EVALUATING TISZA RIVER BASIN DEVELOPMENT PLANS USING MULTIATTRIBUTE UTILITY THEORY

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March 1976 CP-76-3

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This Collaborative Publication reports on research conducted jointly by the International Institute for Applied Systems Analysis and the Hungarian National Water Authority, Budapest. It has been carefully reviewed before publication and represents, in the Institute's best judgment, competent scientific work. Views or opinions expressed herein, however, do not necessarily reflect those of the National Member Organizations supporting IIASA or of the Institute itself and the Collaborating Institution.

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PREFACE

In early 1975 an informal agreement was made between the IIASA Water Project and the Hungarian National Water Authority, Budapest, to carry out joint research on topics of mutual interest. During a subsequent meeting in Budapest (July 23-25, 1975) it was agreed that one such study would be the application of utility theory to long-range planning in the Tisza River basin. This collaborative publication gives the results of the study which was carried out both at IIASA and in Budapest.

Research was conducted under the Water Project research plan for 1975, on the application of utility theory to problems in water resources.

ABSTRACT

Selecting a plan to develop the water resources of a region involves the consideration of economic, environmental, social, and technical objectives. Twelve attributes are defined to indicate the degree to which these objectives are achieved in the Tisza River basin of Hungary. A preliminary multiattribute utility function is assessed over these attributes. This is combined with existing information describing the possible consequences of five alternative development plans to yield an overall rating of their desirability. The utility function explicitly indicates the preference tradeoffs among attributes. Discussion indicates further uses of the utility function in the planning and evaluation processes.

Evaluating Tisza River Basin Development Plans Using Multiattribute Utility Theory

1. INTRODUCTION

The problem of choosing among several development plans for the water resources of the Tisza River in Hungary is complex. Components contributing to this complexity include the multiple conflicting objectives involving economic, environmental, social and technical considerations, the difficult-to-quantify consequences that are crucial to selecting an alternative, and the uncertainties about the overall impact of any particular alternative. In Dávid and Duckstein [2], a multicriterion approach ELECTRE (see Roy [15]) was used in examining five alternatives for Tisza development characterized by multiple objectives and many qualitative considerations. Tradeoffs among attributes were implicitly accounted for and uncertainty was not taken into account.

In this paper, we preliminarily investigate the usefulness of multiattribute utility theory for evaluating these same alternatives. The result, which requires an explicit consideration of the tradeoffs among attributes, is a cardinal evaluation of the alternatives. This indicates how much better one alternative is than another as well as permits a sensitivity analysis of the tradeoffs used. In addition, a multiattribute utility model is appropriate for explicitly including in a rigorous manner the uncertainties of the problem in the formal analysis once the uncertainties are specified.

The paper is arranged as follows: Section 2 describes five distinct possible plans for developing the water resources of the Tisza River basin and states the many planning objectives which need to be considered in evaluating plans. Section 3 defines twelve attributes that measure the degree to which the planning objectives are met. A first-cut assessment of the utility function of one of the authors, L. Dávid, over these twelve attributes is given. Using consequences of the five alternatives as specified in Dávid and Duckstein [2], the alternatives are evaluated in Section 4. Interpretation of the results and possible extensions of the work are given in Section 5.

The effort described here had two purposes: to investigate the usefulness of a multiattribute utility analysis for evaluating development plans for the Tisza River basin; and to illustrate the techniques to planners and decision makers who influence decisions concerning long-range water resource planning. This work was not undertaken to influence directly any decision.

We are well aware that the work is too rough for that purpose. Section 5 suggests major improvements needed in the analysis if it were to be used directly in selecting a plan.

2. THE PROBLEM: PLANNING ALTERNATIVES AND OBJECTIVES [1]

Our description of the region considered (see Figure 1) is adapted from Dávid and Duckstein [2]. The region is very flat, surrounded by mountains and covers about 30,000 km^2. Its elevation ranges from 80 to 600 meters above sea level. The main river in this area, the Tisza River, has about ten tributaries, most of which originate outside Hungary; the whole basin, with a total area of 130,000 km^2, is shared by five countries. The average rainfall is 500 mm/year, which, combined with the continental climate, yields an aridity factor greater than 1. The socio-economic development, necessary to ensure the desired standard of living for the growing population in the region, has been made possible by the regulation of the Tisza River which involved both hydraulic engineering works and operation schemes. The main activities are agricultural, but industrial action has increased in the last 30 years as discussed by Dégen [3].

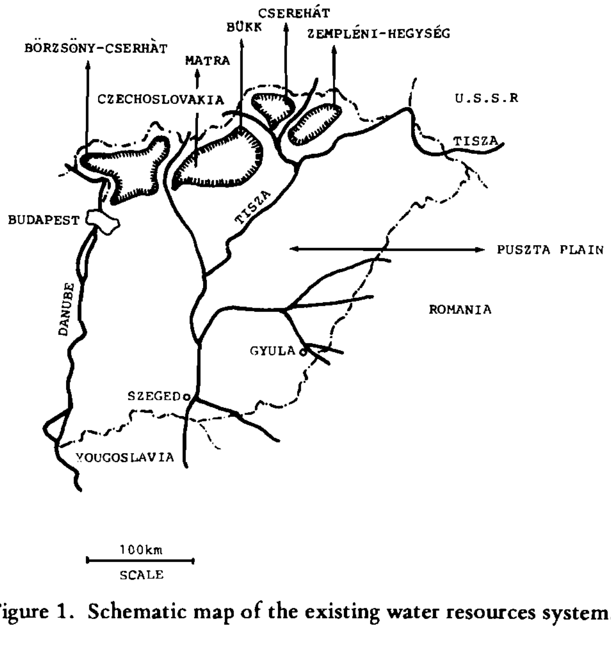

Figure 1. Schematic map of the existing water resources system.

[1]This section adapts material from Dávid and Duckstein [2].

The water has been supplied to these activities by a gradually growing water resources system, the development of which was started in the middle of the last century by flood control and river regulation works. This was followed by the drainage of excess stagnant waters that accumulated behind the flood levees, which primarily gave rise to the rapid development of agriculture. The main task in the present century is to further develop the water supply for agricultural purposes (irrigation and fish pond farming), but increasing demands must be satisfied for industrial and domestic supplies, navigation and riparian recreation. Increasing uses have entailed the deterioration of water quality, which in turn focused attention on pollution control. Careful management of both the quantity and quality of natural supplies, which are becoming increasingly more scarce, has been introduced in recent years (see Dávid [1]). Further development of the existing water system is very important from the standpoint of regional development. A series of plans and estimations have already been prepared for the development (National Water Authority, [11], Dégen [3], and VIKÖZ [16]).

2.1 Description of Development Alternatives

Five distinct alternative water resource systems (WRS) have been proposed for the further development of the Tisza River basin. These five alternatives represent systems which involve basic policy issues that would be made at the highest levels of water management. For example, system I is formulated around the concept of large inter-basin transfers from the Hungarian part of the Danube River to fulfill water demands, while system IV fulfills the water demand by building reservoirs in the upper Tisza River basin through international co-operation. These are two fundamentally different systems from a development viewpoint; and as such, many objectives come into play when the relative attraction of each system is analyzed. Within each system, the best development of configuration was determined. It is assumed that each system can be filled up with water during a gradual development for the next 55 years and that the necessary reuse activity can be developed in due time so that certain systems may satisfy a demand greater than that of storage capacity.

These five systems are described as follows.

System I. Danube-Tisza inter-basin transfer using a multi-purpose canal-reservoir system

The system uses the water resources of both the Tisza and Danube Rivers. The water is transferred all year round from the Danube by a gravity canal in the flat land area and by a pumped canal reservoir system in the Börzsöny-Cserhát Mountains. With system I, which is basically oriented to the utilization of water resources, the importance of reuse is relatively small since not all of the available water resources are used. The storage capacity is 8 km^3, but not all of it is used, thereby making the probability of shortage small. The specific energy demand for storage is high owing to the pump-storage reservoir system; but an important part of this energy is recoverable, and the energy demand of water supply and treatment can be met by the water lifted and stored at high elevation.

There is enough unallocated water available in the Danube River for the present and the future. Therefore, the development and operation of the system does not depend to a great extent on international co-operation. The system is very good from the viewpoints of water quality, recreation, manpower, environmental architecture and development possibility. Water quality management may be accomplished through dilution.

The system has some disadvantages: it would consume large quantities of resources, for example land and forest resources for reservoir sites; it would not be of much help for flood control and drainage; the quality of the Danube River is likely to decrease in the future, so that some treatment will be needed.

<u>System II.</u> <u>Pumped reservoir system in the northeastern part of the region</u>

This pumped reservoir system, supplied only from the Tisza River, is developed in the hilly region of the Sátoros and Bükk Mountains. This system is also basically oriented to water resources utilization, but the natural supply of water is available only four to five months per year. It uses all the natural supply of this part of the Tisza River basin, but not all the available storage capacity. The importance of reuse is relatively small as is the probability of a shortage. The energy needs and reuse possibilities are moderate, as are the treatment needs of the "natural water resource" originating from the Tisza River.

The system is satisfactory from the viewpoints of water quality, recreation, environmental architecture and development possibility. It provides excellent flood protection, but on the other hand, the system consumes large quantities of resources. The water quality and the runoff conditions are based on good international co-operation, but the large storage capacity of the system is beneficial in this respect. Large peak pumping capacities are needed because the pumping time is generally limited to high water in the river.

<u>System III.</u> <u>Flat land reservoir system</u>

This system, which would be developed on the flat land part of the region, is composed of two to four meter deep reservoirs, using water from the Tisza River. Only a limited space of 5.5 km^3 could be used for such reservoirs. This capacity is only adequate to regulate 10 km^3/year of water resources. Thus, the probability of shortage is high. The efficiency of storage (ratio between usable water resources and existing storage capacity), is relatively poor, because water losses by evaporation are expected to be large for a relatively small capacity. Therefore, the importance of reuse is high. The water quality conditions are bad.

The system is very good from the navigation and drainage viewpoints. From the recreation, development possibility, and flood protection viewpoints, it is fair. Much land and forest resources are needed. The development and operation of the system is fairly difficult from the aspect of international co-operation, and nothing is accomplished for environmental architecture.

System IV. Mountain reservoir system in upper Tisza River basin

This system would be located outside the country. It uses and regulates the water resources of the Tisza River by gravity. All storage capacity available within the framework of international co-operation is used, but not all the water resources are used. Nevertheless, the efficiency of storage is very good. The need for reuse is very high, but no energy is needed for storage and very little is required for long-distance transfer; the energy required for supply and reuse is high. The probability of shortage is high owing to system limitations.

The system is excellent for flood control effected by flow regulation, very good from the water quality viewpoint and good for environmental architecture, but considerable land and forest resources located in other countries must be used. Therefore, extensive international co-operation must be initiated and sustained. The alternative is not so good from the recreation and development possibility viewpoints.

System V. Groundwater storage system

This system could be developed mainly on the flat land part of the region, especially in the eastern part. The system using the Tisza water and stored groundwater resources would be composed of underground storage spaces. Since such spaces are limited, reuse would have to be very high. The groundwater is of excellent quality and is to be used mainly for drinking and domestic purposes, but it is less valuable from other users' standpoint. Salinity problems may arise in the future. The estimated energy required is high, and there is no possibility of producing energy. The probability of water shortage is high.

The system is not particularly good from the environmental architecture and development possibility viewpoints. It is bad for recreation and flood protection purposes. Efficient use of the small storage space needs international co-operation so that water may be available for recharging. The system is very sensitive to uncertainties.

2.2 Planning Objectives

The basic aim of these WRS is to develop the natural supply of water resources by comprehensive runoff regulation, including quantity and quality regulation over space and time.

The reason for choosing a distant planning horizon of 55 years is that the system introduces major structural changes in the region, for which short-range planning would not be very realistic. The population, which was 4 million in 1970, is expected to reach 5 million by 2030. The irrigated area during the same time period will grow from 0.3 to about 2 million ha. Plans call for a growth in industry and hydro-electric power generation as well as an implementation of new technologies. As the region develops, the demand for social uses of water, especially for recreation, will also grow. Therefore, the following goals have been established and analyzed.

A. Water Requirements. This goal involves quantity and quality aspects of water delivery, surface and subsurface runoff in space and time. A distinction is made between consumptive and non-consumptive uses. Consumptive uses include needs for irrigation as well as domestic and industrial uses. Non-consumptive uses include hydro-electric power generation, navigation, and recreation.

B. Flood Protection. The difficulty in satisfying this goal is compounded by the fact that the rivers, hence the floods, originate outside the system. By 2030, 3.5 million people are expected to live in areas under flood protection. The development should provide protection against at least the 50-year flood.

C. Drainage and Used Water Disposal. The efficient use and reuse of water is included in this goal. It should be possible on the average to drain an area of 15,000 km^2 in ten days.

D. Utilization of Resources. The natural, social and economic resources needed to implement and operate the system should be kept to a minimum. The resources considered in this study are water, energy, land and forest, capital, and manpower. International co-operation calls for a minimum outflow from the system with regard to downstream users. Thus, consumptive use of water is considered a loss of resource and should be minimized.

The energy requirements for runoff regulation are considered in addition to the energy needed for supply. Throughout the study, the limited availability of energy sources is a constraining factor to the development.

The land and forest resources usable for surface storage and transfer has an upper limit of four percent of the total area, (120,000 ha). The existing system already uses 50,000 ha.

The present value of capital expanded for construction and operation should not exceed a total of 85 x 10^9 forints/year. The discount factor is six percent.

The manpower specifications are: a) the staff in construction and operation of the water management system should be kept at a minimum; and b) the spillover effects of the project should include an upgrading of the available jobs.

E. Environmental Impact. The system investigated includes a special part of the Hungarian great plain called Puszta, which has recently been made a national park. This sets a constraint on groundwater table and design of a conveyance network in addition to the land and forest area constraint given above.

F. Flexibility. The proposed system should be flexible enough to meet a broad spectrum of future requirements, most of which cannot be foreseen at the present time. Therefore, the system should possess the following capabilities:

i) It should be possible to link it with another system implemented at a later date in a neighboring region. This specification has the further advantage of opening international co-operation possibilities.

ii) The system should be able to cope with several types of uncertainties, such as the natural uncertainty inherent to forecasting, the strategic uncertainty due to the unknown future allocation policy, the economic uncertainty pertaining to cost and loss functions and technological uncertainty.

3. ASSESSMENT OF THE UTILITY FUNCTION

This section indicates how the utility function used to evaluate the planning alternatives was assessed. The assessment process consisted of four separate steps:

i) familiarization with utility theory,
ii) investigation of the qualitative preference structure,
iii) assessment of component utility functions,
iv) assessment of scaling factors.

Throughout the assessment process, there were several consistency checks. However, now that we have a preliminary utility function with which to work, many more consistency checks and adjustments can and should be conducted.

3.1 Familiarization with Utility Theory

The first part of any utility assessment involves a discussion of the concepts of the approach within the context of the problem being addressed. In this problem, the manner in which utility theory considers uncertainties, multiple objectives, and subjective factors was discussed.

The other important aspect of the initial discussion is to structure the problem. To do this, we needed to obtain a set of attributes and their ranges to be used in evaluating alternatives. The attributes are used to indicate the degree to which the objectives outlined in Section 2.2 are met. For this problem, fortunately, the work had been previously done and reported by Dávid and Duckstein [2]. A summary of these attributes, labelled $X_1,...,X_{12}$ is given in Table 1. There are two minor alterations from the previous work. The measure for flood protection is now the recurrence interval of a flood rather than the annual probability of a flood, and attribute X_{12}, referred to earlier as sensitivity, is now called flexibility. The meaning of flexibility has been discussed in Section 2.2.

The subjective indices from Dávid and Duckstein have been put on a 0 to 100 scale for convenience in quantifying the utility functions. Earlier work used verbal descriptions. For instance, recreation was categorized as very good, good, fair, bad. The numerical values associated with recreation were defined by 100 as excellent, 80 as very good, 60 as good, 40 as fair, 20 as bad, and 0 as no recreation potential. Similar associations were made for the other subjective scales.

3.2 Investigation of the Qualitative Preference Structure

Before one assesses a utility function, it is important to determine the qualitative structure. This indicates functional forms which are appropriate for quantifying the actual function. To do this, one attempts to verify various preferential and utility independence assumptions. (See the appendix for a definition of these terms.) As it turned out, it seemed appropriate to assume the conditions necessary for the multiplicative utility function. Let us briefly indicate how preferential and utility independence assumptions were verified. Complete details of the verification procedure used are explained in a different context in Keeney [8].

To check whether the pair $\{X_1,X_2\}$ was preferentially independent of the other attributes, we first fixed these others at their best levels, and later at their worst, and considered tradeoffs between X_1 and X_2. For instance, in Figure 2, we found that ($x_1 = 80$, $x_2 = 60$) was indifferent to ($x_1 = 110$, $x_2 = 30$) regardless of the fixed levels of other attributes. This same condition was verified for other specific pairs of attributes $\{X_1,X_2\}$, so it seemed appropriate to assume that

Table 1. Attributes for the Tisza River basin problem.

Attribute	Measure	Worst	Best
$X_1 \equiv$ Costs	10^9 ft/yr	110	80
$X_2 \equiv$ Water Shortage	percent	60	0
$X_3 \equiv$ Water Quality	subjective	0	100
$X_4 \equiv$ Energy (reuse factor)	$\alpha \equiv \frac{\text{energy produced}}{\text{energy used}}$	0	1.0
$X_5 \equiv$ Recreation	subjective	0	100
$X_6 \equiv$ Flood Protection	recurrence interval	40	500
$X_7 \equiv$ Land & Forest Use	1000 ha	100	50
$X_8 \equiv$ Social Impact	subjective	0	100
$X_9 \equiv$ Environment	subjective	0	100
$X_{10} \equiv$ Int'l Cooperation	subjective	0	100
$X_{11} \equiv$ Development Poss.	subjective	0	100
$X_{12} \equiv$ Flexibility	subjective	0	100

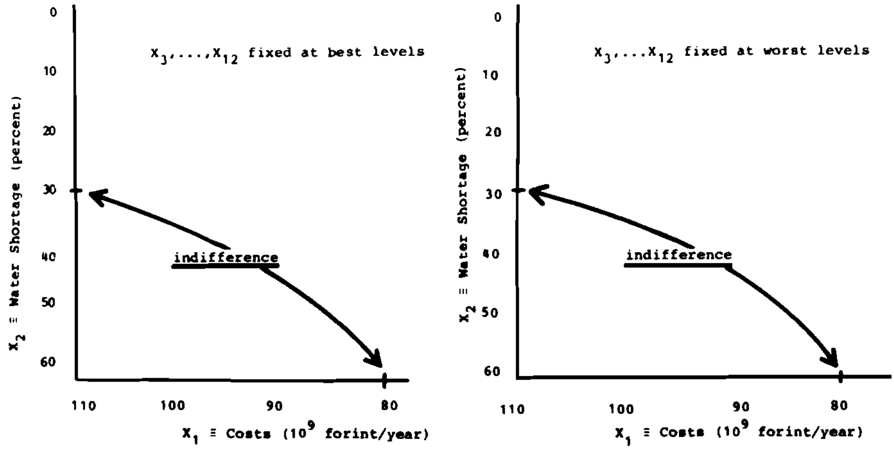

Figure 2. Verifying preferential independence.

$\{X_1,X_2\}$ was preferentially independent of $\{X_3,\ldots,X_{12}\}$. After considering several specific cases involving different pairs of attributes, it seemed appropriate to assume that each pair of attributes was preferentially independent of the other ten.

Next we investigated utility independence properties. To determine whether X_1 was utility independent of $\bar{X}_1$, the set of attributes other than X_1, we fixed all attributes other than X_1 at their worst levels and asked for the level $\hat{x}_1$ such that $\hat{x}_1$ for sure is indifferent to a 50-50 chance at $x_1 = 80$ or $x_1 = 110$. The response was $\hat{x}_1 = 98$. This is referred to as the certainty equivalent for the lottery yielding either $x_1 = 80$, with probability 0.5, or $x_1 = 110$, with probability 0.5. We next found out that the certainty equivalent $\hat{x}_1 = 98$ did not change when only the levels of the other attributes $X_2,\ldots,X_{12}$ were varied. Next, the certainty equivalent for the 50-50 lottery yielding either 80 or 98 was assessed to be 91, and this also did not depend on the levels of attributes other than X_1. Hence, we felt justified in assuming that X_1 was utility independent of $\{X_2,\ldots,X_{12}\}$.

These two certainty equivalents imply that the utility function u_1 scaled from 0 to 1 must pass through the points of Figure 3 and is likely to be similar to the shape indicated.

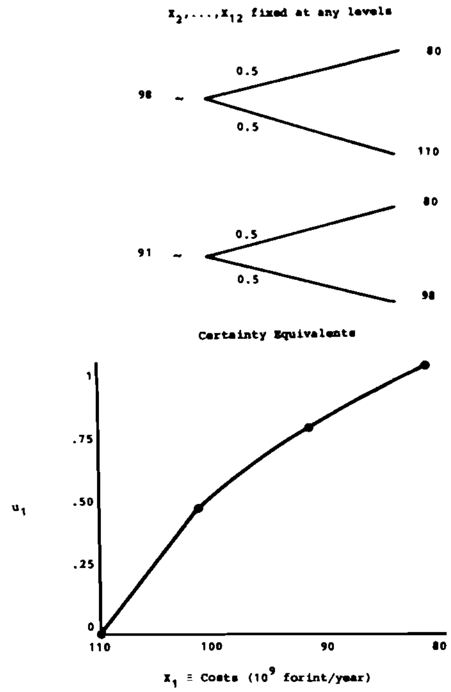

Figure 3. Utility independence and a utility function.

Together, as proven in Keeney [7], the preferential independence and utility independence assumptions imply that a utility function u can be expressed either in the form

$$u(x_1,x_2,\ldots,x_{12}) = \sum_{i=1}^{12} k_i u_i(x_i) \quad , \tag{1}$$

or in the form

$$1 + ku(x_1,x_2,\ldots,x_{12}) = \prod_{i=1}^{12} \left[1 + kk_i u_i(x_i)\right] \quad , \tag{2}$$

where u is scaled 0 to 1, the component utility functions $u_i, i = 1,\ldots,12$ are scaled 0 to 1, the scaling constants

k_i, i = 1,...,12 are positive and less than one, and k is a constant calculated from the k_i's.

To determine which of the forms (1) or (2) was appropriate, we investigated whether there was a preference or an indifference between the two lotteries A and B in Figure 4. Note that lottery A yields either the best or worst of both attributes, whereas lottery B yields the best of one and the worst of the other. It was determined that lottery B was strongly preferred, implying that the appropriate utility function was the multiplicative form (2). Other similar assessments substantiated this.

The next problem was to assess the u_i's and k_i's, which specify the utility function.

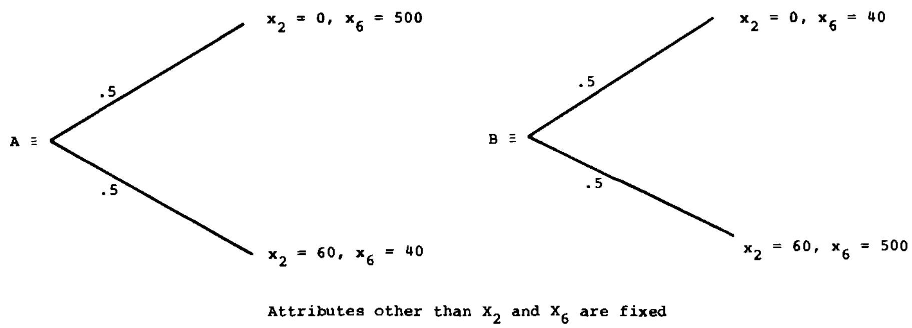

Figure 4. Choosing the additive or multiplicative form.

3.3 Assessment of Component Utility Functions

The component utility functions were assessed by the same techniques as illustrated in Figure 3. Then either an exponential or a linear utility function was fit to the assessed points. These results are illustrated in Figure 5. An implicit assumption in the assessments of utility functions over the subjective factors was that the scales could be interpreted as cardinal scales as opposed to ordinal ones. This assumption is not strictly appropriate, and was made for convenience in these first-cut assessments. In revised assessments, care should be taken to anchor these scales by precisely defining several points on each. Also, each point used explicitly in the assessments should be one of those that are anchored.

3.4 Assessment of the Scaling Factors

The first step in assessing the k_i's in (2) was to order their magnitude. To do this, we set all twelve attributes in Table 1 at their worst levels and asked "if only one could be raised to its best level, which one would be preferred." The response was attribute X_2. This implied k_2 must be the largest of the k_i's. Had there been indifference between moving either x_i or X_j to its best level, then $k_i = k_j$. After several adjustments, this resulted in the order

$$k_2 > k_6 > k_3 = k_{10} > k_8 > k_1 > k_5 = k_9 > k_4 = k_7 > k_{11} = k_{12} \quad . \tag{3}$$

To establish the relative scaling factors, the k_i's, we needed to look at tradeoffs between two attributes at a time.

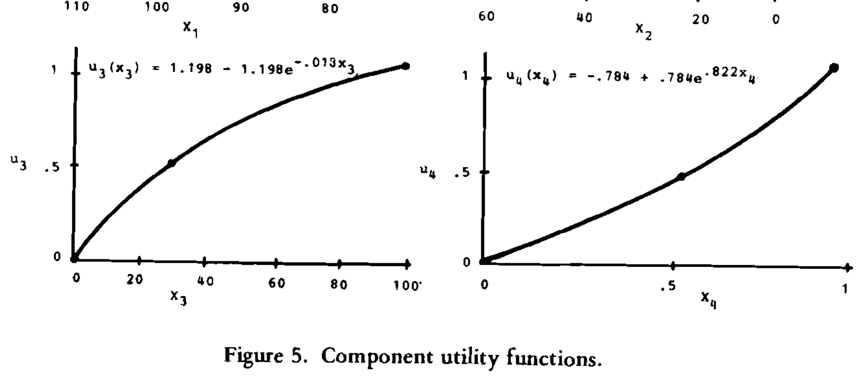

Figure 5. Component utility functions.

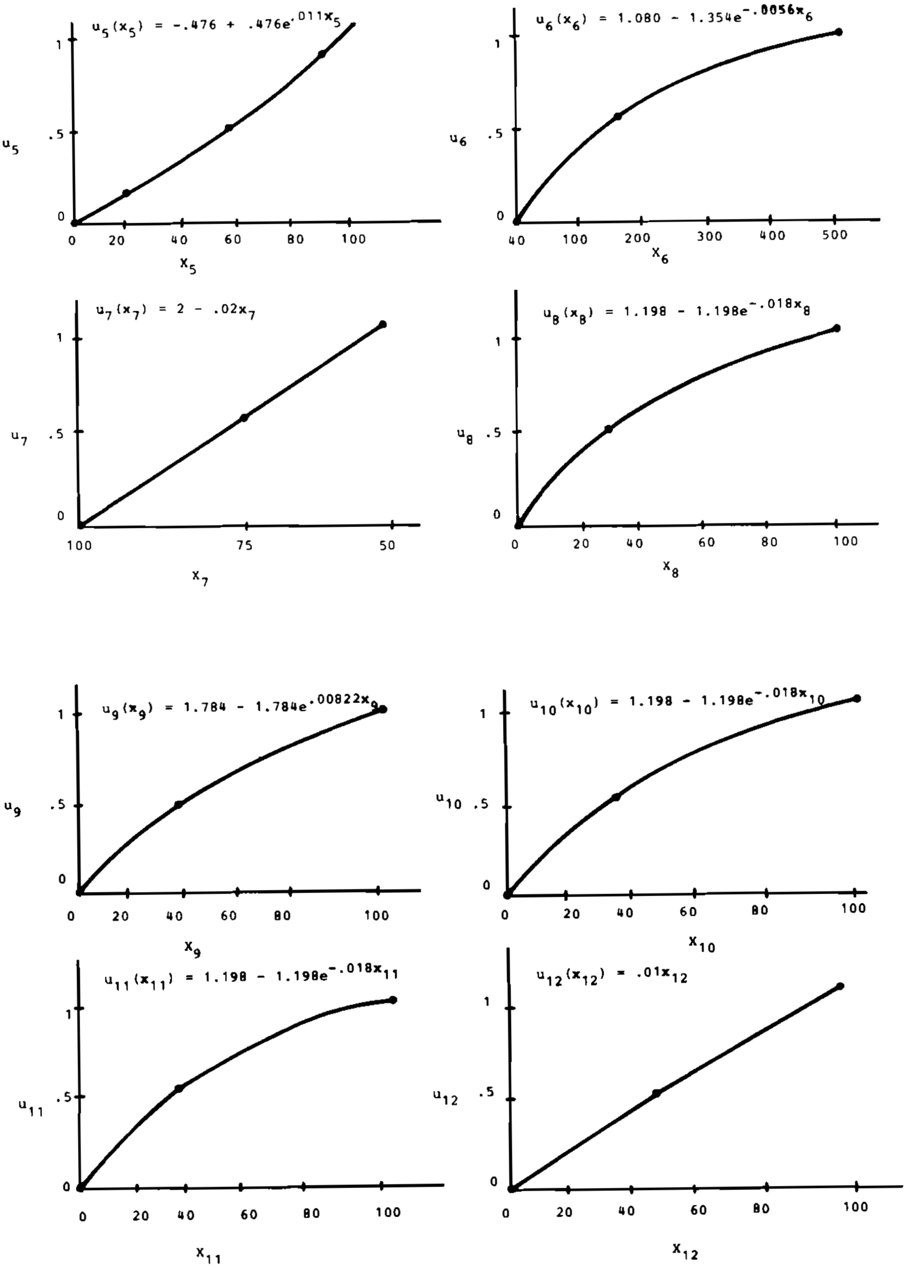

Figure 5. Component utility functions (cont'd.).

For example, in Figure 2, we have two consequences which are indifferent given $X_3,\ldots,X_{12}$ are at any level. Assume that they are at their worst levels so $u_i = 0$, $i = 3,\ldots,12$, and equate the utilities of $(x_1 = 80,\ x_2 = 60)$ and $(x_1 = 110,\ x_2 = 30)$ using the multiplicative utility function (2). We find

$$k_1 = k_2 u_2(30) \quad . \tag{4}$$

From u_2 in Figure 5, we evaluate $u_2(30) = 0.619$, so that

$$k_1 = 0.619 k_2 \tag{5}$$

which fixes the relative values of k_1 and k_2.

Following this same procedure in evaluating tradeoffs, we assessed the indifference pairs in Table 2 from which the equations indicated were calculated using the component utility functions of Figure 5. By assessing tradeoffs between pairs of attributes not involving X_1, we had checks of the tradeoffs in Table 2. As a result of this, some adjustments were made to achieve consistency. Table 2 reports these adjusted responses.

Table 2. Assessed indifference pairs and implications.

Assessed Indifference Pair			Implied Relative Scaling Constants
$(x_1=80,\ x_2=60)$	and	$(x_1=110,\ x_2=30)$	$k_1 = .619\ k_2$
$(x_1=80,\ x_3=0)$	and	$(x_1=110,\ x_3=60)$	$k_1 = .791\ k_3$
$(x_1=95,\ x_4=0)$	and	$(x_1=110,\ x_4=1)$	$k_4 = .601\ k_1$
$(x_1=85,\ x_5=0)$	and	$(x_1=110,\ x_5=100)$	$k_5 = .885\ k_1$
$(x_1=80,\ x_6=40)$	and	$(x_1=110,\ x_6=250)$	$k_1 = .750\ k_6$
$(x_1=95,\ x_7=100)$	and	$(x_1=110,\ x_7=50)$	$k_7 = .601\ k_1$
$(x_1=80,\ x_8=0)$	and	$(x_1=110,\ x_8=80)$	$k_1 = .914\ k_8$
$(x_1=85,\ x_9=0)$	and	$(x_1=110,\ x_9=100)$	$k_9 = .885\ k_1$
$(x_1=80,\ x_{10}=0)$	and	$(x_1=110,\ x_{10}=60)$	$k_1 = .791\ k_{10}$
$(x_1=105,\ x_{11}=0)$	and	$(x_1=110,\ x_{11}=100)$	$k_{11} = .228\ k_1$
$(x_1=105,\ x_{12}=0)$	and	$(x_1=110,\ x_{12}=100)$	$k_{12} = .228\ k_1$

The right side of Table 2 has eleven equations with twelve unknowns. These establish the relative values of the k_i's. Finally, we need specific values for these scaling factors. To do this, we found ($x_2 = 0$, $x_6 = 40$) was indifferent to a lottery yielding either ($x_2 = 0$, $x_6 = 500$) with probability 0.6, or ($x_2 = 60$, $x_6 = 40$) with probability 0.4. Equating utilities with the other attributes at their worst levels implies

$$k_2 = .6(k_2 + k_6 + kk_1k_2) \tag{6}$$

From (2), if we set all the attributes at their best level, we find

$$1 + k = \prod_{i=1}^{12} (1 + kk_i) \quad . \tag{7}$$

Equations (6) and (7) plus the eleven equations in Table 2 were then solved to yield

$$k_1 = .15,\ k_2 = .243,\ k_3 = .189,\ k_4 = .090,\ k_5 = .132,\ k_6 = .200,$$

$$k_7 = .090,\ k_8 = .165,\ k_9 = .132,\ k_{10} = .189,\ k_{11} = .034,\ k_{12} = .034 \tag{8}$$

and

$$k = -.715 \quad . \tag{9}$$

The component utility functions in Figure 5 plus (8) and (9) specify the preliminary utility function represented by the multiplicative form (2).

One should be careful in interpreting the scaling constants in (8). For instance, because k_2 is larger than k_1, one can not conclude that water shortage is more important than costs. The magnitude of the scaling factors, as indicated in the assessment process, depends on the ranges of the attributes specified in Table 1. Thus the scaling factors indicate the relative importance of the ranges of the attribute.

4. RESULTS

In this section, the utility function developed in Section 3 is applied to the five planning alternatives outlined in Section 2. The evaluation using the twelve attributes for the five systems is presented in Table 3, which is adapted from Dávid and Duckstein [2].

Table 3. Attribute levels for alternative systems.

Objective	Measure	Alternative System I	II	III	IV	V
1. Total Cost (20ft $\approx$ 1 US$)	10^9 ft/yr	99.6	85.7	101.1	95.1	101.8
2. Probability Water Shortage	percent	4	19	50	50	50
3. Water Quality	subjective	80	60	20	80	40
4. Energy Reuse	$\alpha \equiv \frac{\text{en. prod.}}{\text{en. used}}$	.7	.5	.01	.1	.01
5. Recreation	subjective	80	60	40	20	20
6. Flood Protection	recurrence interval	100	200	67	200	50
7. Land & Forest Use	1000 ha	90	80	80	60	70
8. Social Impact	subjective	80	80	60	40	40
9. Environment	subjective	80	60	20	60	40
10. Int'l Cooperation	subjective	80	60	40	20	40
11. Development Poss.	subjective	80	60	40	20	40
12. Flexibility	subjective	80	80	20	40	20

Table 4 gives the utility value for the five alternative systems. Since higher utilities are better, these preliminary results imply that alternative system I is somewhat better than system II; which is much better than system IV, which in turn is much better than system V; system III is the least desirable. To help interpret how much better system I is than system II, we increased the cost of system I in Table 3, holding all other factors fixed, until the utility equaled the current utility 0.821 of system II. This occurred at $x_1 = 104.2 \times 10^9$ forint per year, so system I is essentially better than system II by 4.6×10^9 forint per year. Similarly, system II is better than system IV by at least 24.3×10^9 forint per year because even if the cost of system II increases to 110×10^9 forint per year, the utility of system II is greater than the current utility of 0.648 of system IV. Since systems III and V are even worse, it appears that subject to the data of Table 3 and the utility function being used, systems I and II are the only real contenders.

Table 4. Total utility for alternative systems.

System	Utility Value
I	.832
II	.821
III	.503
IV	.648
V	.521

By verifying attribute levels in Table 3 as done above, one can perform a first-cut evaluation of the impacts owing to uncertainties about the attribute levels for each system. This would be especially important in rejecting proposed systems. For example, can system IV, the upper basin reservoir system, be a contender if optimistic levels for each attribute were assigned? This would be an easier analysis than fully analyzing uncertainties; and again, it could serve as a first-cut to the problem.

One can also readily do sensitivity analyses of the k_i weights (i.e. the tradeoffs) of the utility function. For instance, if k_1 in (8) is increased from .15 to .20 and if k_2 is decreased from .243 to .22, while all other k_i factors are held constant, then the utility of system II exceeds the utility of system I. Note that this is true even though k_2 remains larger than k_1. One of the important features of a utility analysis is to identify such crucial tradeoffs.

5. CONCLUSIONS

This study was a first-cut at a problem of water resources planning using multiattribute utility theory. A planning problem in the Tisza River basin of Hungary was used to illustrate the usefulness of the technique. A utility function over twelve objectives was assessed and preliminary results indicate that building inter-basin water transfers from the Danube or from small reservoirs in the north-east is to be preferred to developing three other planning alternatives.

This same problem was analyzed by Dávid and Duckstein [2], using a multicriterion approach called ELECTRE. Their evaluation ranked system II ahead of system I with the other three alternatives far behind. With ELECTRE, it is difficult to do sensitivity analyses to see just how much better one system is than another. Our rough multiattribute utility analysis indicated system I was better than system II by an amount equivalent to an increase in system costs of 99.6 to 104.2 x 10^9 forint per year. System IV would have to have very significant improvements in either or both flood protection and water supply in order to become a contender. Systems III and V are clearly not competitive.

One purpose of the work was to appraise the reasonableness of the approach. The assessed utility function should be interpreted as a preliminary one. However, it does indicate the feasibility of making such assessments with water resource planners. The brief analysis was included to fulfill our other purpose: to illustrate the use of a multiattribute utility evaluation model. It was not done to suggest alternatives that should be chosen. For the latter purpose, a more sophisticated, more careful analysis would be needed. In such an effort it is of primary importance to extend this work in the following ways:

1. Better articulation of the system objectives and better attributes for these various objectives. The present study utilized attributes developed by Dávid and Duckstein who evaluated attribute levels for the five systems. It is our feeling that some attributes may not fully reflect the underlying objectives and further work should be devoted to this task. Also, scales of the subjectively measured attributes should be more carefully defined.

2. Formal inclusion of uncertainty. The level of the twelve attributes for the five systems given in Table 3 are the expected values. Large uncertainties exist around these levels owing to natural events (for example floods), to forecasting complexity (for example technological innovations), and to the appropriateness of the model itself. These uncertainties can be formally included in a rigorous manner using utility theory, and the study should be extended if the results are to be applied.

3. A more thorough utility assessment of the utility function over the revised set of attributes. Special attention should be given to assessing utility functions over the subjectively scaled attributes. These assessments should be conducted with several people concerned with development of the Tisza. It may be appropriate to attempt to determine a concensus preference structure. If this is not possible, an analysis of the differences may help resolve the issues.

4. Expansion into a dynamic decision problem. The water resource development described in this paper has a time span of 55 years. During these 55 years, many issues that are now uncertain will unfold--for example, future water demands, developments in neighboring countries, future uses of the Tisza River for navigation. Furthermore, decisions are made today that are updated and supplemented in ten or fifteen years. This whole process of sequential decisions and resolution of present uncertainties should be included in the analysis because certain alternative systems are flexible to planning changes, while other systems are inflexible and require large additional costs to incorporate changes.

APPENDIX

Let us denote the objectives by $0_1, 0_2, \ldots, 0_n$ and suppose that $X_i, i = 1, \ldots, n$, is an attribute (i.e. measure of effectiveness) to indicate the degree to which 0_i is achieved. A specific level of attribute X_i will be designated by x_i. With this notation, the consequence of any alternative is $\underline{x} \equiv (x_1, x_2, \ldots, x_n)$. If the uncertainties of the problem are quantified, the possible consequences of alternative A_j are specified by a probability distribution of $p_j(\underline{x})$ over consequences.

The problem is to quantify the preferences of the decision maker for the possible consequences $\underline{x}$ in order to help him select the best alternative. Specifically, we want to assess a multiattribute utility function $u(\underline{x})$. This multiattribute utility function is nothing more than an objective function (to be maximized) with one special property: it is scaled in a manner such that when uncertainty is involved, the expected utility of an alternative is an appropriate measure of the desirability of that alternative. If one accepts a set of reasonable axioms postulated by von Neumann and Morgenstern [17], the decision maker should select the alternative leading to the highest expected utility.

A discussion of the reasonableness of utility theory in aiding prescriptive decision making is found in Raiffa [13]. Concerning multiattribute utility theory, the main results [4, 6, 7, 10, 12, 14] are representation theorems stating conditions under which a utility function can be expressed in a simple functional form. Given such a form, the next task is to assess the parameters necessary to choose a particular utility function of that form by asking the decision maker a series of questions. Details on these assessment procedures are found in several sources. See, for example, Fishburn [5], Raiffa [14] and Keeney and Raiffa [9]. Section 3 briefly describes a preliminary assessment for the Tisza problem.

The two basic notions used in deriving the representation theorem used in this paper are the concepts of preferential independence and utility independence. These concepts are defined as follows.

<u>Preferential Independence</u>. The pair of attributes $\{X_1, X_2\}$ is preferentially independent of the other attributes $\{X_3, \ldots, X_n\}$, if preferences among $\{X_1, X_2\}$ pairs, given that $X_3, \ldots, X_n$ are held fixed, do not depend on the level where these attributes are fixed. Preferential independence implies that the tradeoffs between attributes X_1 and X_2 do not depend on $X_3, \ldots, X_n$.

<u>Utility Independence</u>. The attribute X_1 is utility independent of the other attributes $\{X_2, \ldots, X_n\}$ if preferences among lotteries* over X_1 (i.e. lotteries with uncertainty about

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*A lottery is defined by specifying possible consequences which may result and the associated probabilities of their occurrence.

the level of X_1 only), given that $X_2,\ldots,X_n$ are held fixed, do not depend on the level where these attributes are fixed. In Section 3, preferential and utility independence conditions are used to imply the appropriateness of either an additive or a multiplicative utility function.

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