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Towards Agricultural Water Management Decisions in the Context of WELF Nexus †

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Abstract: A Multi-criteria Decision Aid (MCDA) framework based on the combination of Multi-Attribute Utility Theory (MAVT/MAUT) with the Weights Assessment through Prioritization method (WAP) is proposed for decision problems related to agricultural water management in the context of water-energy-land-food (WELF) nexus. The implementation of the framework supports a Decision Maker (DM) to quantify his/her preferences in a structured and rational way, in order to select the best alternative for agricultural water management. Through the use of the Multicriteria Interactive Intelligence Decision Aiding System (MIIDAS), marginal utilities functions for all the criteria are constructed. The criteria are grouped in points of view, which may refer to individual nexus elements and costs for investments or agricultural inputs. The WAP software assists the DM to assess the relative importance of the criteria and estimate their weights.

Keywords: MCDA; MAUT; WAP; nexus; agriculture; water management

1. Introduction

Agricultural river basins are vulnerable to various environmental challenges, such as water scarcity and drought, pollution with nutrients, pollution with chemicals and hydro-morphological alterations of water bodies [1]. The design and implementation of measures by river basin authorities, environmental agencies, environmental scientists and practitioners needs to be logically structured, holistic and comprehensive, thus ensuring the efficiency of allocated resources. However, there has been recent critique that research and policy in the past decades have mostly developed in working “silos”, which has resulted in the development of detached sectoral goals, strategies and policies, and fragmented actions towards environmental protection [2].

The water-energy-land-food nexus (WELF nexus) is a holistic and comprehensive conceptual framework, which underlines the need for integrated and systemic thinking, as well as for cross-sectoral and multi-scale action in the protection and management of resources systems [3,4]. The acknowledgement of the interdependent nature of water, energy, land and food systems, strengthens the environmental analysis for the river basin and facilitates the identification of synergies or trade-offs between the objectives for these resources.

Agricultural water management in the context of WELF nexus, constitutes a complex decision problem with multiple, conflicting and incommensurable objectives. In such real-world problems there is hardly any alternative, which could be objectively determined as the best, dominating all other alternatives. Multi-Criteria Decision Aid (MCDA) constitutes a structured and systematic approach to deal with these semi- or unstructured decision problems. MCDA supports the decision process (a) by providing transparency, accountability and rationalization of the decision process, (b) by modelling the preferences and the subjectivity of the Decision Maker and supporting him/her to explore explicitly the underlying synergies and tradeoffs between the criteria, (c) by balancing the conflicting nature of the criteria and supporting resolution of conflicts between stakeholders' competing interests, and (d) by informing the DM about the robustness of the estimated decision model [5,6].

MCDA applications in the domain of agriculture tend to focus on the evaluation of alternatives related to agricultural resources management, while also a few assess the sustainability of agricultural systems [7–9]. A review of publications related to MCDA applications for agricultural resources management reached the following key conclusions [7]. Decision makers are usually policy makers (at regional level) or farmers (at farm level). The total number of criteria is low, ranging between 4–10 (17 in one occasion). The most frequently used criteria include indicators, such as farmers' revenues and costs, risks for farmers' revenues, agricultural inputs (e.g., utilization of labor, machinery or area), level of agricultural production, environmental concerns (e.g., nitrogen loss, biocide accumulation, soil erosion, water use, conservation of traditional systems). The total number of alternatives varies significantly, ranging between 2–10 (24 and 72 in two occasions). The alternatives are interventions using single farm tools and machinery or combinations of elements forming a strategy. A variety of MCDA approaches is used, depending on the problem: Analytic Hierarchy/Network Processes (AHP/ANP), Multi-Attribute Value/Utility Theory (MAVT/MAUT), Outranking Relations Approaches, Goal and Compromise programming. Moreover, in those cases where a MAVT/MAUT approach is used, two additional findings are reported [7,8]. Firstly, the selected marginal utility functions are mostly linear, ranging between a minimum and maximum value, whereas more complex preference models are rarely used. Secondly, the selected methods for the elicitation of the weights frequently cause difficulties with their assessment and interpretation by the DMs. The applied weighting methods included one of the following: direct rating, criteria ranking, pair-wise ranking, ratio estimation and swing weighting.

The key aim of the present paper is to propose and demonstrate an MCDA framework based on the combination of MAVT/MAUT approach [10,11] with the newly-established WAP method [12] for applications related to agricultural water management in the context of WELF nexus. MAVT/MAUT is supported by the MIIDAS system [13] for the construction of marginal utility functions, while WAP is supported by the relevant WAP software for the assessment of criteria weights through prioritizations. This is the first application of the above framework in the environmental domain. The above combination of methods was selected to suit the type and the dimensions of the decision problem, taking into account the relevant merits of the selected methods. The proposed MCDA framework is considered a relatively flexible approach, which may be adapted depending on the needs of the decision problem. Also, it includes tools to analyze the robustness or sensitivity of decisions, hence improving the process of the decision making.

2. Materials and Methods

2.1. Setting up the Decision Problem: Towards Construction of the Decision Performance Table

A typical MCDA methodological framework identifies the alternatives, the type of recommendation needed on the alternatives and the criteria which are used to evaluate the alternatives. In the context of agricultural water management, alternatives are called the interventions which are planned as responses to the environmental challenges. For example, they could be technical or non-technical measures related to irrigation and fertilization practices. How these interventions are designed and pre-selected for analysis is out of the scope of this paper. A common conceptual model for environmental analysis of river basins and planning of measures, also underpinning the logic of the Water Framework Directive (WFD), is the Driving forces-Pressures-State-Impacts-Responses (DPSIR) model. The type of recommendation which is often needed is to choose one alternative, to sort the alternatives into predefined categories or to rank the alternatives in complete or partial order.

The criteria for the evaluation of the alternatives express important attributes and objectives of the planning. Criteria are represented by relative environmental and socio-economic indicators, which are determined by experts in collaboration with stakeholders. The criteria (and the relative indicators) can be grouped under different points of view in a hierarchical structure to facilitate the DM to express his preferences in two steps. Firstly, on the importance of the various points of view and, secondly, on the importance of the various criteria under each point of view. Criteria and indicators should be tailored to the specific context of the study area and meet the requirements of science and policy. Taking into account the linkages between water, energy, land and food, it is important to evaluate the alternatives related to agricultural water management, from all points of view related to WELF nexus. Thus, the nexus points of view should be made explicit in the overall set of points of view and representative indicators should be selected. Furthermore, criteria modelling is needed to identify physical constraints or regulatory threshold values. In addition, it should be recognized which criteria should be minimized or maximized, and which pairs of criteria create synergies or tradeoffs.

Estimating the values of the indicators for the various alternatives leads to the evaluation of the alternative actions on the various criteria, hence in the construction of the multicriteria performance table. The evaluation of the alternatives on the criteria can be implemented by using a wide range of information sources: ground-based monitoring, remote sensing, official statistics and databases, research publications, published studies, expert judgment and stakeholder processes. In addition, considering the multi-dimensional and multi-sector complexity of the WELF nexus, the use of a simulation engine is considered essential. For example, the Soil and Water Assessment Tool (SWAT) is a prominent distributed GIS-based hydro-environmental model, which has been used in recent studies for integrated and quantified analysis of nexus in river basins [14,15]. SWAT can model water quantity and quality, land use, soil and crop growth processes explicitly. Extension of the analysis towards other fields, such as energy or socio-economics, requires the use of additional thematic models or empirical relationships or proxy data and coefficients derived from existing studies and statistics.

2.2. Preference Modelling: Towards Elicitation of Decision Maker’s Value System

The proposed MCDA methodological framework follows the MAVT/MAUT approach combined with the WAP method. The above combination of methods requires the identification of the DM, who is supported to make the decision. Following MAVT/MAUT principles, the DM must have very good knowledge on the decision problem, behave rationally, keep his/her preferences unchanged for different alternatives and ensure his/her judgments are consistent. It should be highlighted that the DM can be an individual person or an organization represented by a person. In real life situations, the DM may be the head of an authority or an agency, usually the one taking decisions related to budget spending. In the case of multiple DMs, the same approach can be repeated for all DMs resulting in one recommendation for each DM. However, in the end a synthesis of different recommendations is needed. There is a variety of methods to carry out this synthesis, but group decision making is out of the scope of this paper.

In general, preference modelling aims at eliciting the DM’s preferences towards a consistent family of criteria, thus supporting the establishment of the DM’s value system. The estimated value system reflects the DM’s intrinsic and intuitive perception about the value of the criteria and it is a quantitative tool, which helps him manage his subjectivity. Interaction with the DM is important for this part of the methodology. The DM is interviewed using a structured questionnaire, while, in parallel, the process is aided through the use of competent software, which employs artificial intelligence, visual techniques and linear programming. The approach also includes open dialogue sessions, which provide feedbacks and might trigger modifications to previous preference decisions. The process is terminated when the DM feels that the constructed value system is fully compliant with his perceptions and a satisfactory level of robustness is reached.

The proposed methodological framework, which combines MAVT/MAUT with WAP, requires two types of information:

(a) Preferences related to the variation of the criteria value; Determining the variation of preference on the criteria scale will lead to the estimation of the marginal value function for each criterion.
(b) Preferences on the importance of the points of view, as well as on the criteria under the points of view; Information on the relative importance among the criteria will lead to the assessment of the criteria weights.

The core idea of the proposed MCDA methodological framework is to conclude to the estimation of the following additive value model, which is described with Equations (1)–(3):

$$U_i(g) = \sum_{j=1}^{n} p_j u_j(g_{ij}), \tag{1}$$

$$u(g_{j*}) = 0, \qquad u(g_j^*) = 1, \tag{2}$$

$$\sum_{j=1}^{n} p_j = 1, \tag{3}$$

where:
$i = 1, 2, \ldots, m$ is the number of the alternatives A_i
$j = 1, 2, \ldots, n$ is the number of the criteria C_j
$g = (g_1, g_2, \ldots, g_n)$ is the evaluation vector of an alternative action A_i on the n criteria,
g_{j*} and g_j^* are the least and most preferable levels of the criterion g_j, respectively,
$u_j(g_{ij})$ is the non-linear marginal value function for each criterion C_j, expressing the DM's preference variation on the criterion scale,
p_j is the weight for each criterion C_j, expressing its relative importance among the other criteria, with $0 \le p_j \le 1$

2.2.1. Estimation of Marginal Value Functions Using the MIIDAS System

The MIIDAS system supports the estimation of the marginal value functions $u_j(g_{ij})$, which are included in the additive value model (Equation (1)), utilising a set of built-in general functions in the form of u(a, b, c; g) with $u(a, b, c; g_{i*}) = 0$ and $u(a, b, c; g_i^*) = 1$, corresponding, close enough, to the preference variation. The estimation of the a, b and c parameters, which are control parameters for the shape of the marginal value functions, can be achieved interactively through two steps:

(a) The DM is assisted by the software to select the general form of the value function (e.g., linear, sigmoid) and, then, the shape of the function can be further adapted by changing its curvature or selecting specific points to pass it through.
(b) The values of a, b and c parameters are estimated utilising the mid-value splitting technique of MAUT. For an interval of performance $[g_{j,t}, g_{j,t+1}]$, the value $g_{j,k}$ corresponds to the mid-value point, if the ranges $[g_{j,t}, g_{j,k}]$, $[g_{j,k}, g_{j,t+1}]$ are differentially value-equivalent (with $t \le k \le t + 1$). This is achieved by solving an equations' system of the type: $u_j(a, b, c; g_{j*}) = 0$, $u_j(a, b, c; g_j^*) = 1$, $u_j(a, b, c; g_{j,k}) = 0.5$, where $(g_{j,k}, 0.5)$ constitutes the mid-value point.

2.2.2. Estimation of Criteria Weights Using WAP Technique

The WAP software supports the estimation of the criteria weights p_j, which are included in the additive value model (Equation (1)), following a two-step process:

a. The DM ranks the n points of view (or criteria under the points of view) into s classes ($s \le n$), from the most important to the less important.
b. The DM is asked to compare the successive points of view (or criteria under the points of view) in a pairwise manner, following their previous ranking. Supported by the visual tools of WAP software, the DM compares the most important point of view/criterion with the less important

point of view/criterion of the pair and provides their relative importance in the form of a ratio, which is index Z_r, which is given in Equation (4). The Z_r indices are not required to be determined with strict precision, but they are required to be articulated in a range format [$Zmin_r$, $Zmax_r$], where the value of Z_r could vary. The WAP software offers scroll bars to assist the visualisation of the difference in the relative importance.

$$Z_r = \frac{p_r}{p_{r+1}}, \tag{4}$$

where:

r = 1, 2, …, s − 1 is the random importance class for the criteria

p_r, p_{r+1} are respectively the weights of the r and r + 1 importance classes for the criteria

The above preference information, when elicited for all points of view (or criteria under the points of view), corresponds to infinite weights vectors, which are bordered into a n-dimensional hyper-polyhedron. Linear Programming techniques are employed in order to estimate the minimum and maximum values of the weights. Then, the mean value of the minimum and maximum values of the weights for each criterion is estimated. This leads to the estimation of the barycentre of the hyper-polyhedron. The estimated weights vector of the barycentre can be used in the additive value model, if its values and the level of robustness are considered satisfactory.

2.3. Robustness Analysis

The robustness of the DM's value system is monitored using the Average Stability Index (ASI) [16], which is given in Equation [5]. A value equal to 1 corresponds to total robustness of the preference model.

$$ASI = 1 - \frac{\sum_{j=1}^{n}\sqrt{\left(v\left(\sum_{j=1}^{v} {p_j}^2\right) - \left(\sum_{j=1}^{v} p_j\right)^2\right)}}{v\sqrt{(n-1)}} \tag{5}$$

where:

j = 1, 2, …, n is the number of the criteria C_j

h = 1, 2, …, v is the number of the hyper-polyhedron vertices

If the value system is found of low robustness, a set of feedbacks can be triggered, in order to introduce new preference information from the DM. This may lead to changing the criteria modelling or altering specific initial preferences (e.g., criteria ranking; relative importance of criteria).

2.4. Evaluation of Alternatives

After the construction of the final additive value model, then each alternative gets a marginal value on each criterion and a global value by aggregating all marginal values of each alternative. Then, the alternatives can be ranked based on their global values. The alternative with the highest global value is recommended.

2.5. Sensitivity Analysis

Sensitivity analysis can be carried out to understand how the estimated weights for the points of view (and the criteria under the points of view) influence the final ranking of the alternatives. The weight of each attribute can increase or decrease to its estimated maximum and minimum value, while the weights of the rest attributes get the values of the corresponding weight vector.

3. Results

For demonstration purposes, an illustrative example of the above methodology has been developed in Pinios river basin, which is a major agricultural river basin in Greece, facing issues with water scarcity and nutrient pollution. A number of alternatives have been developed (Table 1), taking into account previous research and stakeholder processes in the region [14,17,18]. In the example, the alternatives aim at addressing the pressures to the environment (e.g., water abstraction, application of fertilisers) through increased resource efficiency on the farm level. The evaluation of the alternatives is carried out using 6 points of view (i.e., Investment needs, Agricultural inputs, Water quantity and quality, Energy (water-related), Land/Soil, Food/Fiber) and 11 criteria on total (Figure 1). The evaluation on the criteria is implemented applying the methodology in Section 2.1. After the construction of the evaluation performance table, an expert on environmental and agricultural issues, with good knowledge of the region from previous research, is called to role-play the DM and provide his preferences on the criteria. The purpose of the MCDA process is to recommend the best alternative based on the DM's preferences. Preference elicitation is done using the methodology in Section 2.2.

The estimated criteria weights, the marginal values and the global values of the alternatives are presented in Table 2. The DM's value system was found very robust, since the ASI index reached close to 1 (>0.9887). For this specific example, and based on the DM's preferences, the alternative with the highest global value is "Combined Deficit Irrigation (−30%) & Reduced Fertilization (−30%) for cotton, maize and alfalfa". The sensitivity analysis showed that this alternative remains first for all estimated weight vectors with the WAP method.

Table 1. Presentation of alternatives for agricultural management.

Alternative	Description	Crops to Be Applied
Baseline (REF)	Conventional farming	cotton, maize, alfalfa, wheat
Deficit Irrigation (DI)	−30% in irrigation doses	cotton, maize, alfalfa
Reduced Fertilization (RF)	−30% in fertilization doses	cotton, maize, alfalfa
Combined Deficit Irrigation & Reduced Fertilization (DIRF)	−30% in irrigation and fertilization doses	cotton, maize, alfalfa
Precision Agriculture (PA)	Automated irrigation and fertilization doses	cotton

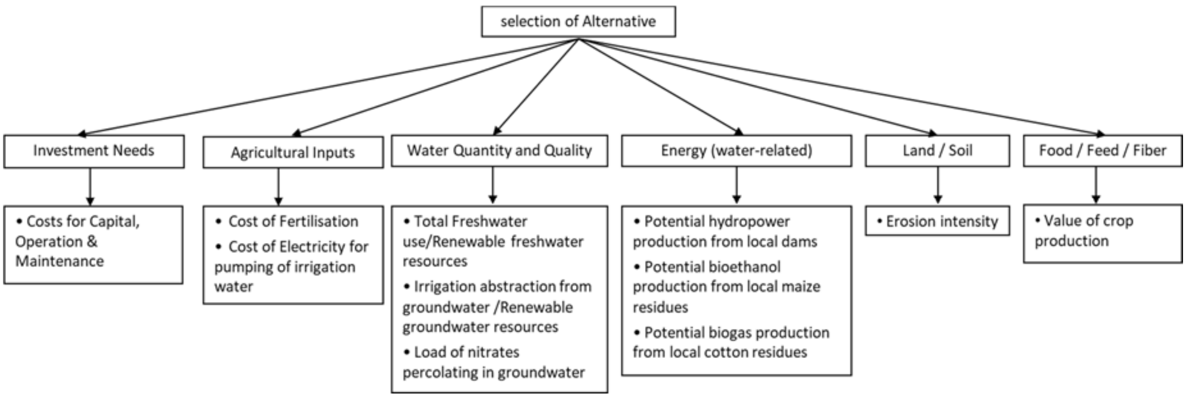

Figure 1. Presentation of points of view and criteria for the evaluation of alternatives.

Table 2. Final results for weights, marginal values and global values of agricultural management alternatives.

	Points of View and Criteria											
	Investment Needs	**Agricultural Inputs**		**Water Quantity & Quality**			**Energy (Water-Related)**			**Land/ Soil**	**Food/Feed /Fiber**	
Weights for Points of View	**0.199**	**0.158**		**0.218**			**0.147**			**0.120**	**0.171**	
	Additional annual equivalent cost for equipment	Average annual cost of fertilization with N	Average annual cost of electricity for pumping	Average annual total use/ Renewable resources (freshwater)	Average annual irrigation abstraction/ Renewable resources (ground-water)	Average annual load of nitrates percolating in groundwater	Average annual value of potential hydropower production from local dams	Average annual value of potential bioethanol production from local maize residues	Average annual value of potential biogas production from local cotton residues	Average annual erosion intensity	Average annual value of crop production	
Intra-relative weights		0.500	0.500	0.303	0.370	0.328	0.299	0.351	0.351			
Weights for criteria	0.199	0.079	0.079	0.066	0.080	0.071	0.044	0.052	0.052	0.120	0.171	
Alternative Actions	**Marginal Values**											**Global Values**
DIRF	1.000	0.574	0.706	0.380	0.224	0.629	0.518	0.541	0.544	0.603	0.750	0.667
DI	1.000	0.499	0.706	0.380	0.224	0.511	0.518	0.551	0.544	0.603	0.754	0.654
RF	1.000	0.574	0.599	0.097	0.023	0.623	0.601	0.571	0.601	0.599	0.792	0.638
REF	1.000	0.499	0.599	0.098	0.023	0.499	0.601	0.601	0.601	0.599	0.801	0.626
PA	0.253	0.558	0.589	0.084	0.483	0.704	0.632	0.601	0.615	0.601	0.808	0.536

4. Discussion and Conclusions

The proposed MCDA framework for agricultural water management in the context of WELF nexus is characterised by flexibility, which allows the inclusion of more alternatives or more criteria, than those selected in the demonstration example. For a small number of alternatives, the framework is more suitable than other methods (e.g., UTA), which require the existence of a reference set before the preference information can be extrapolated to a larger number of alternatives. Unlike other methods (e.g., AHP), the criteria weights remain the same even if new alternatives are added to the existing ones during the planning procedure of measures. Furthermore, the newly-established WAP technique, which is used for the estimation of the criteria weights, includes tools which support robustness analysis of the estimated value systems. Future research work on the proposed MCDA framework will focus on the incorporation of uncertainty and fuzziness on the decision parameters and the exploitation of social choice theory for the analysis of different stakeholders' perspectives to the decision problem.

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