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Multicriteria Analysis for Land-Use Management

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Multicriteria evaluation methods in renewable resource management: integrated water management under drought conditions

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Abstract

The limits inherent in conventional decision theory methodologies and the necessity to analyse conflicts between policy objectives have led to many calls for more appropriate analytical tools for strategic evaluation. As such multicriteria evaluation does not itself provide a unique criterion for choice; rather it helps to frame the problem of arriving at a political compromise. This paper, as a first step, deals with the role of multicriteria evaluation methods in the framework of renewable natural resource management. As a second step, the possibility is studied of using multicriteria evaluation methods to tackle problems of integrated water management under drought conditions. We take water management under drought conditions into account because this is an important issue in many southern countries. The term "integrated water management" is used because it is evident that the problems underlying water management can be dealt with only if all the conflicting activities and uses that affect the resource are taken into account. A real-world example in the area of the city of Palermo (western Sicily) is also considered. From this case study, which is a part of a larger project that has been commissioned by the Sicily region, a number of useful lessons can be learned for comparing alternative strategies for the management of a water system under drought conditions.

Keywords: environmental sustainability, water management, drought conditions, multicriteria evaluation, fuzzy uncertainty, NAIADE method.

1. Multicriteria evaluation in integrated natural resource management

The growth of the world's population and the rapid growth of economic activities have caused environmental stress in all socio-economic systems. There is a wide scientific consensus that problems such as the greenhouse effect, ozone depletion, acid rain, loss of biodiversity, toxic pollution and renewable and non-renewable resource depletion are clear symptoms of environmental un-sustainability. It is evident that fabricated environments (cities, industrial areas, airports, etc.) are neither self-supporting nor self-maintaining. They are sustained by their dependence on the solar-powered natural and domesticated environments (life-supporting ecosystems). Stress, caused by the disposal of wastes and pollutants, negatively affects recycling, feedback loops and control mechanisms in the life-supporting ecosystem and thereby the production and maintenance of environmental goods and services.

In the eighties, the awareness of actual and potential conflicts between economic growth and the environment has led to the concept of *"sustainable development"*. Such a concept is based on the assumption that certain sorts of natural capital are deemed critical, and not readily substitutable by man-made capital (see e.g. Costanza *et al.*, 1996; Munda, 1997; and for applications in water management, Simonovic, 1996). As a consequence, a sustainable economy is an economy that maintains the exploitation of renewable resources (fish, trees, water) within the limits of their rates of renewal; it is an economy that uses non-renewable resources (e.g. petroleum) in line with achievement of a transition (through substitution, technological change, etc.) to a base of renewable resources. It is an economy that keeps the production of waste and contamination within the assimilative capacity of the environment. A sustainable economy is an economy that preserves biodiversity in all its expressions.

Unfortunately, human beings are currently witnessing the emergence of serious problems in the ecological, economic and social dimensions. These problems are interconnected and urgent, thus there is a need to develop synthetic conceptual framework and analytical approaches which begin to explore the interconnections among these three dimensions and the prospects for solutions that simultaneously address problems in all those domains. This is the aim of integrated environmental assessments (IEA) (Bailey *et al.*, 1995). Most IEA applications are based on a cost-benefit analysis approach.

Cost-benefit analysis (CBA) is based on the neo-classical maximisation premise on behaviour, stating that rational decisions coincide with utility maximisation. This approach is based on the assumption that different objectives can be expressed in terms of a common denominator by means of trade-offs (complete commensurability), so that the loss in one objective can be evaluated against the gain in another. From a theoretical point of view, the optimising principle is elegant since it provides an unambiguous tool to evaluate alternative strategies on the basis of their contributions to community welfare. From an operational point of view, the value of the optimising approach is rather limited, because the specification of a community welfare function requires complete information about all possible combinations of actions, about the relative trade-offs between all actions and about all constraints prevailing in the decision making process. Such information is generally not available in the context of environmental decision making, and in any case the validity of the proposed trade-offs is likely to be contested by affected groups (Munda, 1996).

During the last two decades, more support has emerged for the view that welfare is a multidimensional concept (Bana e Costa, 1990; Munda, 1995; Nijkamp *et al.*, 1990; Paruccini, 1994). One should note that incommensurability (i.e. taking into account of all the different dimensions of a decision problem without any monetary reductionism) does not imply incomparability. It is possible to distinguish between the concepts of strong commensurability (common measure of the different consequences of an action based on a cardinal scale of measurement), weak commensurability (common measure based on an ordinal scale of measurement), strong comparability (there exists a single comparative term by which all different actions can be ranked), and weak comparability (one has to accept the existence of conflicts between all different consequences of an action) (Martinez-Alier *et al.*, 1996). Weak comparability can be considered to be the philosophical basis of multicriteria evaluation.

A great number of multicriteria methods have been developed and applied for different policy purposes in different contexts. As a tool for conflict management, multicriteria evaluation has demonstrated its usefulness in many environmental management problems (Munda *et al.*, 1994). From an operational point of view, the major strength of multicriteria methods is their ability to address problems marked by various conflicting evaluations. Real-world problems are generally not direct win-lose situations and a certain degree of compromise is needed. Multicriteria evaluation techniques cannot solve all conflicts, but they can help to provide more insight into the nature of conflicts and into ways to arrive at political compromises in case of divergent preferences in a multi-group or committee system so increasing the transparency of the choice process.

In general, a multicriteria model presents the following aspects:

- there is no solution that optimises all the criteria at the same time and therefore the decision maker has to find compromise solutions;
- the relations of preference and indifference are not enough in this approach, because when an action is better than another one for some criteria, it is usually worse for others, so that many pairs of actions remain incomparable with respect to a dominance relation.

The main advantage of multicriteria models is that they make it possible to consider a large number of data, relations and objectives which are generally present in a specific real-world decision problem, so that the decision problem at hand can be studied in a multidimensional fashion. On the other side, an action **a** may be better than an action **b** according to one criterion and worse according to another. Thus when different conflicting evaluation criteria are taken into consideration, a multicriteria problem is mathematically ill-defined. The consequence is that a complete axiomatization of multicriteria decision theory is quite difficult (Arrow and Raynaud, 1986).

According to Simon (1983), a distinction must be made between the general notion of rationality as an adaptation of available means to ends, and the various theories and models based on a rationality which is either substantive or procedural. This terminology can be used to distinguish between the rationality of a decision considered independently of the manner in which it is made (in the case of substantive rationality, the rationality of evaluation refers exclusively to the results of the choice) and the rationality of a decision in terms of the manner in which it is made (in the case of procedural rationality, the rationality of evaluation refers to the decision making process itself). Other authors question the usefulness of choice as a pervasive metaphor for describing and interpreting human behaviour in the traditional paradigm of decision making, claiming that the issue is not that of choosing but of generating (March, 1978; Winograd and Flores, 1988). Thus, we can conclude that the validity of a given multicriteria method depends on two main factors (Roy, 1985):

- mathematical and descriptive properties which make it conform to given requirements;
- the way it is used and integrated in a decision process.

An important point is the way in which a problem is structured. The results of any decision model depend on the available information. Since this information may assume different forms, it is useful that decision models can take this differentiation into account. Another problem related to the available information concerns the uncertainty associated with this information. Ideally, in the Laplacian perspective on science and decision making, the information should be precise, certain, exhaustive and unequivocal. But in reality, it is often necessary to use information which is known not have those characteristics.

If it is impossible to establish exactly the future state of the problem faced, a stochastic uncertainty may be postulated; this type of uncertainty is well known and it has been thoroughly studied in probability theory and statistics. According to a well-established tradition originating with by the classical contributions of Knight (1921) and Keynes (1921), a distinction is made between two kinds of uncertainty: a weak variety called "risk" and a strong one called "uncertainty". In particular, risk refers to probability distributions based on reliable classification of possible events and uncertainty refers to events whose probability distribution is not fully definable for lack of reliable classification criteria. Existing decision theories, based on substantive rationality, are limited in dealing with environmental decision situations characterised by a high degree of uncertainty about nature, incidence and/or timing of possible environmental costs, especially situations where the effects may be catastrophic for future generations.

Another framing of uncertainty, called fuzzy uncertainty, focuses on the ambiguity of information, in the sense that the uncertainty does not concern the occurrence of an event but the event itself, which cannot be described unambiguously (Zadeh, 1965). This sort of situation is readily identifiable in complex systems. Spatial-environmental systems in particular, are emergent complex systems characterised by subjectivity, incompleteness and imprecision (e.g., ecological processes are quite uncertain and little is known about their sensitivity to stress factors such as various types of pollution). Fuzzy set theory is a useful mathematical theory for modelling situations of such a type, i.e. it aims to portray in terms of fuzzy uncertainty, some of the indeterminacy of the socio-ecological system under study.

2. The NAIADE method

In designing models for environmental and resource policy making the following three main types of policy objectives may be distinguished:

- socio-economic objectives, e.g. "maximum production of goods and services";
- nature conservation objectives, e.g. "minimum exploitation of natural systems", "optimum yield";
- mixed objectives, e.g. "maximum sustainable use of resources and environmental services at minimum (private and social) cost".

It is clear that in policy-relevant economic-environmental evaluation models, socio-economic and nature conservation objectives are to be considered simultaneously. Consequently, multicriteria methods are in principle an appropriate modelling tool for environmental decision making issues: a compromise solution that takes account of different conflicting values can in principle be identified.

Given the problem of the differences in the measurement levels of the variables used for economic-ecological modelling, multicriteria methods able to deal with mixed information (both qualitative and quantitative measurements) can be considered particularly useful. A new multicriteria method, based on some aspects of the partial comparability axiom, called NAIADE[1] (Novel Approach to Imprecise Assessment and Decision Environments) has been developed in Munda (1995). It is a discrete multicriteria method whose impact (or evaluation) matrix may include either crisp, stochastic or fuzzy measurements of the performance of an alternative a_n with respect to a judgement criterion g_m, thus it is very flexible for real-world applications. From an empirical point of view, this model is particularly suitable for economic-ecological modelling incorporating various degrees of precision of the variables taken into consideration. From a methodological point of view, two main issues are then faced:

- the problem of equivalence of the procedures used in order to standardise the various evaluations (of a mixed type) of the performance of alternatives according to different criteria;
- the problem of comparison of fuzzy numbers typical of all fuzzy multicriteria methods.

Both problems are tackled by means of a new semantic distance presenting relevant theoretical properties (Munda *et al.*, 1995). Since in a fuzzy context, any attempt to reach a high degree of precision on the results tends to be somewhat artificial, a pairwise linguistic evaluation of alternatives is used. This is done by means of the notion of fuzzy relations and linguistic quantifiers. In the aggregation process, particular attention is paid to the problem of diversity of the single evaluations, while the entropy concept is used as a measure of the associated "fuzziness". Such linguistic evaluations can be used in different ways according to the decision environment at hand.

In short, the main properties of the NAIADE method can be synthesised as follows (for more details see Munda, 1995):

[1] Naiade is the Italian name for the Greek nymphs of rivers.

- communication with the decision maker is required to elicitate different relevant parameters, thus a constructive decision aid framework is implied;
- the method is based on some aspects of the partial comparability axiom, in particular, a pairwise comparison between alternatives is carried out, and incomparability relations are allowed;
- intensity of preference is taken into account; this implies that a certain degree of compensation between criteria is allowed, given the characteristics of the method it may be classified among partial compensatory methods;
- for the indifference relation no transitivity is implied, the preference relation is max-min transitive;
- a partial (or total) order of feasible alternatives is supplied. It has to be noted that the final ranking is a function of all the alternatives considered, this implies that if a dominated or a dominating action is introduced, the ranking may change; moreover if the best action is eliminated, the ranking of the other alternatives may also change, thus NAIADE does not respect the independence of irrelevant alternatives axiom.

Since in environmental and resource management and policy aiming at an ecologically sustainable development many conflicting issues and interests emerge, particular attention has to be given to the problem of different values and goals of different groups in society. Equity and conflicting values in multicriteria decision aid are traditionally introduced in two different ways:

(1) by weighting the different criteria (unfortunately, in public decision making a single point-value solution (e.g. weights) tends to lead to deadlocks in a decision process because it imposes too rigid conditions to reach a compromise);
(2) by taking into consideration a set of ethical evaluation criteria (a weak point of this approach is that it could lead to an excessive number of evaluation criteria. Furthermore, the identification of ethical criteria may not be an easy task).

A third possibility is the use of conflict analysis procedures to be integrated with multicriteria evaluation in order to allow policy-makers to seek for "defendable" decisions that could reduce the degree of conflict (in order to reach a certain degree of consensus) or that could have a higher degree of equity on different income groups. NAIADE uses a fuzzy conflict resolution procedure. Starting with a matrix showing the impacts of different courses of action on each different interest/income group, a fuzzy clustering procedure indicating the groups whose interests are closer in comparison with the other ones is used. Therefore, finally a compromise solution that takes into account the three conflicting values of efficiency, equity and sustainability can in principle be identified.

3. Multicriteria analysis of integrated water management under drought conditions: the case of Palermo

3.1. Decision making in water system management under drought conditions

Water resource management is characterised by the presence of a strong competition among different categories of consumptive water uses and, as a consequence, among various interest groups. Such a competition also exists between consumptive uses as a whole and "ecological uses" (strongly supported by environmental pressure groups) which aim at limiting water diversion for off-stream uses in order to preserve the ecological equilibrium of ecosystems (in-stream flow uses). It is evident that the issues underlying water management can be dealt with only if all the competitive uses and activities, that effect the resources, are taken into account according to the concept of "integrated water management" (OECD, 1989).

This permanent condition of competition may become a real conflict under drought conditions, i.e. when there is a temporary and casual reduction of available water resources due to a long and severe decrease of rainfall (compared to mean or median natural values). The problem of water shortages due to drought is particularly relevant in Southern Europe for the following main reasons:

- the high variability of the annual precipitation,
- the increase of the used percentage of the mean available water resources (this leads to an increased risk of not satisfying water demands during the years with the biggest deviations from normal conditions).

As a consequence, correct water management rules have to take into account the need for various measures that can reduce the risk of water shortages and/or minimise drought impacts. Water shortages depend not only on hydrological drought which in turn follows from meteorological drought, but also on water supply system characteristics and demand levels, which are both affected by different drought mitigation measures (see Figure 1).

When a complex water supply system is considered, i.e. a water system which has to satisfy multiple purposes (e.g. municipal, irrigation and industrial water demands) by using various water sources, water management under drought conditions implies decisions on (Rossi *et al.*,1995):

- the sharing of water shortages among different users,
- the inter-temporal distribution of release from each source,
- the priority of release from various sources.

In the following sections, we will present a multicriteria approach to this kind of decision making situation in the case of the water supply system of the city of Palermo (western Sicily). This case study is part of a project which has been commissioned from the Sicily region and executed in the context of the European Commission DGXVI structural funds (Paruccini, 1996). This case study was developed over two years of interaction mainly between the authors of this article and the management body of the water supply system of the city of Palermo (plus some social actors involved in the final step of the study).

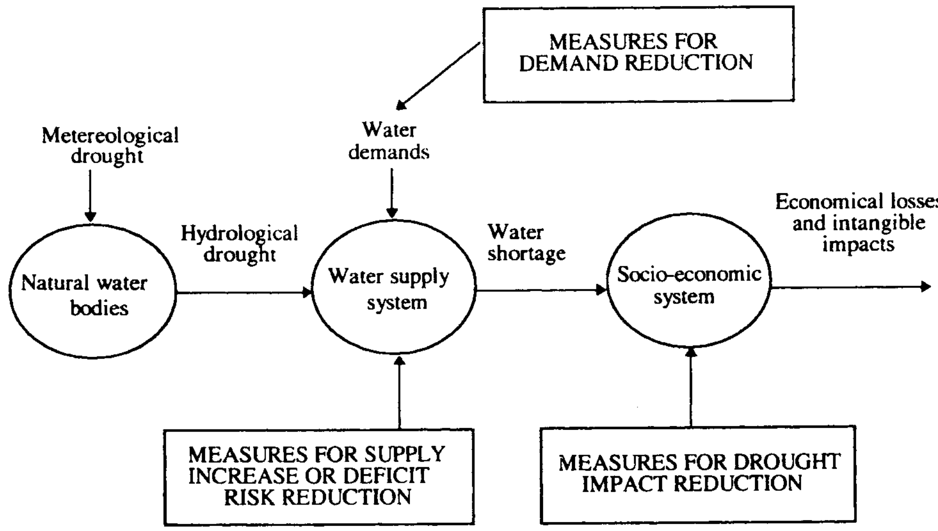

Figure 1. *Drought Effects on Water Supply System and Socio-Economic System.*

3.2. The Palermo Water Supply System

In general terms, a water system is composed of a set of natural elements (water bodies), a set of artificial elements (e.g. reservoir, conveyance conduit, distribution network) and a set of institutional-management structures which interact to achieve one or more objectives (Rossi *et al.*, 1995). A water supply system includes all facilities which allow the supply of surface water, ground water and non-conventional resources to different types of users (municipalities, irrigation districts, industrial districts and so on).

The water system of Palermo has to supply water to municipal, agriculture and industrial users by using surface water and groundwater. The water of the "Piana degli Albanesi" reservoir is also used for energy production. In order to evaluate the vulnerability of the water supply system to future severe droughts, here a few facilities that are not yet in operation, such as the "Rosamarina" reservoir and the "Acque dei Corsari" treatment plant, have been introduced in the scheme of the system.

The Palermo water system under consideration includes (see Figure 2):

- The reservoir of Scanzano, on the river Eleuterio, which provides mainly drinking water (only a very small percentage is used for agriculture);
- The reservoir of Piana degli Albanesi on the river Belice is mainly used for energy production. Only the volume above 11 Mm^3 is available for agriculture and drinking

water. The percentages are 90% for drinking water and 10% for agriculture. The upper annual constraints are 9 Mm^3 for drinking water and 1 Mm^3 for agriculture;

- The reservoir Poma, on the river Iato, is used for agriculture (60%) and drinking water (40%). Sometimes part of the water is used for municipalities close to Palermo. The total annual available volume is 30 Mm^3;
- The spring-water Scillato mixed with the waters of "Galleria Presidiana" (in the ratio of 3:1) supplies drinking water to Palermo and some municipalities in the east of the city;
- Other springs (Risalaimi, Gabriele) which provide water to Palermo and several wells supplying municipal and agricultural uses;
- A few surface water diversions (Imera, Monte Tesoro, S.Caterina) devoted to supply drinking water to Palermo;
- The reservoir Rosamarina, on the river San Leonardo is used for agriculture (65%) and drinking water (35%). The total annual available volume is 55 Mm^3;
- The waste waters of Palermo, treated by the plant of "Acqua dei Corsari" are used for agriculture only in the volume of 5 Mm^3 (the annual possible maximum volume being 13 Mm^3).

3.3. Drought mitigation alternatives and evaluation criteria

The alternative management options under drought conditions can be divided into two main groups:

- alternatives that try to satisfy 100% of the water demand (group A),
- alternatives that do not satisfy completely the water demand (group B).

Group A:

a1: Reduction of the hydroelectric use of water in Piana degli Albanesi (i.e., it is possible to use the water volume under 11 Mm^3 for municipal use). In this case, a penalty to the company managing the hydroelectric production (ENEL) has to be paid.

a2: Use of the waste water treatment plant of "Acqua dei Corsari" up to its maximum capacity (13 Mm^3) for irrigation.

a3: Relaxation of the ecological constraint of maintaining minimum in-stream flows on the whole set of rivers and use of these resources for water supply.

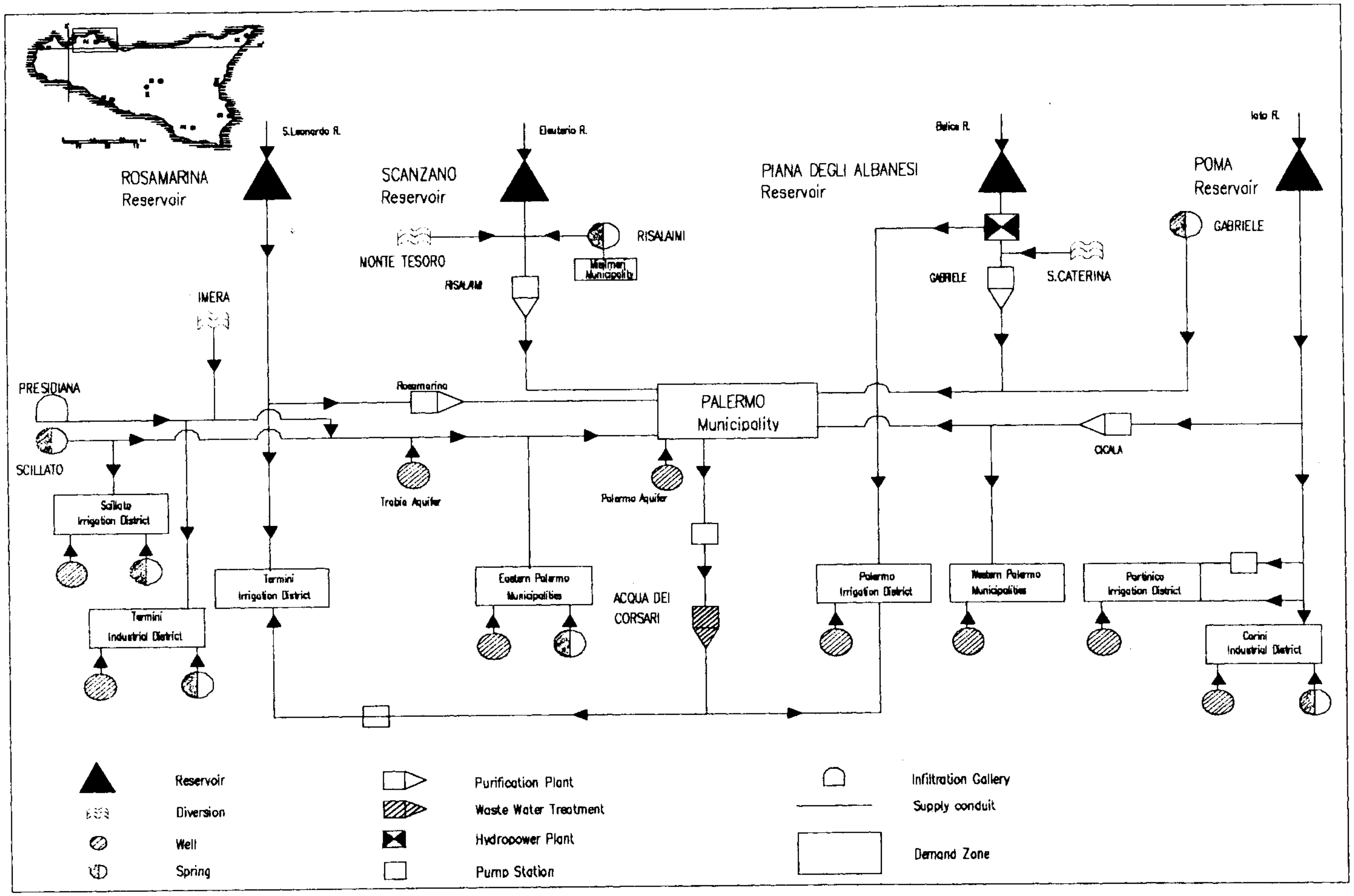

Figure 2. *Scheme of the Palermo Water Supply System.*

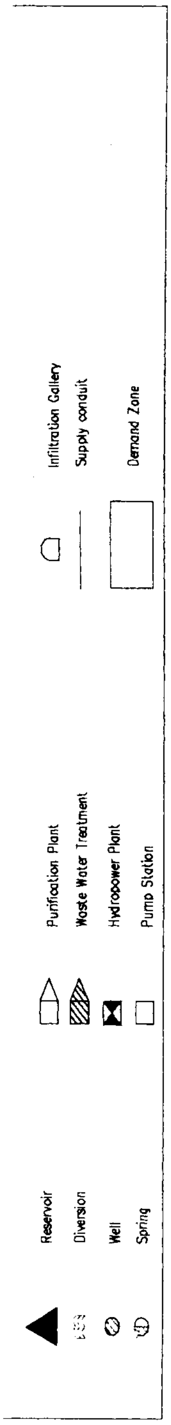

Figure 2. Scheme of the Palermo Water Supply System.

Group B:
The demands are satisfied only in the following percentages:
b1: Drinking water 100%; agriculture 85%; and industry 85%.
b2: Drinking water 100%; agriculture 70%; and industry 85%.
b3: Drinking water 90%; agriculture 70%; and industry 85%.

These alternatives were evaluated for the longest drought experienced in the past (4 years) according to the following set of criteria.

Economic criteria
These criteria measure the monetary impact of the different alternatives on the different economic activities of the region. Costs are computed for the 4 years of the drought period. Both costs and returns have been considered for the organisation in charge of the water system (AMAP):

(1) The costs for AMAP include penalties due to ENEL, total costs connected to water pumping, and incremental costs for the operation of the distribution network under drought conditions.
(2) Returns for AMAP include all categories of users and are referred to the consumed volumes.
(3) Industrial costs measure the additional costs of searching for alternative water sources during drought events. The industrial areas of Carini and Termini Imerese are considered.
(4) Agriculture is very sensitive to water supply. The criterion used measures the total return of each alternative.

For AMAP and industry the values are crisp. For agriculture the uncertainty is quite high, so symmetric fuzzy numbers of a Gaussian form are used. All the values are in Billion Italian Lire (approximately 1US Dollar is 1600 Italian Lire).

Social criteria
Hygienic risk and social discomfort are considered.

(5) Hygienic risk refers to the risk of water contamination linked to low pressure in the water distribution network. This phenomenon is connected to a number of different factors, e.g. maintenance of the network, sewer conditions and distribution, etc.. Here, a good proxy has been considered the number of days in four years for which the threshold of unsatisfied demand is exceeded.
(6) Social discomfort is considered as a consequence of three hydrologic indicators obtained by means of simulation models. The indicators are average quantity of water not supplied (deficit), frequency of water deficit, and maximum quantity not supplied in a month. The aggregation of these indicators is not easy. After technical simulations, a linguistic score has been selected based on the ranking obtained with a multicriteria application.

Environmental criteria

(7) The in-stream flow requirement (IFR), defined as the discharge which maintains a stream ecosystem or aquatic habitat, has been considered because it is easy to quantify and gives a good picture of the ecological conditions of the ecosystems affected. This criterion measures the water deficit to satisfy the minimum in-stream flow requirement constraint. The measurement unit is $10^6 m^3$ per year.

The multicriteria evaluation matrix shown in Table 1 shows all the performance scores of the alternatives under evaluation.

Table 1. Multicriteria evaluation matrix.

	business as usual	a1	a2	a3	b1	b2	b3
1.costs AMAP (10^3 IT. Lire)	106,968	101,988	103,106	99,832	106,121	106,831	100,721
2.returns AMAP (10^3 IT. Lire)	523,321	549,240	575,514	559,747	527,193	541,411	515,270
3.Incr.Ind.par costs (10^9 IT. Lire)	0	0	0	0	6437	6437	6437
4.Agricul. product. (10^9 IT. Lire)	about 864	about 865	about 1143	about 864	about 737	about 618	about 711
5.Hygienic risk (No. of days)	89	54	36	34	83	54	33
6.Social Discom. (Linguis.)	very high	more or less high	moderate	moderate	very high	more or less high	high
7.Missing water for IFR (10^6 m^3)	48.4	48.4	43.1	97.3	45.8	44.7	39.8

3.4. Application of an aggregation procedure: the NAIADE method

Given that our problem is characterised by mixed information and various distributional issues, the NAIADE method has been considered particularly suitable. By applying NAIADE to the impact matrix described in Table 1, a quite stable ranking of the alternatives is obtained. The subset {**a1**, **a2**, **a3** and **b3**} contains the best alternatives. **b3** is always worse than the others. Thus, the decision is among **a1**, **a2** and **a3**. In particular, **a2** seems to be slightly better than the others.

The interest groups taken into account are the following: city inhabitants, farmers, industrial organisations, ENEL, AMAP and environmentalists. The impacts have been evaluated by means of interactions with relevant local people (various interviews with representatives of the interest groups). The equity impact matrix is shown in Table 2.

Table 2. Equity Impact Matrix.

	business as usual	a1	a2	a3	b1	b2	b3
city inhabit.	bad	moderate	good	good	bad	moderate	more or less bad
Farmers	more or less good	more or less good	very good	more or less good	moderate	bad	bad
Industr.	good	good	good	good	bad	bad	bad
ENEL	good	bad	good	good	good	good	good
AMAP	more or less bad	more or less good	good	good	moderate	moderate	more or less bad
Environ.	moderate	moderate	good	very bad	good	good	good

By applying NAIADE, the dendrogram shown in Figure 3 is obtained. The results are quite well in agreement with prior expectations about the attitudes and behaviour of the interest groups. The interests of the city inhabitants and AMAP seem to run fairly parallel. The same applies to the industrial organisations and the farmers. Anyway, the group composed by farmers, industrial organisations, city inhabitants and AMAP may have some common compromise solutions. ENEL and environmentalists presents a more individualistic character. One should note that **a2** has a good impact on all the interest groups considered. On the contrary **a1** and **a3** could be vetoed by ENEL and environmentalists, thus by considering the minority principle **a2** would be strongly recommended.

4. Conclusions

Some lessons were learned from the experience made in this case study. First of all, the use of a multicriteria framework is a very efficient tool to implement a multidisciplinary approach necessary in natural resource management. The technical actors involved had various backgrounds (mainly in engineering, economics and mathematics). At the beginning the communication process was very difficult. However, it was astonishing to realise that a common language emerged as soon as it was decided to structure the problem in a multicriteria fashion. Since some of the criterion scores were characterised by approximate evaluations, the use of fuzzy sets was very useful. It was also evident that the possibility of taking into account distribution issues explicitly increased the transparency of the study. It also made the interaction with and between various social actors possible and effective. We think that these characteristics of the approach make it suitable for applications in other spatial and cultural contexts.

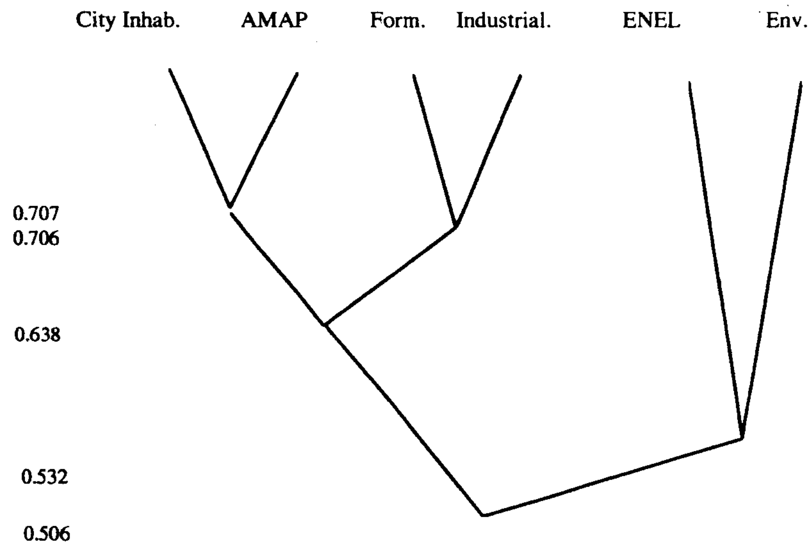

Figure 3. *Dendrogram of the coalition formation process.*

The results of this study were considered relevant for the real-world integrated management of Palermo water supply system. However, one has to admit that time and resource constraints limited the possibility of a better structuring of the decision problem at hand (e.g. a more complete set of criteria, more technical simulations on the hydrological behaviour of the system, and so on). Attempts to improve these aspects of the approach will be the aim of future researches.

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