve drought preparedness. They consist of *long-term measures* oriented to increase the reliability of water supply systems to meet future demands under drought conditions through a set of appropriate structural and institutional measures (Dziegielewski 2003). The measures taken after the start of a drought are *short-term measures* which try to mitigate the impacts of the particular drought event within the existing framework of infrastructures and management policies, on the basis of a contingency plan developed in advance and adapted to the ongoing drought, if necessary.

The development of an appropriate drought mitigation strategy requires assessment of an appropriate mix of long- and short-term measures, which are able to meet some predefined objectives. When an existing system is not able—or is expected not to be able in the future—to face droughts, appropriate modifications and/or enlargements of the system are generally proposed to reduce its vulnerability to drought. The choice of the structural measures must be carried out along with the selection of short-term, nonstructural measures able to reduce the impacts of the residual deficits that cannot be avoided by means of structural measures because of technical, economical, or environmental feasibility issues.

The proposed procedure for assessment of the drought mitigation alternatives, shown in Fig. 1, includes as a first step assessment of the system vulnerability to drought in the current configuration. Such an assessment can be carried out either with respect to a historical period or to generated hydrological scenarios, representing the future water supply availability. Then, the short- and long-term measures for coping with drought are identified among those exhibiting higher technical and economical feasibility, also considering political and institutional constraints, and their effects are assessed. This assessment is generally carried out with respect to predefined criteria, that attempt to take into account both the operational as well as the economical, social, and environmental point of views. The choice of criteria depends on the nature of the vulnerability to drought of the present configuration of the water supply system as well as on the courses of actions that water agencies, government at the local and regional levels, and users have adopted during past droughts, or have proposed as possible solutions to future drought threats. In any case, the assessment requires adoption of appropriate simulation tools, which are able to take into account both structural modifications to the system, as well as the implementation of short-term measures during a drought period.

The next step in the procedure is application of the multicriteria technique for the comparison and ranking of the alternatives, which are to be evaluated according to a set of different criteria. This requires preliminary selection of MCDA technique, identification of the alternatives, definition of the criteria against which to compare them, and elicitation of the stakeholder preferences.

On the basis of the estimated rating value assigned to every alternative according to each criterion, an impact matrix describing the rating of the criteria versus the alternatives can be compiled. This is in fact a payoff matrix, which synthetically describes the structure of the problem at hand. Selection of the preferred alternatives requires some kind of analytical method, because the heuristic methods usually followed by decision makers do not lead to the best solutions. The choice of the MCDA method depends on the problem to be faced. Discrete MCDA methods apply when the number of alternatives is finite, and evaluation is carried out on the basis of a common set of non-commensurable criteria (Goicoechea et al. 1982). This is generally the case for drought mitigation alternatives, because they are formulated as combinations of a finite number of long- and short-term drought mitigation measures. Discrete methods can take into

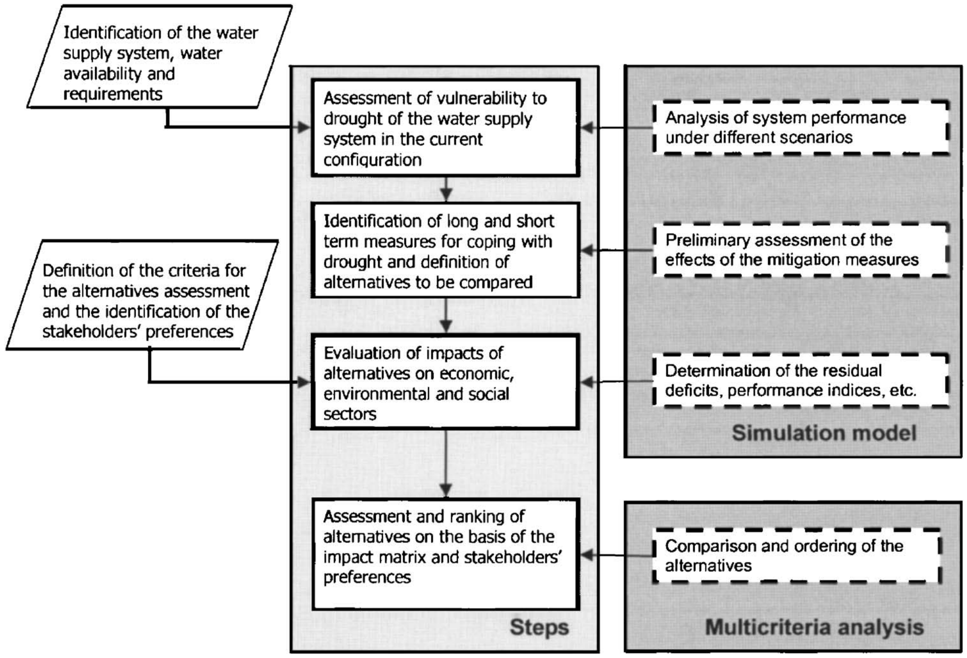

Fig. 1. Proposed methodology for assessment of drought mitigation measures

account a decision maker's preferences either via a progressive or a prior articulation of preferences. In the former iterative approach, the decision maker is asked to provide feedback about the solution selected at each iteration, and the MCDA problem is reformulated accordingly. The process continues until a target level of acceptability is achieved (provided one exists). Among the methods based on progressive articulation of preferences are the step method and compromise programming methods, while methods based on a prior articulation of preferences include the weighted average, ELECTRE, and PROMETHEE models.

In this paper, the MCDA NAIADE model (Novel Approach to Imprecise Assessment and Decision Environments) developed by Munda (1995) has been selected, because it is a discrete multicriteria method particularly oriented to evaluate a finite number of alternatives for resources management and/or environmental protection. Alternatives can exhibit some degree of complementarity or be totally incompatible, although each of them is to be implemented as a whole, meaning that 100% of its features is pursued. NAIADE allows including either crisp, stochastic, or fuzzy measurements of the performance of an alternative with respect to a judgement criterion; thus, it is very flexible for real world applications. The NAIADE method is based on a two-phase algorithmic procedure. In the first phase a pairwise comparison of alternatives is carried out, taking into account the intensity of preference of one alternative with respect to the others. The result is a partial ranking of the alternatives, allowing for incomparability relationships to hold. It is worthwhile to note that preferences of the decision maker in terms of weighting of the criteria are not accounted for within this task, in order for the decision maker to identify nondominated solutions without biases due to the relative importance of criteria. Because no weighting method of the criteria is assumed, the second phase of the procedure aims at identifying the solutions that can potentially gain higher consensus among stakeholders. This is basically a conflict minimization method that, on the basis of the similarity of judgments of the different stakeholders towards alternatives, tries to identify coalitions that are most likely to be formed among groups of interest. Each coalition identifies its own preferred alternatives and in turn vetoes alternatives. Therefore, preferred alternatives can be identified on the basis of the consensus reached within each coalition, and which are thus most likely going to be realized.

Assessment of Drought Mitigation Measures: Case Study

Description of System

The water system, located in eastern Sicily around Catania Plain, includes various agricultural, municipal, and industrial uses, mainly supplied by a set of multipurpose plants for regulation and diversion of Salso-Simeto streamflows. The system infrastructures include two dams (Pozzillo on the Salso River and Ancipa on Troina River, both tributaries of Simeto), three diversion dams located on the Simeto River (S. Domenica, Contrasto, and Ponte Barca), and six hydropower plants operated by the Electric Energy Agency (Enel). In addition, the Lentini reservoir is connected to the system via the Ponte Barca diversion dam on the Simeto River (see Fig. 2). The Ancipa reservoir has a design net capacity of $27.8 \cdot 10^6$ m^3, which is currently limited, due to structural problems, to $9.35 \cdot 10^6$ m^3. It regulates both the flows of the direct basin and of other tributaries, which are connected through a diversion canal. A small portion of the Ancipa releases are used to supply several municipalities in central Sicily, whereas the remaining portion is used for hydropower generation and irrigation purposes. The Pozzillo reservoir, which is mainly devoted to irrigation, has a current storage capacity of $123.0 \cdot 10^6$ m^3. Most of the releases are used for hydropower generation and irrigation of the main district of the Catania Plain (an irrigated area of about 18,000 ha), whose water conveyance and distribution network is operated and managed by the Land Reclamation Consortium no. 9 (LRC9).

The Catania Plain irrigation district is particularly drought-prone, because of the significant variability of available water

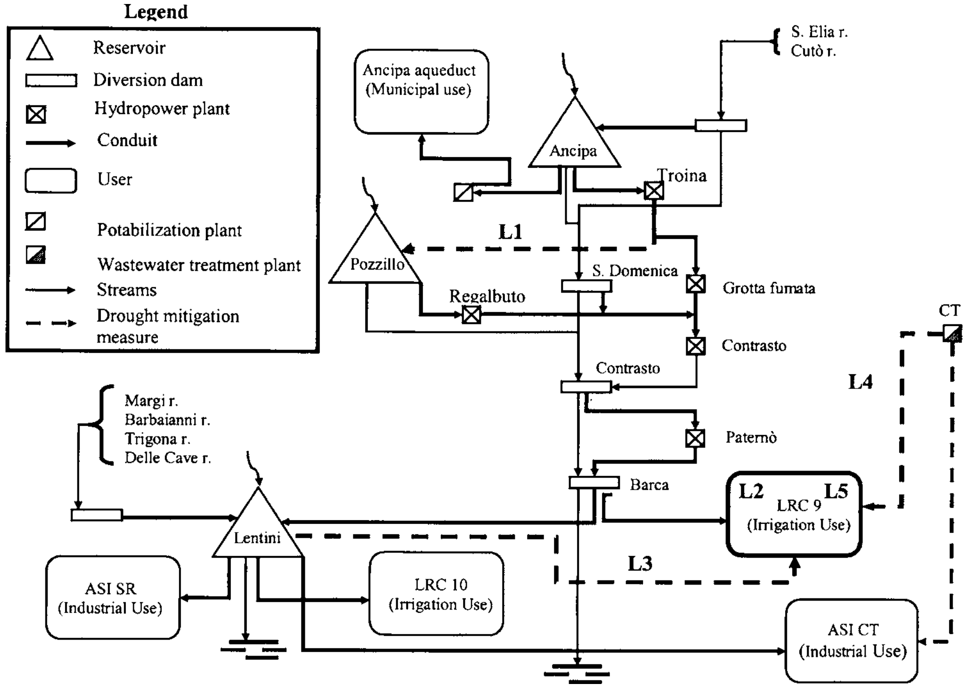

Fig. 2. Scheme of Simeto water supply system with long-term measures

resources. The Lentini reservoir has been built on the S. Leonardo River in order to meet the demands of the irrigation districts managed by LRC9 (Catania) and LRC10 (Siracusa) and of the industrial areas of Siracusa and Catania. It partly regulates the flows of the Simeto River, through the Barca diversion, and the flows of four tributaries of S. Leonardo River: Dalle Cave, Trigona, Barbajanni, and Zena. It has been designed for a net storage capacity of $127 \cdot 10^6$ m^3, although at present, storage is limited to $21.7 \cdot 10^6$ m^3.

Assessment of Vulnerability to Drought of System in Current Configuration

The simulation of the system operation in the current configuration has been performed by means of the SIMGES module of the AQUATOOL software package (Andreu et al. 1996; Andreu 2003) for the period 1959–1998 in order to acquire useful information about the system performance, as well as suggestions about the drought mitigation measures to be implemented. In the current system configuration, the maximum capacity of Ancipa reservoir has been limited to $9.35 \cdot 10^6$ m^3 due to the aforementioned structural problems, whereas the Pozzillo maximum capacity is $123.0 \cdot 10^6$ m^3. The Lentini reservoir has been excluded from the simulation because its dam is still under testing. Furthermore, minimum storage volume constraints have been imposed for Ancipa, in order to safely meet the municipal demand.

Net irrigation requirements of the Catania Plain irrigation district no. 9 have been estimated based on a study by the Land Reclamation Consortium of Catania Plain. Net irrigation demand throughout the whole irrigation season (May–October) has been assumed to be equal to $85.0 \cdot 10^6$ m^3/year, whereas the gross demand (including losses in the conveyance and distribution networks, consisting mostly of open channels) is $121.4 \cdot 10^6$ m^3/year. The percent distribution within the irrigation season is as follows: May 11%, June 17%, July 28%, August 23%, September 14%, and October 7%. Monthly municipal demands to the Ancipa reservoir have been assumed constant throughout the year and equal to $1.0 \cdot 10^6$ m^3/month.

The results of the simulation during the period 1959-1998 show that municipal demands are met almost every year, except for a very small deficit occurring in 1990, because municipal use has priority over irrigation. As a consequence of this, the mean annual release is practically equal to the demand and the volumetric and temporal reliability are very close to one. The average annual irrigation deficit resulted in $23.6 \cdot 10^6$ m^3 and the highest irrigation annual deficit is $103.3 \cdot 10^6$ m^3; temporal reliability for irrigation (percentage of number of years where the irrigation demand is met) on a yearly basis equals 30.8%, whereas volumetric reliability equals 80.5%. The average duration of deficit is 3.9 years, with a peak duration of 10 years. Both the durations and the amounts of irrigation deficits suggest that long-term drought mitigation measures should be implemented, in order to improve system capability to face severe drought conditions.

Alternatives for Drought Mitigation and Evaluation of System Performance

Drought mitigation measures for the investigated system have been preliminarily identified among those proposed by the water supply management agencies and by government representatives at the local and regional level (Sicilian Drought Emergency Committee). The considered long-term measures are oriented to increase the water supply through water transfers and reuse of treated wastewater as well as to reduce water losses through replacement of existing distribution channel networks with pressure pipes and development of small farm ponds. Short-term measures, on the other hand, are oriented to increase supply through overexploitation of groundwater, to reduce demands by restricting irrigation only to perennial crops, and to minimize the drought impacts by providing public aids to the most affected areas.

Table 1. Simeto Water Supply System: Selected Alternatives for Drought Mitigation

Measure	Alternatives							
	A	B	C	D	E	F	G	H
Long-term measures								
L0: system in current configuration	×							
L1: water transfer from Ancipa reservoir to Pozzillo reservoir		×					×	×
L2: modernization of irrigation network			×					
L3: release for irrigation from Lentini reservoir				×			×	
L4: treated wastewater reuse from Catania plant					×			×
L5: construction of small reservoirs by farmers						×		
Short-term measures								
S1: supplementary resources from groundwater and ponds	×	×	×	×	×	×	×	×
S2: management criteria to face water scarcity	×	×	×	×	×	×	×	×
S3: natural calamity aids	×	×	×	×	×	×	×	×

More specifically, the selected long term measures are as follows:

- *L1: Water transfer from Ancipa reservoir to the Pozzillo reservoir*. This measure consists in partly transferring winter spills from the Ancipa to the Pozzillo reservoir through a pipeline.
- *L2: Modernization of the irrigation network*. This measure consists in replacing open channels with pressure pipes. Only 30% of the capital and operation and maintenance costs have been accounted for in order to consider the fact that network modernization is required even during normal (nondrought) periods, either for loss reduction or for enabling more advanced irrigation techniques.
- *L3: Release for irrigation from Lentini reservoir*. This measure consists in using waters from the Lentini reservoir to supply the irrigation area of LRC 9, the irrigation area of the Siracusa district (LRC 10), and the industrial areas of Siracusa and Catania.
- *L4: Treated wastewater reuse from Catania plant*. This measure consists in constructing the facilities necessary to use wastewater from the Catania treatment plant for the irrigation of a portion of the Catania Plain.
- *L5: Construction of small reservoirs by farmers*. This measure consists in constructing new small private reservoirs by farmers, which is currently a common practice, to be used as a strategic reserve for drought periods.

Fig. 2 shows the scheme of the water supply system, where the considered long-term measures are highlighted. In computing costs, an interest rate has been assumed for the investments equal to 3.5%, considering a 40 year lifetime for the structural works and a 20 year life for the electromechanical parts. Measure L2 is the most expensive, but may ensure a high reduction of drought vulnerability; therefore, its implementation would make the other measures redundant. On the other hand, measures L1, L3, L4, and L5 are the most cost-effective, but their single effects are not as important as measure L2, so they must be combined in order to obtain a satisfactory performance of the system. Preliminary computations showed that further analysis can be reduced to considering all measures alone and measures L1+L3 and L1+L4 as the eligible set of long-term measures to be assessed, because other combinations do not show significant improvements in performance indices while costs remain unaltered or slightly increase.

The following short-term measures have been identified, based on an analysis of the management of past droughts:

- *S1: Supplementary resources from groundwater and ponds*. Groundwater withdrawals and storage in private ponds is a common practice adopted by farmers that ensures a consistent additional water supply during droughts. Water unitary cost has been determined by weighting unitary costs for storing water in ponds, pumping groundwater, and using water stored in ponds, and is equal to 0.16 Euro/m^3.
- *S2: Management criteria to face water scarcity*. This measure consists of restricting irrigation to perennial crops, excluding irrigation of annual crops, increasing vigilance to prevent water thefts, and ensuring the respect of irrigation scheduling. The cost of additional vigilance is estimated to be 78,000 Euro per year.
- *S3: Natural calamity aids*. This measure consists of public aids in the form of refunds for damages, low-interest rate loans, and tax relief. The cost has been estimated based on similar actions taken by regional and national governments during past droughts and is equal to 7.2 million Euro per year.

When a drought occurs, all of the short-term measures are supposed to be put into place. In fact, during droughts that have occurred in the past, all of these short-term actions have been adopted in order to reduce the economic effects of droughts recognized as natural calamities, and similar measures are expected for future drought events.

The alternatives for drought mitigation in the Catania Plain are a combination of long- and short-term measures, which are summarized in Table 1, where the long-term measure L0 refers to the system in the current configuration. It can be inferred from the table that the alternatives consist of all three short-term measures and of one or more long-term measures.

Evaluation of Performance Indices of System Simulation with Long- and Short-Term Measures Implemented

Assessment of the performance of the system considering the different measures for coping with drought has been carried out in terms of releases and deficits, by considering as alternatives the combinations of one or more long-term measures plus the short-term measure S1. Short-term measures S2 and S3, on the other hand, have not been considered explicitly in the simulation, because they do not affect the releases and deficits, but are rather

Table 2. Simeto Water Supply System: Impact Analysis Matrix

Alternatives	1a (10^6 Euro)	1b (10^6 Euro)	1c (10^6 Euro)	1d (years)	2a (% months)	2b (% months)	2c (quality)	2d (quality)	3a (10^6 m^3)^2	3b (*at*)	3c (quality)	3d (quality)
A	0	0	142.5	6	4.1	29.7	EB	P	24,682	59.0	P	VB
B	10.119	7.837	55.9	4	13.3	16.2	B	VG	14,511	82.1	VG	MLG
C	81.978	73.616	22.4	1	13.2	5.6	G	G	4,660	94.9	VB	P
D	12.867	12.397	23.9	1	17.1	6.0	B	M	4,777	94.9	M	G
E	7.033	6.776	47.9	3	13.5	11.8	P	G	8,667	89.7	MLG	M
F	4.132	5.596	48.2	3	13.5	12.0	M	VB	8,777	89.7	G	MLB
G	22.986	20.234	23.9	1	17.1	6.0	MLB	MLB	4,777	94.9	M	VG
H	17.152	14.613	44.9	3	10.7	13.5	G	G	8,489	89.7	MLG	G

Note: EB=extremely bad; VB=very bad; B=bad; MLB=more or less bad; M=moderate; MLG=more or less good; G=good; VG=very good; and P=perfect.

oriented to reduce the consequent economic losses. Their effects, however, have been taken into account within the multicriteria assessment of the alternatives.

After simulation of each alternative, performance indices of the behavior of the system have been computed. In particular, reliability indices (both temporal and volumetric), resilience indices (computed as the inverse of the average deficit period duration), and various vulnerability indices have been used here. In addition, the sustainability index proposed by Loucks and Gladwell (1999) has also been computed. The indices related to the irrigation demands of LRC9 and LRC10 (not reported here for the sake of brevity) show that the system in the status quo performs poorly in terms of all the indices, whereas all the other options significantly increase temporal reliability and sustainability, computed as a function of the temporal reliability itself, the resiliency index, the maximum annual deficit, and the maximum deficit duration.

Furthermore, all alternatives reduce the sum of the squared annual irrigation deficits and the number of years where the annual deficit exceeds the 25% of the annual demand. Municipal and industrial uses demands are generally satisfied, because a higher priority has been given to these uses. Consequently, the corresponding performance indices reflect an almost 100% reliability, a very high resilience and very low vulnerability in all cases.

Definition of Criteria and Identification of Stakeholders

The criteria to assess each alternative have been chosen in order to take into account the different economic, environmental, and social consequences of drought measures adopted in each alternative. Accordingly, three types of criteria have been selected:

Economic Criteria

Construction costs (1a), *operation and maintenance costs* (1b), *and short-term measures costs* (1c) are expressed in millions of Euro. These costs refer to the present worth of the expected cost of the measures. Short-term measures costs include those for measures S1 (groundwater pumping and water ponds use), S2 (increased vigilance of the conveyance and distribution network), and S3 (public aid).

Damages to perennial crops (1d) are computed as the number of years with deficits greater than 25% of demand. Economic estimation of damages occurring to perennial crops in case of severe water deficits is quite difficult and uncertain, because during drought the unitary cost for crop production may appreciably vary. Therefore, as a proxy for the estimation of such damages, the percentage of years when the residual annual deficits are greater than the 25% of the demand is considered here.

Environmental Criteria

Failures to meet minimum storage volumes (2a and 2b) are computed as the percentage of months when such minimum storage volumes are not met in the Pozzillo (criteria 2a) and Ancipa (criteria 2b) reservoirs. Minimum storage volumes for Pozzillo and Ancipa are $8.0 \cdot 10^6$ m^3 and $1.5 \cdot 10^6$ m^3, respectively.

Sustainability (2c) is a qualitative criterion taking into account the different sustainability degrees of each alternative. In particular, the alternatives that do not involve groundwater overexploitation but favor the use of renewable sources are preferred.

Reversibility (2d) is a qualitative criterion taking into account the reversibility of the measures, i.e., the possibility of restoring the initial conditions of the system within economic and/or environmental feasibility.

Social Criteria

System vulnerability (3a) is a proxy of the system vulnerability, computed as the sum of the squared irrigation deficits in 10^6 m^3. Because higher concentrated deficits will cause more severe effects, a water system can be considered less vulnerable to drought if it tends to distribute deficits over time.

Temporal reliability (3b) is computed as the percentage of years when a given irrigation demand is met.

Realization time of the infrastructures (3c) is a qualitative criterion taking into account the time of realization of the infrastructures, discriminating between alternatives whose realization is not feasible in a short period and alternatives with faster implementation.

Employment increase (3d) is a qualitative criterion taking into account the increase in employed persons during the phases of construction and operation and maintenance of the infrastructures.

Among the groups of stakeholders, the following have been identified: G1 irrigation management agency (Land Reclamation Consortia 9 and 10); G2 farmers of the Catania Plain district; G3 hydroelectric power agency (ENEL); G4 industries; and G5 environmentalists.

Analysis of Results

Impact Analysis

As previously mentioned, the impacts of each alternative have been assessed by simulating the system considering the long-term

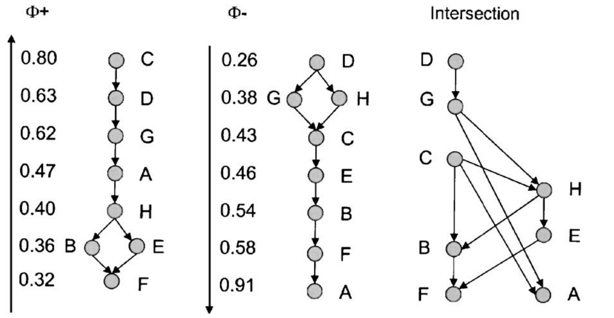

Fig. 3. Ranking of drought mitigation alternatives in Simeto water supply system

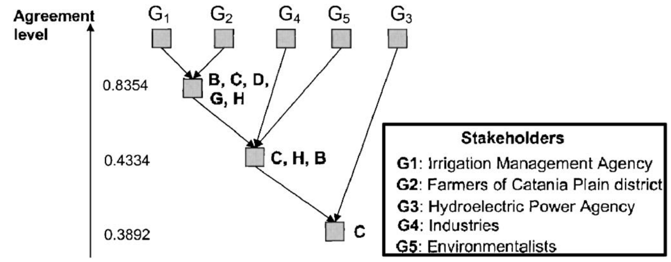

Fig. 4. Process of coalition formation and related agreement levels among stakeholders

measures and by reducing the annual deficits to take into account the increase of supply consequent to the implementation of short-term measure S1, up to a volume of $20.0 \cdot 10^6$ m^3/year. When residual deficits exceed $15.0 \cdot 10^6$ m^3/year, short-term measures S2 (mandatory limitation of irrigation to perennial crops) and S3 (public aid to drought-affected stakeholders) have been introduced in the analysis.

In evaluating the impacts, the following assumptions have been made:

- Only 30% of the capital cost 1a and of the operation and maintenance costs 1b of alternative L2 have been considered, to take into account the fact that modernization of the whole conveyance and distribution network is necessary, regardless of drought mitigation, in order to ensure good performance of the irrigation system even in normal (nondrought) periods.
- In the computation of the temporal reliability, only the irrigation use (LRC9) has been taken into account, because both the municipal demand and the industrial demands (Catania and Siracusa industrial areas) are always fully met.

In Table 2, the impact analysis matrix is reported. The resulting rankings of the alternatives obtained through application of NAIADE are depicted in Fig. 3. The Φ+ ranking is based on the *better* and *much better* preference relations and indicates how an alternative is "better" than all others. Similarly, the Φ− ranking is based on the *worse* and *much worse* preference relations and indicates how an alternative is "worse" than all others.

The two rankings differ because, for instance, an alternative may slightly perform better than the others only for a few criteria (low Φ+ ranking), but can perform worse than the others for many criteria (low Φ− ranking), or vice versa. However, in our case, there are no great differences in the two rankings, which is indicative of a proper balance of the alternatives. The main differences involve alternatives A and H. In fact, alternative A is significantly better than alternatives B and E, whereas it is significantly worse than all the other alternatives. Alternative H performs a little worse than alternative A with respect to the Φ+ ranking, but it performs much better in terms of the Φ− ranking.

The resulting intersection of the two rankings provides the final ordering of the alternatives. In particular, dominance comparison of the two alternatives may result in either a dominance relationship, when one alternative dominates the other in both prerankings, or in incomparability, where one alternative dominates the other in one preranking but is dominated in the other. It can be inferred that the alternatives with the highest ranking are D (release for irrigation from the Lentini reservoir as a long-term measure, as well as the short-term measures S1+S2+S3), G (water transfer from the Ancipa to the Pozzillo reservoir plus release for irrigation from the Lentini reservoir) and C (modernization of the irrigation network). The current system configuration (alternative A) along with the construction of small reservoirs (alternative F) have the lowest ranking.

Conflict Analysis

Alternatives D, G, and C perform on the whole better than the others therefore, in principle they should be preferred. However, ranking of the alternatives represents only a partial information, because it is known that in a political decision-making process the final solution is often a result of a compromise between the different stakeholders.

From the preference matrix reported in Table 3, which expresses the preferences of each stakeholder with respect to each alternative, it is possible to build the dendrogram of coalitions shown in Fig. 4, which describes the process of coalition formation and the related agreement levels.

The coalition formation process points out that the first coalition is formed by the groups G1 and G2, namely, the irrigation management agency and the farmers of the Catania Plain district, which is quite obvious, because they have basically the same goals. This coalition only vetoes alternatives E, F, and A, namely,

Table 3. Simeto Water Supply System: Preference Matrix by Stakeholders

	Alternatives							
Stakeholders	A	B	C	D	E	F	G	H
G1: irrigation management agency	VB	G	VG	G	MLG	MLG	P	VG
G2: farmers of Catania Plain district	EB	G	P	G	MLG	MLG	P	VG
G3: hydroelectric power agency	P	EB	VG	G	G	G	EB	EB
G4: industries	M	VG	VG	M	VB	G	G	EB
G5: environmentalists	M	MLG	VG	B	P	VB	VB	VG

Note: EB=extremely bad; VB=very bad; B=bad; MLB=more or less bad; M=moderate; MLG=more or less good; G=good; VG=very good; and P=perfect.

the reuse of treated wastewater, the construction of small reservoirs by farmers, and the status quo. Therefore, the alternatives to be preferred from the point of view of this group are B, C, D, G and H.

However, from previous experience, it could be argued that, to reach a solution, a wider consensus of interest groups is required. Considering the coalition of groups G1, G2, G4, and G5, the vetoed alternatives would be D, G, E, F, and A, which narrows the set of eligible alternatives to C (modernization of the irrigation network), H (water transfer from the Ancipa to the Pozzillo reservoir plus treated wastewater reuse), and B (water transfer from the Ancipa to the Pozzillo reservoir). Because alternative B performed poorly in the ranking, the feasible set is further reduced to C and H. However, since in the first phase of the procedure alternative C ranked better than alternative H, eventually modernization of the irrigation network seems to be the most preferable alternative.

Conclusions

Within a proactive approach of coping with drought, a mitigation strategy based on the implementation of long- and short-term measures plays a key role. But there is still a lack of standardized methodologies for the assessment of drought measures; therefore, the selection of the best alternatives is a rather controversial issue.

This study aimed at setting a conceptual framework for a proactive approach to drought mitigation, by proposing a methodology to assess alternatives based on an MCDA technique that takes into account economic, environmental, and social impacts of different measures. The procedure makes use of a simulation model for assessing the effects of the different measures on the performance indices of the system operation. The multicriteria analysis technique NAIADE is then used to assess and rank the different alternatives. The research falls into the mainstream of economics and engineering studies oriented toward a sustainable development of water resource systems. In particular, it follows the general framework set up by the pioneering work by Duckstein (1983) for the assessment of drought mitigation measures, introducing a distinction between the long and the short term. Such a distinction has also been adopted by Dziegielewski (2003), who however followed a traditional economic comparison between measures.

Preferred alternatives are selected based both on the scores of each alternative with respect to the selected criteria and, most importantly, on the capability to gather stakeholders' consensus. Criteria mainly refer to simulation results and are mostly based on objective data, thus avoiding subjective judgments when possible. In fact, although one can clearly see that subjectivity cannot be avoided when dealing with decisional problems, actors can be led to behave in a more transparent and rational manner if subjectivity is kept within its proper context. Results of the application to the Simeto River basin water supply system in Sicily show the importance of the latter feature, because ultimately alternatives that seem to perform better than others according to the selected criteria are not necessarily as feasible, as they can be vetoed by some influential stakeholders' coalitions.

The main conclusion of the paper is that the proposed methodology, although based on sophisticated MCDA tools, enables an intuitive and transparent comparison of drought mitigation measures; thus, it constitutes a potentially useful tool for decision makers. An improved approach to the comparison of drought mitigation measures should take into account the intrinsic stochastic nature of droughts and not be based solely on simulating the system during a historical period. Further research is undergoing to overcome this limitation, by use of a synthetically generated hydrological series.

The study has taken advantage of the continuous feedback from the water resources agency actually operating the system, which has in turn gained a deeper knowledge of the problem at hand. In light of this, one of the significant outcomes of this research can be considered the partial overcoming of what is generally recognized as one of the major limits of the applicability of system analysis methodologies to real water resources systems, namely, the gap between theory and practice.

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