MULTICRITERION DECISION ANALYSIS (MCDA) FOR CONFLICT RESOLUTION IN SHARING GROUNDWATER RESOURCES

JACQUES GANOULIS*
UNESCO Chair and Network INWEB: International Network of Water/Environment Centres for the Balkans, Department of Civil Engineering, Aristotle University of Thessaloniki,
54124 Thessaloniki, Greece
http://www.inweb.gr

Abstract. Different socio-economic attributes and goals of countries sharing transboundary aquifer resources may lead to potential conflicts and political tensions. The MCDA methodology is adapted in order to compromise different management strategies suggested by adjacent countries. The methodology incorporates the results of a Risk-based Integrated Transboundary Aquifer Resources Management (RITAM) approach, which is presented in Ch. 12, in order to suggest common acceptable policies. An example of its application is given for the case of Mesta/Nestos River flowing between Bulgaria and Greece.

Keywords: attributes, criteria, risk, transboundary groundwater resources management

1. Introduction

There are many examples where potential conflicts over the use of internationally shared groundwaters could arise. In South Eastern Europe (SEE) for example, since the collapse of the Yugoslav Federation, about 90% of the region lies within international basins, as compared to a world average of 50%. More than half of these transboundary basins belong to three or more riparian states. Transboundary groundwater resources are the most important source for drinking water in the region and competition over the use of this water is

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*Corresponding author: Prof. Jacques Ganoulis, UNESCO Chair and Network INWEB, Department of Civil Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece; email: iganouli@civil.auth.gr

constantly increasing, not only between different sectors within each country but also between countries (Ganoulis et al., 1996). The case of the Dinaric karst aquifer system situated along the Adriatic coast is very characteristic of the natural complexity of transboundary groundwater resources and the involvement of two or three countries (INWEB, 2007). In this area, huge amounts of water are stored in karst aquifers originating in high mountains and distributed between two or three countries. Waters may recharge and circulate through deep karst formations located in one country (inner Dinarides) and appear in the form of karst springs in an neighbouring country, usually along the Adriatic coast (outer Dinarides).

The case of sharing groundwaters in the Middle East is also very acute, especially since 1967 when Israel occupied the West Bank where strategic aquifers are located. Although the Palestinian-Israeli accords (Oslo II) were concluded in 1994, Palestinians still protest over the sharing of groundwater in the region.

Potential conflicts in sharing transboundary groundwaters may arise at two different scales:

1. national or internal scale and
2. international or external scale.

Internal conflicts are often due to competition over sharing water quantities among various sectors, like agriculture, urban water supply and industry. International conflicts may occur between neighbouring countries for different reasons

- sovereignty and other rights,
- national jurisdiction,
- historical reasons,
- competition over resources,
- complexity of regional issues and
- lack of participation of involved stakeholders.

To deal with potential water-related problems, UNESCO developed a special educational training project called PCCP: from Potential Conflict to Cooperation Potential. PCCP is a programme component within UNESCO's World Water Assessment Programme (WWAP, UN WWDR, 2003). The WWAP was conceived to respond to the 7 key challenges formulated in the Declaration of the Ministerial Conference held in The Hague during the 2nd World Water Forum in March 2000. One of the key challenges identified was

"Shared Water Resources Management." Within WWAP, UNESCO was given the task of elaborating the response to this challenge. The objectives of PCCP, moreover, are consistent with achieving the Millennium Development Goals (MDGs) agreed at the World Summit in Johannesburg in 2002, since PCCP aims at strengthening man's ability to cope with water related problems and to govern wisely in water related issues. This is vital if increased water security is to be achieved, extreme poverty to be eradicated and environmental sustainability to be ensured. Through PCCP, UNESCO has produced and published an extremely valuable and comprehensive knowledge base on conflict resolution in the water context, which was first presented at the 3rd World Water Forum in March 2003. This knowledge base consists of:

- 19 papers, reports and papers reviewing the legal, technical and diplomatic tools available for the anticipation and resolution of water conflicts.
- 9 case studies from around the world drawing lessons from both root causes of conflicts and successful cooperation in water resources management.

5 educational modules addressed to a large target audience with an interest in water management, ranging from post-graduate students to high-ranking decision makers.

Many alternate negotiation strategies are available to modify a complex framework of transboundary groundwater management issues. The best policy is that which provides benefits to both sides. This is a "win-win" solution or a "positive-sum" policy. On the contrary, the worst overall policy is a "zero-sum" or "win-lose" solution, in which one country wins and the other loses. In all cases, potential water-related conflicts may worsen when there is water scarcity in the region (Ohlsson, 2004).

Since it is very difficult to increase the actual amount of water available, the best way to reverse a "win-lose" situation is through developing cooperation between riparian countries and implementing common management policies. In fact a study conducted by Wolf (1998) concluded that around the world there are more agreements for cooperation on sharing waters than conflicts between countries on the same issue. In the Transboundary Freshwater Dispute Database developed by Wolf, the full text of 140 water-related treaties is available, as well as negotiating notes from 14 basins and files on water-related agreements. Good examples of cooperation along big international river catchments are cited in the literature, such as the Rhein and the Danube Rivers in Europe and the Mekong River in South Eastern Asia.

The main problem is the implementation of existing agreements by local institutions and decision makers. In this context, MCDA methodology for conflict resolution may be a helpful tool in order to develop trust and initiate a compromise strategy based on a "win-win" policy.

2. Optimisation versus Compromise Solutions

In the past, traditional engineering approaches for water resources management emphasized the effective use of economic resources in planning and operation. Whilst still providing a reliable framework, investment and maintenance costs were to be minimised. As shown schematically in Fig. 1, the main objective was to minimise total costs under a given degree of technical reliability. If only one objective is taken into account, an optimisation problem can be formulated.

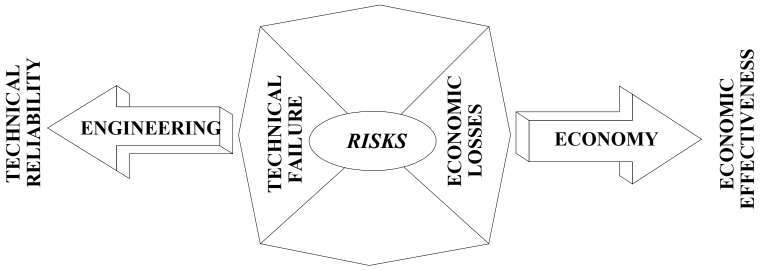

Figure 1. Economic effectiveness versus technical reliability.

2.1. ECONOMIC OPTIMISATION UNDER RISK

When using engineering modelling for the design of a water management plan, a number of options or alternative solutions usually emerge. The selection of any one particular solution depends upon the criteria used and is part of the decision process. In some simple cases, the particular objectives can be formulated as functional relationships between the problem variables. In cases where there is only one objective, analytical or numerical optimisation techniques can be applied (Ang and Tang, 1984; Mays and Tung, 1992). Using such techniques, maximisation or minimisation of the objective function and the choice of an "optimum" solution may be achieved either under conditions of certainty or risk (Ganoulis, 1994).

To clarify this, let us first consider a simple, one-dimensional decision problem. As shown in Fig.2 a flood levee is to be constructed having a crest height h above the mean water level h_o (free board). To determine one value of the variable h, which ensures an acceptable protection from possible floods, first the uncertainty conditions and the objectives of the project should be defined.

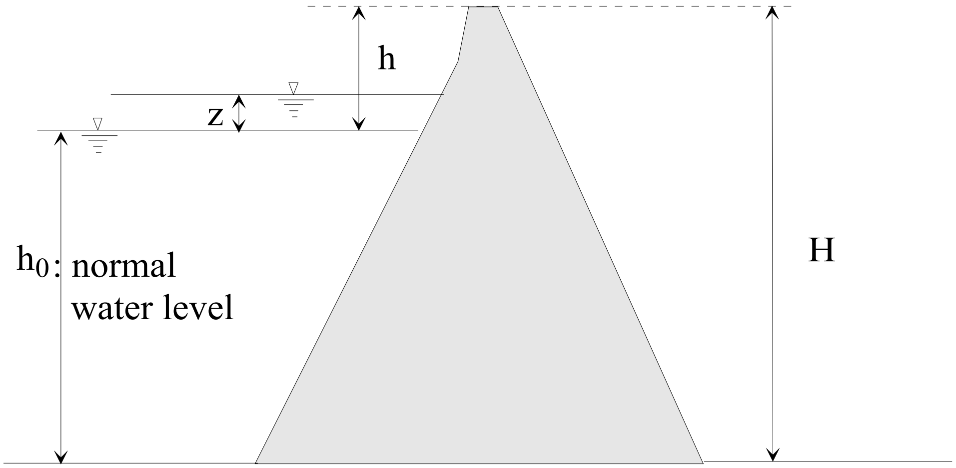

Figure 2. The flood levee optimisation problem.

If sufficient experience from other cases is available, then we can assume that the levee operates under deterministic or certainty conditions, although overtopping of the levee is still possible. Apart from the investment costs of building the levee, we should also consider the costs arising from the consequences of a flood, when the water overtops the levee. Different kinds of damage behind the levee can be considered: damage to property, loss of life, environmental consequences, decrease in aesthetic values, etc. One reasonable objective should be to minimise the sum of both investment and damage costs.

For example, let us assume that investment costs C_I increase proportionally to the free board height h (Fig. 2). The function C_I (h) has the form

$$C_I = C_o + A\,h \tag{1}$$

Damage costs C_D may decrease exponentially with h (Fig. 2), i.e.

$$C_D = Be^{-\lambda h} \tag{2}$$

The *objective function* f(h) is written as

$$f(h) = C_I(h) + C_D(h) = C_0 + Ah + Be^{-\lambda h} \tag{3}$$

and the optimal solution (Fig. 2) is at the minimum f(h), i.e.

$$f_{opt} = \min f(h) \tag{4}$$

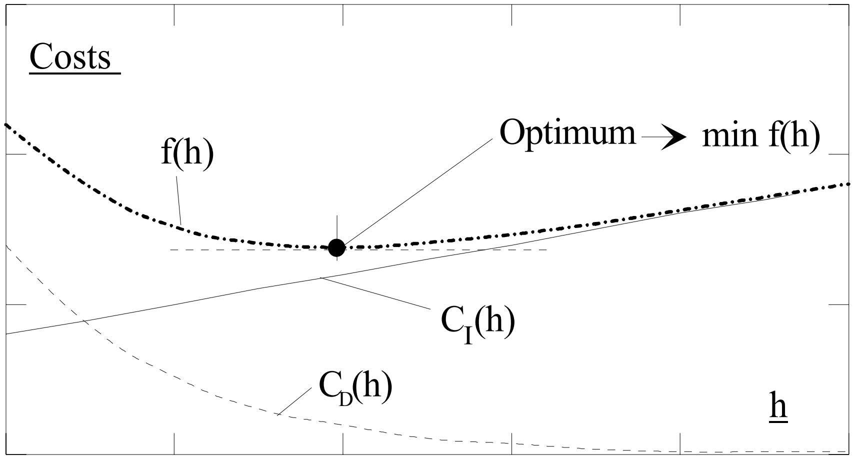

Figure 3. Optimisation of total costs under certainty.

In reality, the decision problem of flood protection usually involves uncertainties. These uncertainties may be quantified in terms of risk, which may be taken as a decision variable in optimisation.

In a simple example such as the flood levee, let us consider the hydrological risk p_F as the probability of overtopping. This may be expressed as

$$p_F = P(z + h_o > H) = P(z > H - h_o) = F(h) \qquad (5)$$

where

P: is the probability
z: is the elevation of the flood above the normal water level h_o, and
h= H - h_o : is the free board, i.e. the height of the levee above h_o (Fig. 1).

From Eq. (5) a relation may be found between p_F and h. The objective function given by Eq. (3) may be written as a function of p^F and the optimum solution may be found in terms of p^F or (-ln p^F). At every level of risk there are consequences implying potential damages. These may be expressed in terms of *damage costs* having monetary or non-monetary values. Protection against damage should imply some other costs, called *protection costs.*

For low risk, the damage costs are low and they increase as risk increases. The opposite is true for the protection costs: high investment is necessary to keep the risk as low as possible. As risk increases so protection costs decrease. Generally speaking, we can state that:

(a) *damage costs* increase as risk increases and decrease as safety increases

(b) *protection costs* decrease as risk increases and increase as safety decreases.

To illustrate these statements let us consider a simple example in which the probability of overtopping is known. It is assumed that the probability density distribution of the flood elevation above the normal water height is exponential (Ang and Tang, 1984), with a mean value 2 m above h_o. In order to find the risk corresponding to the economically optimum design and the corresponding height h of the water level above h_o, it will be assumed that only one overtopping is expected with damage cost (C_D / overtopping) = 70,000 US$. The construction costs have the functional form (1), with C_o = 20,000 and A = 7,500 US$.

It is given that the probability density function of the flood elevation z above the normal water level is known. It can be expressed as an exponential distribution with a mean value 2 m above h_o. We have:

$$f(z) = \lambda\ e^{-\lambda z} \tag{6}$$

$$E(z) = <z> = 1/\lambda = 2 \tag{7}$$

$$\begin{aligned} P\ (h_0 + z > H) &= \int_{z=H-h_0}^{\infty} f(z)dz = \int_{z=H-h_0}^{\infty} \lambda e^{-\lambda x}dx = \\ &= -\ e^{-\lambda z}\Big|_{H-h_0}^{\infty} = e^{-\lambda(H-h_0)} = e^{-(H-h_0)/2} \end{aligned} \tag{8}$$

The probability of overtopping, i.e. the probability of having z > h (Fig. 1) may be calculated as:

The probability of overtopping is by definition the *engineering risk* or *probability of failure* p_F. From Eq. (8) it follows that:

$$p_F = e^{-h/2} \qquad \text{or} \qquad h = -2\ \ln\ p_F \tag{9}$$

Protection Costs: C_p

These are proportional to h. The general expression is:

$$C_p = C_0 + Ah = C_0 - 2\ A\ \ln\ p_F \tag{10}$$

From Eq. (10), C_p decreases as p_F increases.

Damage Costs: C_D

Suppose that B represents the expected costs for every overtopping. Then the total damage costs are

$$C_D = E\,(\text{less/overtopping})\;P\,(\text{overtopping}) = B\,p_F$$

The total costs are

$$C_T = C_p + C_D = C_0 - 2\,A\,\ln p_F + B\,p_F$$

It can be seen from Fig. 4 that if safety ($-\ln p_F$) is chosen as a variable, investment costs are an increasing function of safety, whereas damage costs decrease with increasing safety. The risk corresponding to the optimum (minimum) cost is shown in Fig. 4.

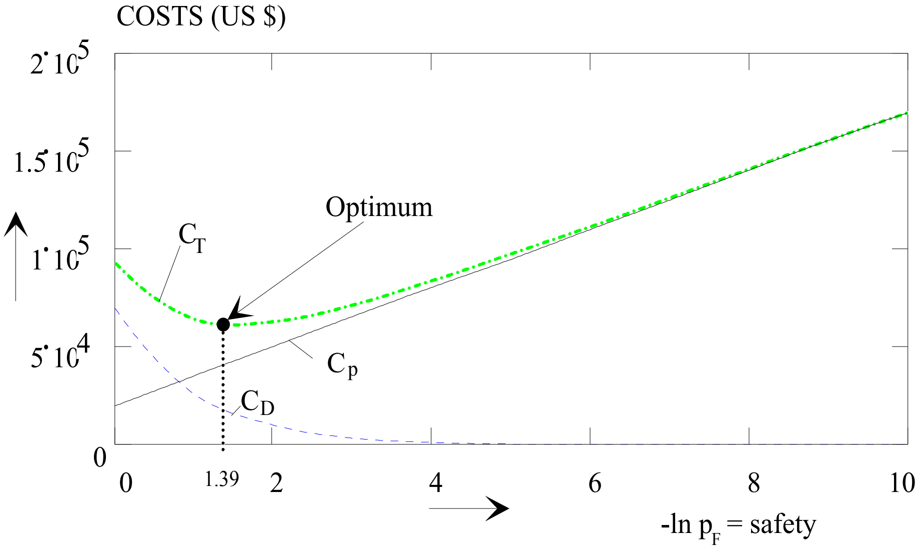

Figure 4. Economic effectiveness versus technical reliability or safety.

2.2. MULTI-CRITERIA COMPROMISE METHODOLOGIES

To obtain sustainable water resources management the four pillars of sustainability should be respected, which, as shown in Fig. 5, are:

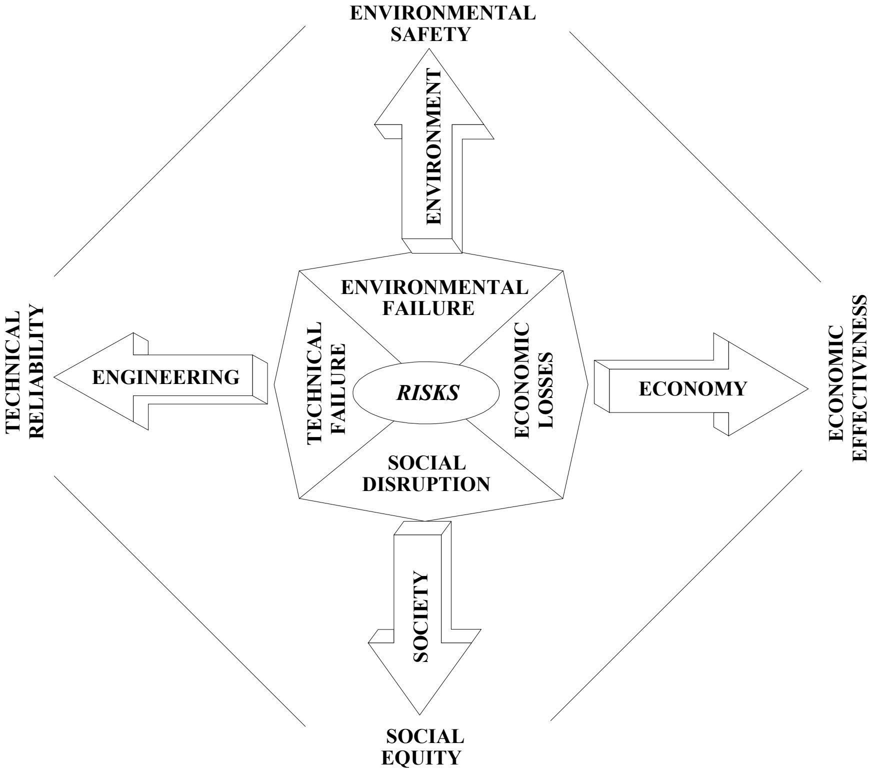

Figure 5. The four pillars for sustainable water resources management.

1. Technical Reliability,
2. Environmental Safety,
3. Economic Effectiveness, and
4. Social Equity

For every specific case of a given river basin the above four objectives can be hierarchically structured in attributes and goals. This is the hierarchical MCDA approach, shown in Fig.6 (Bogardi and Nachtnebel, 1994; Vincke, 1989).

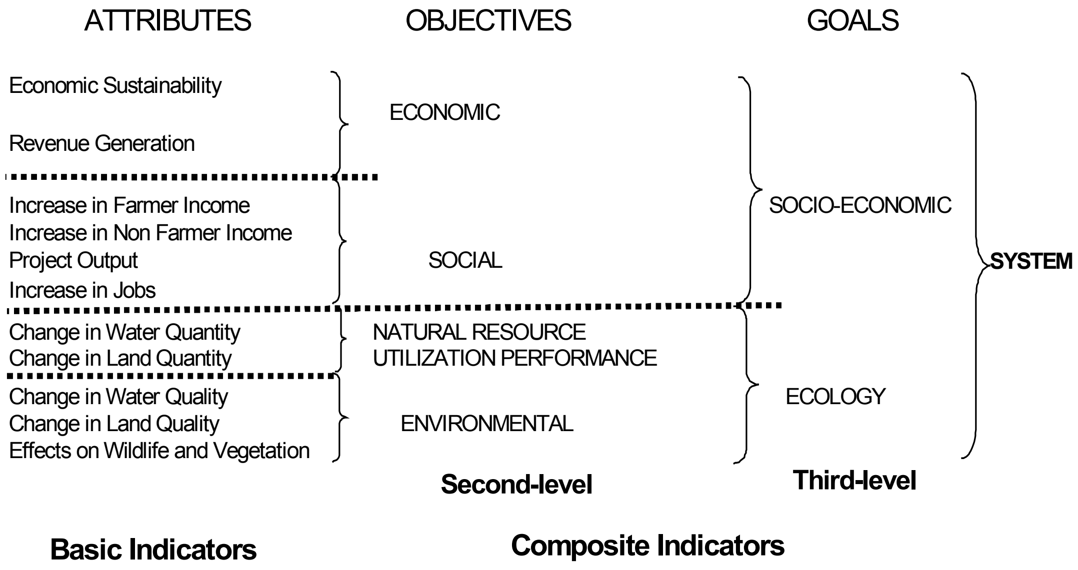

Figure 6. Attributes, objectives and goals for sustainable water resources management.

MCDA techniques are gaining importance as potential tools for solving complex real world problems because of their inherent ability to consider different alternative scenarios, the best of which may then be analysed in depth before being finally implemented. (Goicoechea et al., 1982; Szidarovszky et al., 1986; Pomerol and Romero, 2000).

In order to apply MCDA techniques, it is important to specify the following:

- *The attributes*, which refer to the characteristics, factors and indices of the alternative management scenarios. An attribute should provide the means for evaluating the attainment level of an objective.
- *The objectives*, which indicate the directions of state change of the system under examination, and which need to be maximised, minimised or maintained in the same position.
- *The criteria*, which can be expressed either as attributes or objectives.
- *The constraints*, which are restrictions on attributes and decision variables that can or cannot be expressed mathematically.

A multi-criterion programming problem can be represented in a vector notation as:

"*Satisfy*" $\mathbf{f}(x) = (f_1(x), f_2(x), \ldots, f_I(x))$ (11)

Subject to $g_k(x) \leqq 0, \; k = 1,2,\ldots, K$ (12)

$x_j \geq 0, \; j = 1,2,\ldots, J$ (13)

Here there are I objective functions each of which is to be "*satisfied*" subject to the constraint sets (12) and (13). The region defined by this constraint set is referred to as the feasible region in the J-dimensional decision space. In this expression, the set of all J-tuples of the decision variable x, denoted by X, forms a subset of a finite J-dimensional Euclidean space; in many other applications, X is defined to be discrete. In the further special case when X is finite, then the most satisfying alternative plan has to be selected from that finite set X. It is important to note at this point that the word "optimum" which includes both the maximisation of desired outcomes and minimisation of adverse criteria is replaced by the word "satisfactum" and "optimise" is replaced by "satisfy" in this discussion. The reason is that when dealing with two or more conflicting objectives one cannot, in general, optimise all the objectives simultaneously (Simon, 1957) as an increase in one objective usually results in a deterioration of some other(s). In such circumstances trade offs between the objectives are made in order to reach solutions that are not simultaneously optimum but still acceptable to the decision-maker with respect to each objective (Goicoechea *et al.*, 1982; Roy, 1996).

In a mathematical programming problem such as the one defined by equations (11), (12) and (13), the vector of decision variables and the vector of the objective functions **f**(x) define two different Euclidean spaces. These are (1) the J-dimensional space of the decision variables in which each coordinate axis corresponds to a component of vector X, and (2) the I-dimensional space F of the objective functions in which each coordinate axis corresponds to a component of vector **f**(x). Every point in the first space represents a solution and gives a certain point in the second space that determines the quality of that solution in terms of the values of the objective functions. This is made possible through a mapping of the feasible region in the decision space X into the feasible region in the objective space F, using the I-dimensional objective function.

2.2.1. *Feasible, Non-Dominated and Efficient Solutions*

In Multi-Criterion Decision Analysis (MCDA) the question is not to obtain an optimal solution as in the case of one objective. Instead of an optimum solution we speak about a "non-inferior" or "non-dominated" solution. This is a solution for which no improve in a single objective can be achieved without causing a degradation of at least another objective.

Let us consider, for example, the problem of “maximising” two conflicting objectives Y_1 and Y_2 subject to a set of constraints

$$g_j(x_1, x_2, ..., x_n) \leq = \geq 0 \quad j = 1, 2, .., m$$

As shown in Fig. 7, each couple of values Y_1 and Y_2 that satisfy the constraints lies within the *feasible region or feasible space*. This region is limited by a curve ABCD called a *feasibility frontier*. All points of this frontier form the set of "*non-inferior*" or *"non-dominated*" solutions. Every decision vector on this curve is defined by a maximum value of the objective Y_2 given a value of the objective Y_1. This particular solution is "optimal" in the sense that there can be no increase in one objective without a decrease in the value of the other objective.

A selection of one particular solution from a set of non-inferior solutions depends on the preferences of the decision maker. This may be indicated by a family of *iso-preference* or *indifference curves* (Fig. 7). In this figure the *efficient solution* is defined by the point B on the feasibility frontier that has the maximum level of preference.

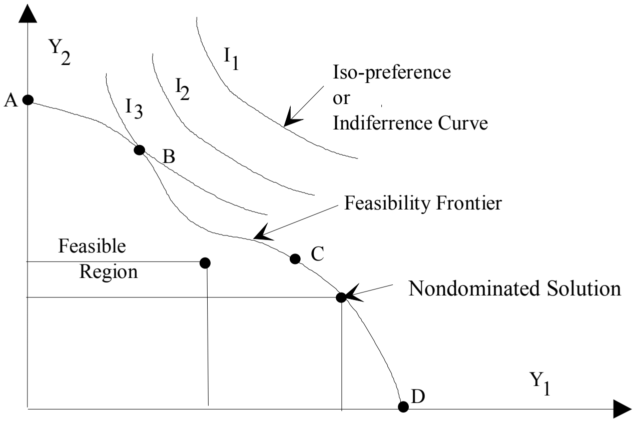

Figure 7. Non-dominated solutions for a two-objective problem.

2.2.2. *Solution Procedures and Typology of MCDA Techniques*

Finding the set of efficient solutions of a mathematical programming problem is usually determined using a generating procedure, in which an objective function vector is used to identify the non-dominated subset of feasible decisions. This procedure deals mostly with the objective realities of the problem (e.g., the set of constraints) without necessarily taking into consideration the preference structure of the decision-maker.

In order to clarify the technique choice procedure, the classification of MCDA models given in Tecle and Duckstein (1994) is now summarised. Five types are distinguished:

1) *Value or utility-type*, which essentially coalesce the multiple objectives into a one-dimensional "multi-attribute" function It can be a value function that is deterministic or a utility function that includes a measure of risk.
2) *Distance-based techniques*, which seek to find a solution as "close" as possible to an ideal point, such as *compromise* and *composite* programming or else, a solution as "far" as possible from a "bad" solution, such as the Nash cooperative game concept.
3) *Outranking techniques*, which compare alternatives pair wise, and reflect the imperfection of most decision-makers' ranking process (Roy, 1996) namely, alternative A(j) is preferred to alternative A(k) if a majority of the criteria C(i) are better for A(j) than for A(k) and the discomfort resulting from those criteria for which A(k) is preferred to A(j) is acceptable. As a result, non-comparability of certain pairs of alternatives is an acceptable outcome; this is in contrast with the previous two types of approaches where a complete ordering of alternatives is obtained. Techniques such as ELECTRE and PROMETHEE are recommended.
4) Direction-based, interactive or dynamic techniques where a so-called progressive articulation of preferences is undertaken.
5) Mixed techniques, which utilise aspects of two or more of the above four types. In planning problems a general class of methodology has been developed to rank different alternatives with various conflicting objectives under risk. (Goicoechea et al., 1982).

One of the promising methods is the *Composite* or *Compromise* Programming. First, trade-offs between objectives may be made in different levels to obtain some composite economic or ecological indicators. Then, ranking between different strategies or options may be done using different techniques, such as the one based on the minimum composite distance from the ideal solution (Fig. 8) (Duckstein and Szidarovszky, 1994).

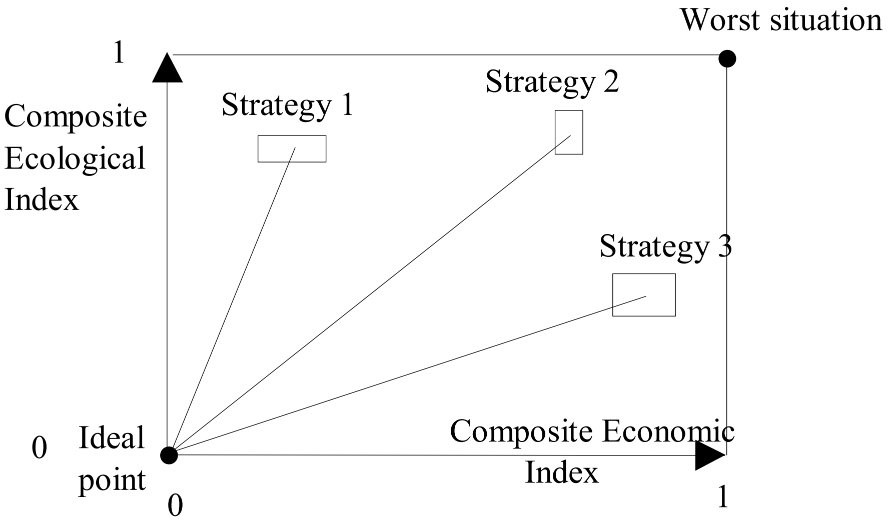

Figure 8. Ranking of different strategies expressed in terms of economic and ecological indexes.

3. Modelling TransboundaryConflicts

Conflict situations in transboundary groundwater resources management may occur on at least two levels:

1. conflict among specific attributes, in particular economic, environmental and social ones and
2. conflicts of goals or general interests between countries and among groups of actors involved.

Goals:

Broadly speaking, every state has social, economic and political goals linked to water resources development, conservation, and control and protection of the river basin. Economic goals may be to obtain new water resources in order to increase food production, conservation goals may be to control water pollution, and control and protection goals may concern defence against floods or drought control. These goals may be achievable by jointly building water reservoirs. This would entail the states involved cooperating together and solving possible areas of conflict.

Purposes in accomplishing goals:

Goals are accomplished by various water resources developments, transfers of water from the water-surplus adjacent river basins, water conservation, control and protection. Each particular goal means satisfying some particular purpose, which may have to do with irrigation, drainage, hydropower production, navigation, water supply, water pollution control, flood defence, drought control, or other.

Objectives and attributes in accomplishing purposes and goals:

Finally, to satisfy the purposes of state goals in water resources development one must define and then maximise or minimise particular economic, social, monetary and political attributes. The particular purposes, attributes and interests in water resources development of the river basin should be strictly taken into consideration in any future cooperation on conflict resolution between the states.

3.1. MCDA FOR CONFLICT RESOLUTION

Three different approaches are suggested for conflict resolution. In the *first approach,* each country proceeds separately and evaluates alternatives according to its own objectives (Fig. 9).

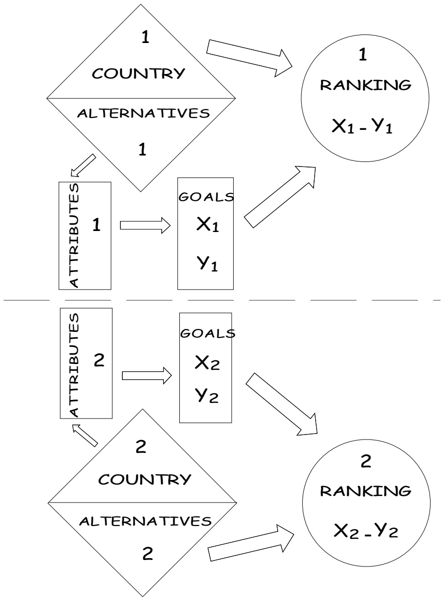

Figure 9. Each country uses MCDA separately according to its own objectives.

In the *second approach* the different attributes used by the two countries are first traded-off and then alternatives are ranked according to the composite objectives (Fig. 10).

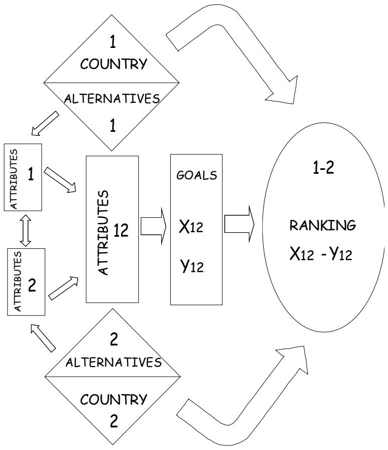

Figure 10. Compromising countries' different attributes.

The *third method* is based on the aggregation of the countries' different alternatives in order to obtain a consensus between them (Fig. 10).

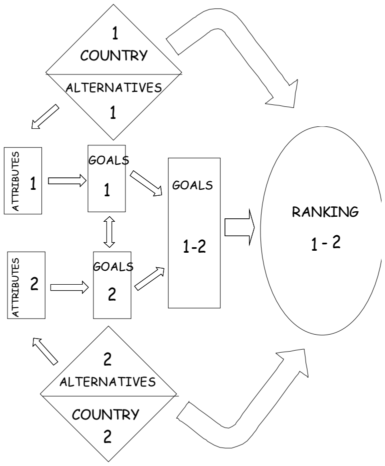

Figure 11. Compromising countries' different goals.

As an extension of the present methodology, two different types of uncertainties can be taken into consideration:

1. uncertainties in attribute and goal values
2. uncertainties in the preferences of the decision makers and other interest groups.

The methodology can be applied either for internationally shared surface or groundwaters. As an example, the case of the transboundary Nestos/Mesta River, flowing between Greece and Bulgaria is presented.

4. A Case Study: the Mesta/Nestos Transboundary Waters

Different management alternatives and different projects were suggested from both countries in order to address the following regional problems:

1. *water availability*: water supply for urban and rural settlements, agriculture, recreational activities and hydro-power generation are competing for more water especially in summer and in periods of drought
2. *water quality*: the lack of landfills and wastewater treatment facilities upstrem, the unsystematic breeding of cattle and the overuse of groundwater resources for irrigation and drinking water downstream has caused water quality problems and salinisation of coastal areas near the river's delta
3. *environmental*: the upper part of the basin is part of the Pirin national park and the delta region is a RAMSAR convention protected area. Water quality degradation created negative impacts on fauna and flora and loss of biodiversity
4. *development problems:* Poor infrastructure and lack of facilities has resulted in a very low level of tourism, aquaculture and industry in the area.

For this case study, four different management options (1 to 4) were suggested by the country A and four other options (5 to 8). by the country B. Because of different attributes and goals, every country gives preference to their options. Individual rankings by country give the following results: Country A 3,2,6,8 and country B 6,8,5,7. By compromising the different countries' attributes and goals and using non-dimensional aggregated *socio-economic* and *ecological indexes* varying from 0 (worst) to 1 (ideal) the obtained results are shown in Figs. 12 and 13.

Both methods suggest that management options 3 and 6 have higher priority over the others because they are located closer to the ideal point. This is consistent with the countries' individual preferences.

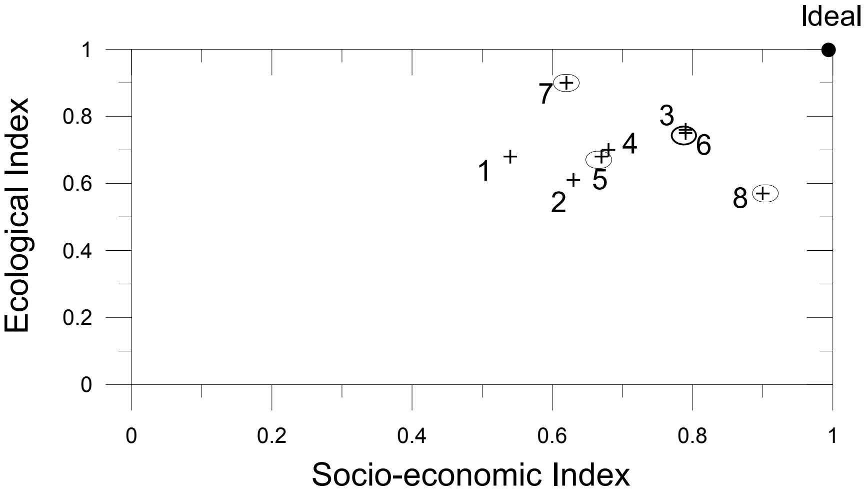

Figure 12. Conflict resolution (1) by trading off countries' different attributes.

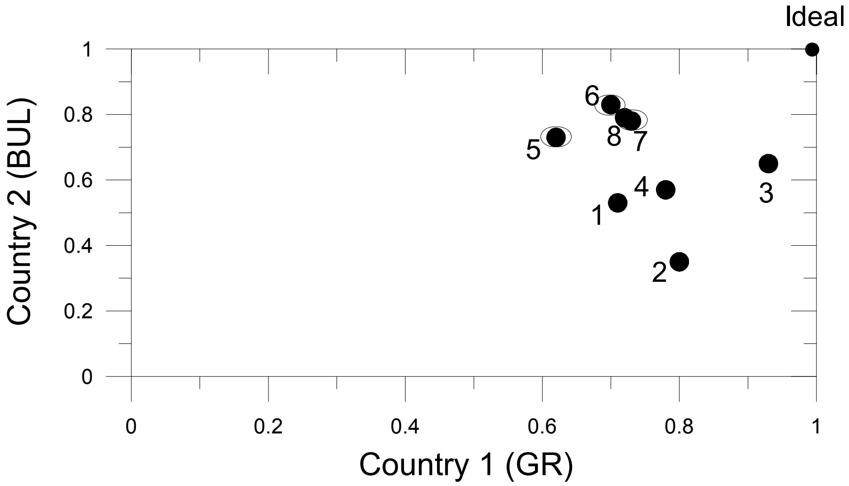

Figure 13. Conflict resolution by trading off countries' different goals.

5. Conclusions

The Risk-based Integrated Transboundary Aquifer Management (RITAM) methodology presented in Ch.12 is based on mathematical modelling techniques or expert judgments in order to evaluate for every specific management project risk indices for technical reliability, cost effectiveness, environmental safety and social equity.

In this chapter, the MCDA methodology was adapted in order to rank alternative strategies for transboundary groundwater resources management and conflict resolution. The technique in based on aggregating countries' different attributes or goals deriving by application of the RITAM multiple risk indices.

The methodology is illustrated by a case study, were trade-offs made either at the level of countries' different attributes or countries' different goals lead to similar compromise results.

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