



# MCDA approach for agricultural water management in the context of water–energy–land–food nexus

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Received: 24 January 2018 / Revised: 17 July 2018 / Accepted: 3 October 2018 /  
Published online: 15 October 2018  
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## Abstract

An integrated methodological framework, combining methods for environmental analysis with multi-criteria decision aid (MCDA), is proposed for decision problems related to the selection of agricultural water management measures in river basins. The proposed framework for environmental analysis combines the driving forces–pressures–state–impacts–responses model with the water–energy–land–food (WELF) nexus model to ensure structured, comprehensive and systemic thinking regarding the definition of the alternatives, the points of view and the criteria of the decision problem. The MCDA framework follows a multi-attribute value/utility theory approach for the estimation of marginal value functions for the selected criteria. This process is supported by the multicriteria interactive intelligence decision aiding system. The estimation of points of view and criteria weights is conducted following the newly-established weights assessment through prioritisation method (WAP), which is supported by the relevant WAP software. The MCDA framework includes strong interaction with a decision maker (DM) to elicit the required information for the above methods. Feedback loops and indicators for robustness analysis are applied, aiming at concluding to a robust value system, which models the preferences of the DM as close as possible. An additive value model is used to aggregate all the criteria and express the global value of all examined alternatives. The framework concludes to a recommended alternative for selection by the DM. The strengths and weaknesses of the proposed framework are identified. The framework is applied in a demonstration example from the Pinios river basin in Greece to showcase its use. The outcomes on the potential WELF nexus trade-offs and the identified sources of uncertainty are discussed.

**Keywords** MCDA · MAUT · WAP · DPSIR · Nexus · Agricultural water

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## 1 Introduction

Agricultural river basins are vulnerable to various environmental challenges, such as water scarcity and drought, pollution with nutrients, pollution with chemicals and hydromorphological alterations of water bodies. The monitoring programmes facilitate the identification of the specific challenges related to each river basin and they provide scientific evidence for the design of competent measures and the assessment of their effectiveness. 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 added value and the efficiency of allocated resources. However, there has been recent critique that policy and research 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 (Leck et al. 2015). In addition, implementation of water policies in practice has faced many difficulties. For example, there has been incomplete understanding and targeting of the multiple agents, which cause the environmental issues. Also, the design and prioritisation of measures has resulted in slower progress than anticipated, despite high investments (Brack et al. 2017; Voulvoulis et al. 2017).

The driving forces–pressures–state–impacts–responses (DPSIR) model (Smeets and Weterings 1999) constitutes a well-established conceptual framework, which links socio-economic activities with environmental conditions. The DPSIR model focuses on the causal relationships between the driving forces, the pressures, the status, the impacts and the responses related to an environmental challenge. It is a structured and rational approach for environmental analysis, which, despite its shortcomings (Marttunen et al. 2017), may underpin the delivery of a comprehensive environmental assessment. Furthermore, the water–energy–land–food nexus (WELF nexus) is a holistic 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 (Hoff 2011; Ringler et al. 2013). Adopting the WELF nexus model in environmental analysis leads to the acknowledgement of the interdependent nature of water, energy, land and food systems. This facilitates the identification of synergies and trade-offs between the objectives related to the management of these resources. The combination of DPSIR and WELF nexus models, forms a competent framework for structured, integrated and responsive environmental analysis. The implementation of this framework in practice may improve the management of river basins, also including water management in agriculture.

Agricultural water management in the context of WELF nexus, constitutes a complex decision problem with multiple, conflicting and incommensurable objectives, which are frequently characterised by uncertainty or fuzziness. 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 rationalisation of the decision process, (b) by modelling the preferences and the subjectivity of the decision maker (DM) 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 analysing the degree of robustness on the estimated decision model, which provides to the DM a deeper understanding of the decision problem (Hajkowicz and Collins 2007; Zopounidis and Pardalos 2010). Cost–benefit analysis (CBA) has been extensively applied in water and environmental decision problems to synthesize the different conflicting criteria, but two serious limitations have been identified so far. These are the need for monetisation of all the criteria and the difficulties in integrating various angles (points of view) and perceptions from different audiences (stakeholders) regarding the criteria. For example, various environmental risks and benefits are difficult to be evaluated in monetary terms (e.g. soil, biodiversity, health), which causes their exclusion from the decision process. Furthermore, because of the different or conflicting interests of stakeholders, costs and benefits may be defined and understood differently. However, combining MCDA with evaluation results from CBA can be an improved approach (Feuillette et al. 2016; Hajkowicz and Collins 2007).

MCDA approaches can be categorised in four main theoretical trends, depending on the form of the models, the model development process and the scope of the application (Pardalos et al. 1995; Siskos and Spyridakos 1999). These are: (a) the Value System approaches including the Analytic Hierarchy/Network Processes—AHP/ANP (Saaty 1987, 1980; Saaty and Sodenkamp 2010) and the Multi-Attribute Value/Utility Theory—MAVT/MAUT (Dyer 2005; Fishburn 1982, 1970; Keeney 1996; Keeney and Raiffa 1976), (b) the Outranking Relations approaches—ELECTRE (Roy 1976, 1985, 1989; Vanderpooten 1990); PROMETHEE (Brans et al. 1984); other Outranking approaches (Martel and Matarazzo 2005) including TOPSIS and VIKOR, (c) the Disaggregation–Aggregation Approach (Jacquet-Lagrange and Siskos 1982; Siskos 1980; Siskos et al. 2005; Siskos and Yannacopoulos 1985) and (d) the Multi-Objective Optimization approach (Ehrgott and Wiecek 2005; Evans and Steuer 1973; Korhonen and Wallenius 1990; Steuer 1985; Zeleny 1974).

Past and recent literature review (Cegan et al. 2017; Huang et al. 2011; Kiker et al. 2005; Mardani et al. 2016) suggests that MCDA applications in the environmental field, including the domains of water and natural resources, have shown an essential growth in the last decades, both in number of publications and as a share of total publications related to environmental sciences. AHP/ANP has been applied more frequently, especially in publications incorporating spatial analysis using geographic information systems (GIS). In the domain of water and natural resources MAVT/MAUT is the second most frequent approach used. Furthermore, it should be noted that many research works employ more than one approaches, with MAVT/MAUT and AHP/ANP being a classic duo. In addition, TOPSIS and VIKOR are two methods which have gained considerable attention in water and natural resources decision problems over the last decade.

In general, the selection of the most appropriate MCDA approach for each decision problem depends on the information which is required by the DM and how

this information is translated into a preference structure under reasonable behavioral assumptions (Stewart 1992). The type of the decision problem, the dimensions of the decision performance table (i.e. number of alternatives and criteria), the treatment of uncertainty and the available robustness analysis techniques for each methodology are important features, which determine the suitability of an MCDA approach for a given problem. However, several authors (Cegan et al. 2017; Cinelli et al. 2014; Huang et al. 2011; Yatsalo et al. 2016) argue that the selection of an MCDA approach in practice is also affected by other factors, such as the user's technical background and expertise, the availability of user-friendly and commercially supported software packages, the historical and geographical legacy, and the existence of enthusiastic and engaged user communities. For example, the attractiveness of AHP/ANP in MCDA applications is attributed to a number of reasons, including the long record of relevant publications in a wide range of journals, the existence of strong user communities in North America and Asia, its simplicity in the process for the assessment of a value system and its availability in many software packages. On the other side many arguments have been raised (Bana e Costa and Vansnick 2008; Siskos and Spyridakos 1999) for the accuracy, the theoretical foundations and the demanding information required during the preferential elicitation phase of the above mentioned methodological frame. In addition, several literature reviews (Cegan et al. 2017; Cinelli et al. 2014) suggest that researchers and practitioners in the environmental field usually miss to define properly the specific reasons for choosing a certain MCDA method instead of another. Also, they do not discern between different methods and they rarely mention the relative merits of each method. This could mean that there is a significant knowledge gap, which calls for closer collaboration between environmental scientists and operational researchers.

Regarding the topics of MCDA applications in the domain of water and natural resources, these often include the following: management of marine protected areas and fisheries, site prioritisation for dams and water reuse schemes, reservoir systems operation, water resources vulnerability and management, flood risk mapping and management, climate change adaptation and environmental restoration (Azarnivand and Malekian 2016; Hajkowicz and Collins 2007; Huang et al. 2011; Kiker et al. 2005; Mardani et al. 2016). Furthermore, MCDA applications in the domain of agriculture tend to focus on topics related to agricultural resources management, while also a few assess the sustainability of agricultural systems (Dantsis et al. 2010; Gómez-Limón and Sanchez-Fernandez 2010; Hayashi 2000).

The present paper aims to propose and demonstrate an MCDA methodological framework addressing decision problems related to agricultural water management in the context of WELF nexus. The MCDA framework is based on the combination of a traditional approach (MAVT/MAUT) with a newly-established method (WAP). Overall, the methodology is considered relatively flexible and it may be further adapted, depending on the needs of each specific case study. The methodology includes tools to analyse the degree of robustness of the proposed solution, improving in that way the decision-making process on agricultural measures. This is the first application of the above MCDA methodological framework in the environmental domain and the paper aspires to support the further uptake of emerging MCDA methods and combinations of methods by the domains of water, natural resources

and agriculture. In addition, the paper provides explicit justification on the reasons for selecting the above methods, hence calling for higher awareness about the relative merits of each MCDA method in environmental applications.

An additional feature of the paper is the relative focus on methods for integrated and comprehensive environmental analysis (e.g. DPSIR combined with WELF nexus), which may lead to the formulation of the decision problem from environmental perspective. The paper explains the links between the framework for environmental analysis and the framework for MCDA, thus facilitating the collaboration and common understanding between environmental scientists and operational researchers.

## 2 Methodology

### 2.1 Typical structure of MCDA methodological frameworks

The decision problems addressed by MCDA can be categorised in four problem statements (Roy 1975): (a) choice, where one or a limited set of alternatives ought to be selected, (b) sorting, where the alternative decisions are assigned to predefined categories, (c) ranking, which concludes to a complete or partial order of the alternative actions and (d) description, which focuses on the identification of the distinguishing features among the alternatives and on the enrichment of the available information about the decision problem. MCDA frameworks conclude to a recommendation to the DM for the problem statement under consideration, which is harmonised with his/her preference attitudes and compatible with the specific conditions of the decision situation. The term “recommendation” is used in MCDA literature to note that, ultimately, the DM is completely free to determine which will be the final decision regardless of the recommendation (Roy 1996).

The various alternatives of the decision problem are evaluated and compared according to different points of view and criteria. In MCDA, the term “criteria” refers to functions, either quantitative or qualitative, by which the performance of alternative actions is evaluated. It should be highlighted that it is crucial for the MCDA methodological framework to be based on a “consistent” family of criteria, which satisfies the following conditions (Roy and Bouyssou 1993): (a) exhaustiveness—only if for each pair of alternative actions with the same evaluation for all the criteria, the DM considers them as indifferent, (b) monotonicity—only if for each pair of alternatives  $a_1$  and  $a_2$  for which  $g_i(a_1) > g_i(a_2)$  for one criterion  $g_i$  and  $g_i(a_1) = g_i(a_2)$  for every other criterion, it could be assumed that the DM prefers the alternative  $a_1$  to  $a_2$ , (c) non-redundancy—only if the removal of any criterion, it will contradict one of the two above conditions. The evaluation of the alternative’s performance on the criteria family leads to the development of the decision performance table.

A fundamental step towards the final evaluation of the alternatives and the conclusion to a recommendation is the elicitation of the DM’s preferences. Depending on the utilised MCDA method, the information required for the preference modeling differs. It could be the result of direct comparison between the alternatives or

determination of a preference relation regarding the performance of the alternative actions on the criteria (Vincke 2001).

In the MCDA framework the high interaction between the DM and the decision analysts during the whole decision process is crucial for the quality and success of the final recommendation. The determination of the alternative actions, the specification of the recommendation needed, the criteria modeling, the construction of the performance table, the preference elicitation phase, the analysis of results and feedbacks regarding the outputs require interaction with the DM. Therefore, a well-defined DM is important for the decision process. 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, especially related to budget spending. In the case of multiple DMs (or organisations represented by DMs), a group decision making approach should be followed, assisted by social sciences approaches for the synthesis of preferences. However, this aspect is out of the scope of the current paper.

In summary, the typical structure of MCDA methodological frameworks is illustrated in Fig. 1. The proposed MCDA methodological framework in this publication follows similar structure. It is worth mentioning that adaptations, expansions and enrichments of MCDA general methodological frameworks have been proposed, illustrated and exploited through the years for specific decision problems, which suffer uncertainty (Stewart 2005), fuzziness (Siskos 1982; Zimmerman 1983) and low

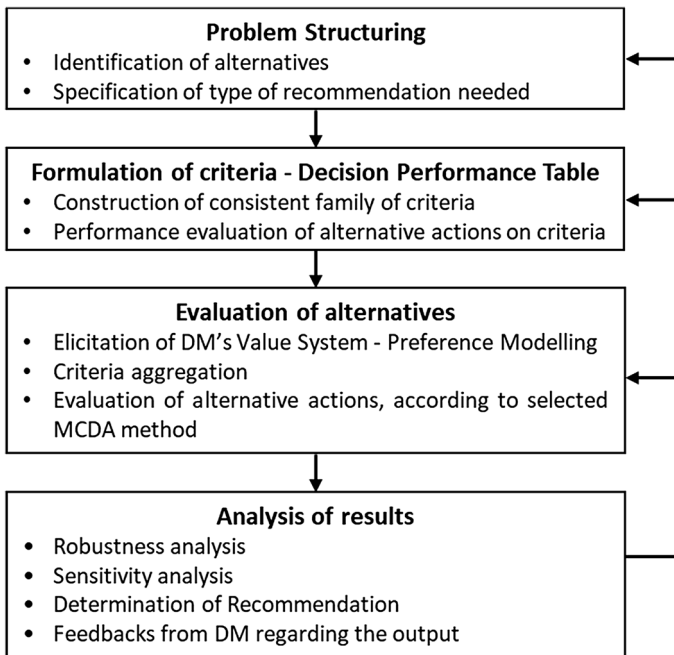


Fig. 1 A typical MCDA methodological frame. Adapted from Roy (1985)

robustness (Roy 2010) of preference models or imperfect preference information (Bouyssou 1989).

## 2.2 Setting up the decision problem from environmental perspective: combining DPSIR model with WELF nexus analysis

The management of agricultural water in the context of WELF nexus is complex and challenging, because of the conflicting nature of goals, such as water security, food security, energy security, environmental protection, economic and social growth. For example, a community might need more food for its increasing population, but this will require more water for irrigation. The need for irrigation might lead to higher water abstractions from groundwater, but lower water tables of coastal aquifers might cause seawater intrusion. Abstracting water from greater depths will result in increased costs of energy for pumping, while seawater intrusion may cause the degradation of the aquifer as a source for irrigation water, due to high levels of salinity in groundwater. On the other hand, applying less water than required for irrigation might lead to lower crop yields, lower food production for the community and lower income for farmers and their families.

Before designing and implementing measures related to agricultural water management, a proper environmental analysis of the river basin needs to be conducted. This analysis may support the identification of key agents affecting the environmental status, the river basin mechanisms which could offset the suggested measures and the potential side-effects from the measures. Consequently, it may strengthen the overall planning of measures and lead to solutions which are more effective, efficient and multi-objective. This paper adopts two tools for environmental analysis in river basins. In specific, the DPSIR model is combined with the WELF nexus model to create a framework, which is logically structured, holistic and comprehensive. It should be noted also, that the interaction with stakeholders is essential at this stage. The relevant dialogue allows the exploration of social behaviours and social trends, while it ensures that social preferences towards recommended solutions are captured early in the overall planning process.

The DPSIR model is the backbone of many environmental assessments, because it helps organise the complex interacting agents in a causal order (D–P–S–I–R: driving forces–pressures–status–impacts–responses). A recent review of publications where DPSIR is combined with MCDA (Marttunen et al. 2017) has reached several interesting conclusions. The authors suggest that DPSIR provides a powerful framework to aid initial understanding, structuring and communication of complex environmental issues. For example, the reflection on D–P–S–I elements supports the identification of responses targeting the above elements. Therefore, in MCDA terminology, the “responses” of the DPSIR model constitute the “alternatives” of the decision problem. In addition, if the designed responses/alternatives are implemented, they will introduce interventions to the existing D–P–S–I elements. Hence, the updated D–P–S–I elements, and especially the updated impacts, are good candidates for criteria to evaluate the performance of the alternatives. The ex-ante



evaluation of the updated impacts caused by responses/alternatives, can improve planning by acting pro-actively to reduce risks and increase benefits.

However, if the DPSIR analysis is conducted with limited perspective, focused on water affairs, then it might miss the complex interactions between water and other environmental resources. Also, it may miss the synergies and trade-offs between the relevant goals for these resources. Since 2011 there has been a significant increase in global attention to the notion of “nexus”, following the publication of a relevant thematic report by the World Economic Forum (Vaughan 2011) and the organisation of the Bonn 2011 international conference on “The Water, Energy and Food Security Nexus—Solutions for the Green Economy” by the German Federal Government (Martin-Nagle et al. 2012), which contributed to the United Nations Conference on Sustainable Development (Rio+20). The Water–Energy–Food security nexus approach, introduced in that conference, recognises a central role for water availability, which interacts with the goals of water, food and energy security. The whole system is driven by external forcings and delivers a range of services to environment and society (Hoff 2011). The above conceptual framework was later adapted (Ringler et al. 2013) taking the form of a triangle with water, energy and land in its corners, and an additional node for food in the centre. All agents interact with each other, while the whole WELF nexus interacts with external drivers of change, including climate change, demographics or science and technology. Finally, the WELF nexus delivers services related to human well-being and environmental sustainability. Adopting a WELF nexus perspective, when addressing the individual elements of the DPSIR model, can lead to more integrated thinking and planning of responses/alternatives. For example, the “state” element can be seen as the state of nexus, rather than the state of water. Similarly, driving forces, pressures and impacts can be linked to this new state of nexus. Furthermore, the element of “responses” needs to take into account the goals and policies in other sectors. Therefore, the adoption of the WELF nexus model introduces points of view and relevant criteria for the evaluation of the water management alternatives.

### 2.3 Setting up the decision problem from MCDA perspective: towards construction of the decision performance table

In general, a decision problem consists of a set of alternatives  $A_i$  and a set of criteria  $C_j$ . In matrix form, the decision problem can be expressed using the following decision performance table (Eq. 1):

$$D = \{g_{ij}\} = \begin{bmatrix} g_{11} & g_{12} & \dots & g_{1n} \\ g_{21} & g_{22} & & g_{2n} \\ \vdots & & \ddots & \vdots \\ g_{m1} & g_{m2} & \dots & g_{mn} \end{bmatrix}, \quad (1)$$

where  $A_i$  is the  $i$ th alternative ( $i=1, 2, \dots, m$ ),  $C_j$  is the  $j$ th criterion ( $j=1, 2, \dots, n$ ) and  $g_{ij}$  is the performance of alternative  $A_i$  on criterion  $C_j$ .



In the context of agricultural water management, the planned alternatives can be technical or non-technical measures related to irrigation and fertilisation practices on the field. Information about best management practices (BMPs) in agriculture can be found in various publications and guidance documents (Brouwer et al. 1990; Liu et al. 2017; Panagopoulos et al. 2014; Roy et al. 2006; Tanji and Kielen 2002).

In addition, points of view and criteria usually express important attributes and objectives of the planning. The criteria are represented by relative environmental and socio-economic indicators, which are determined by experts in collaboration with stakeholders. There are various frameworks proposing criteria and indicators related to sustainable watershed management, water security and sustainable agricultural systems (Dickson et al. 2016; Van Cauwenbergh et al. 2007; Varady et al. 2016; Vishnudas et al. 2008). Criteria and indicators should be tailored to the specific context of the study area and meet the requirements of science and policy. Thus, criteria modelling is needed, in order to identify any physical constraints or regulatory limit and threshold values. Furthermore, it is important to recognise if the preferable condition is the maximisation or minimisation of each criterion and which pairs of criteria create synergies or trade-offs.

A review of publications related to MCDA applications for agricultural resources management reached a number of key conclusions on the structure of the decision problems (Hayashi 2000). For example, decision makers were usually policy makers (at regional level) or farmers (at farm level). The total number of alternatives varied significantly, ranging between 2 and 10 (24 and 72 in two occasions). The alternatives were interventions using single farm tools and machinery or combinations of elements forming a strategy. The total number of criteria was low, ranging between 4 and 10 (17 in one occasion). The most frequently used criteria addressed farmers' revenues and costs, risks for farmers' revenues, agricultural inputs (e.g. utilisation of labour, machinery or area), level of agricultural production and environmental concerns (e.g. nitrogen loss, biocide accumulation, soil erosion, water use, conservation of traditional systems).

The evaluation of the performance of the agricultural management alternatives on the selected criteria can be implemented by using a wide range of information sources. Taking into account the multi-dimensional and multi-sector complexity of the 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 (Karabulut et al. 2016; Psomas et al. 2016). In addition, SWAT has been applied in a broad range of studies for designing water-related measures in agricultural catchments (Arabi et al. 2008; Asharf et al. 2014; Huang and Li 2010). SWAT can model water quantity and quality, land use, soil and crop growth processes explicitly (Neitsch et al. 2011). Extension of the analysis towards other fields, such as energy or socio-economics, requires the use of additional thematic models or empirical relationships or data and coefficients derived from existing studies and statistics. Therefore, the output of the model (e.g. water stocks, water flows, nutrient loads, sediment loads, crop yields) combined with other information sources, can be further processed to extract the target indicators for each criterion. Moreover, the establishment, calibration and validation of

the model requires data and knowledge, which may be retrieved from ground-based monitoring, remote sensing, official statistics and databases, research publications, published studies, expert judgement and stakeholder processes.

## 2.4 Estimation of the evaluation model for the alternative agricultural management practices

The core idea of the proposed MCDA methodological framework is to conclude to the estimation of the following additive value model (Eq. 2):

$$\begin{aligned}
 U_i(g) &= \sum_{j=1}^n p_j u_j(g_{ij}) \\
 u(g_{j*}) &= 0, \quad u(g_j^*) = 1 \\
 \sum_{j=1}^n p_j &= 1, \quad 0 \leq p_j \leq 1,
 \end{aligned} \tag{2}$$

where:  $g = (g_1, g_2, \dots, g_n)$  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 marginal value function for 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.

Preference modelling aims at capturing the DM's preferences towards a consistent family of criteria and supports 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 the DM manage his/her subjectivity. Two types of information are required by the DM:

- (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; Information on the relative importance among the criteria will lead to the assessment of the criteria weights.

A common MCDA method used for the estimation of the above additive value system is MAVT/MAUT, in which the marginal value functions of the criteria  $u_j(g_{ij})$  and the criteria weights  $p_j$  are estimated in two separate phases. The estimation of the marginal value functions is implemented applying a complementary set of compensatory methods and techniques, such as the Lock-Step procedure and the mid-value splitting technique (Keeney and Raiffa 1976). In MAVT/MAUT, as well as in other MCDA approaches, the estimation of the criteria weights can be implemented separately by using a large number of proposed methods, including the MAUT compensatory technique (Keeney and Raiffa 1976), AHP (Saaty 1980), the Simos

technique (Figueira and Roy 2002; Simos 1990a, b) and the Weight Assessments through Prioritisation (WAP) method (Tsotsolas et al. 2016).

In the proposed MCDA methodological framework, the additive value model (Eq. 2) is estimated by combining MAVT/MAUT approach with the WAP method using the following procedure (Fig. 2):

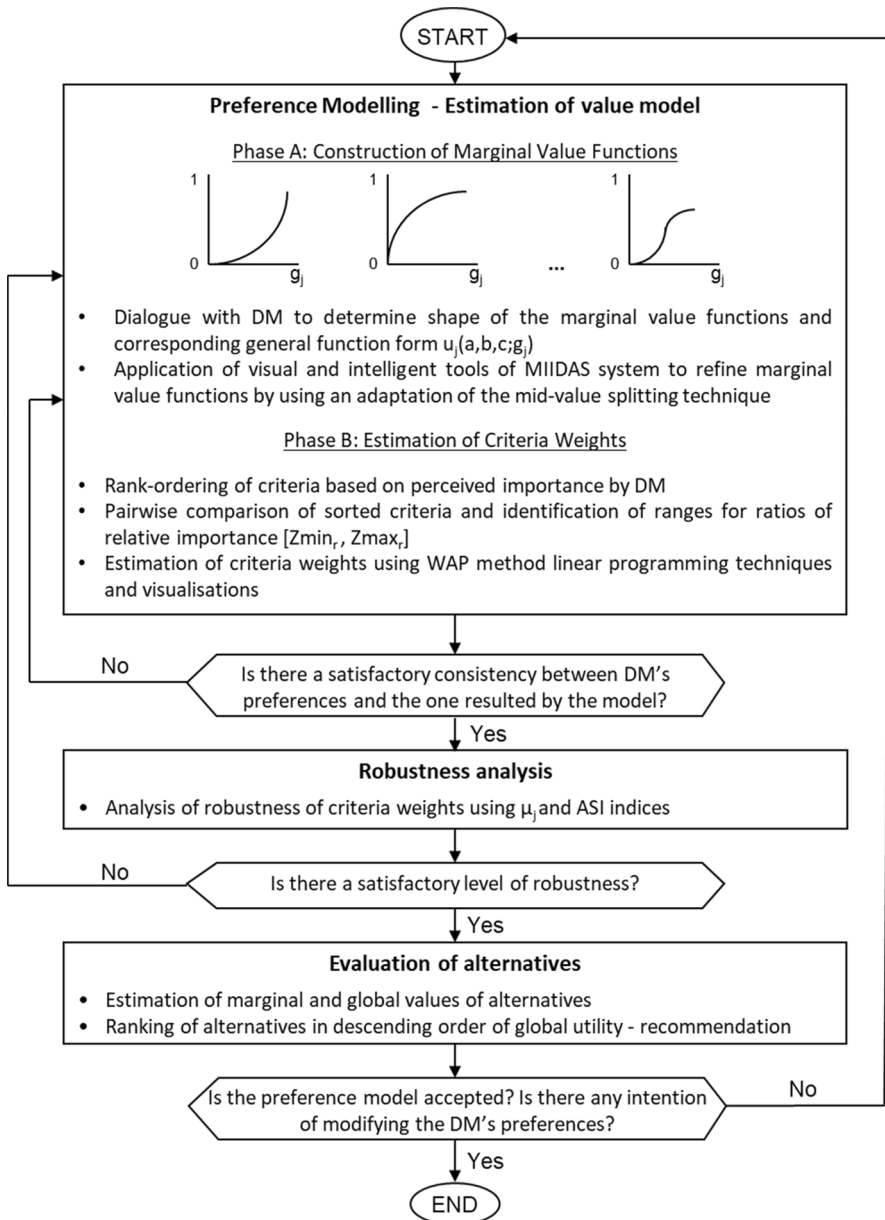


Fig. 2 Additive value model estimation procedure using MIIDAS and WAP methods

- In the first phase of preference modelling, the marginal value functions for each criterion are estimated using the Multicriteria Interactive Intelligence Decision Aiding System (MIIDAS), which combines artificial intelligence with visual techniques for preference disaggregation analysis (Siskos et al. 1999). The estimation of the marginal value functions using the MIIDAS system is based on compromising techniques, which constitute adaptations of MAUT. Here, the DM provides preference information related to the variation of the criteria values (see Sect. 2.4.1).
- In the second phase of preference modelling, the criteria weights are estimated using the relevant software for the WAP method (Tsotsolas et al. 2016), which combines criteria prioritisations with linear programming techniques and visualisations. Here, the DM provides preference information on the importance of the points of view and criteria to him/her (see Sect. 2.4.2).
- Robustness analysis tools are utilised to evaluate the robustness of the estimated criteria weights (see Sect. 2.4.3).
- The alternatives are evaluated using the estimated preference model (see Sect. 2.5)

The above procedure includes strong interaction between the decision analysts and the DM. Throughout the process, the DM is being interviewed using a structured questionnaire to capture his/her preferences, while at the end of each step he is asked to re-examine and confirm his/her choices. Especially, after the analysis of the results and the conclusion to a recommendation, the DM is free to reject the estimated value model and provide updated feedback for any of the previous steps. This feedback triggers new iterations, which are terminated, when the value model is finally accepted.

#### 2.4.1 Estimation of marginal value functions using the MIIDAS system

The MIIDAS system includes a set of built-in general functions in the form of  $u_j(a, b, c; g_j)$ , which correspond, close enough, to the DM's preference variation in relation to the performance  $g_{ij}$ . For example, one of the functions supported by MIIDAS system has the form  $y = u(g) = a + be^{cg}$ ,  $g \in [g_*, g^*]$ ,  $c > 0$ ,  $c \in [0.0001, 1.5]$ . The estimation of the  $a$ ,  $b$  and  $c$  parameters, which are control parameters for the shape of the marginal value function for the  $j$ th criterion  $u_j$ , can be achieved interactively through a set of techniques provided by the MIIDAS systems the most familiar of which are the following.

The first one is based on the mid-value splitting technique and is implemented in two steps:

- The DM is assisted by the software to select the general form of the value function (e.g. linear, concave, non-concave, sigmoid). The identification of the general form could be achieved by the rank ordering, provided from the DM, of the importance of changes from the less to the most preferred value for six equal and complementary ranges of the criterion's total range. The intelligent component

of MIIDAS system proposes the general form(s) which corresponds to DM preferences variation into the criterion scale.

- The values of a, b and c parameters are estimated utilising the mid-value splitting technique of MAUT. It is assumed that  $g_j$  is the value of the  $j$ th criterion and  $g_{j*}, g_j^*$  are the best and worst values of  $g_j$ , respectively. For an interval of performance  $[g_{j,t}, g_{j,t+1}]$  with  $t=1, 2, \dots, a_{j-1}$ , where  $a_j$  is the scale of the  $j$ th criterion with  $g_{j*}=g_{j,1}$  and  $g_j^*=g_{j,a_j}$ , 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  $t \leq k \leq t+1$ ). This is achieved by solving a system of equations 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. In addition, the shape of the function may be further adapted by changing its curvature or selecting specific points to pass it through.

The second technique for the construction of the marginal value function is focused on the design of the functions by the DM. For limited specific values of the  $j$ th criterion  $g_j \in [g_{j*}, g_j^*]$ , the DM is asked to provide the corresponding marginal values in the scale of  $[0, 1]$ . By this way, specific points of the marginal value function  $(g_{j,k}, u_j(g_{j,k}))$  are identified. Then, the shape of the general form of the marginal value function is assessed and utilizing the visual components of the MIIDAS system this function is adapted, so as to pass through the points  $(g_{j,k}, u_j(g_{j,k}))$ .

### 2.4.2 Estimation of criteria weights using the WAP technique

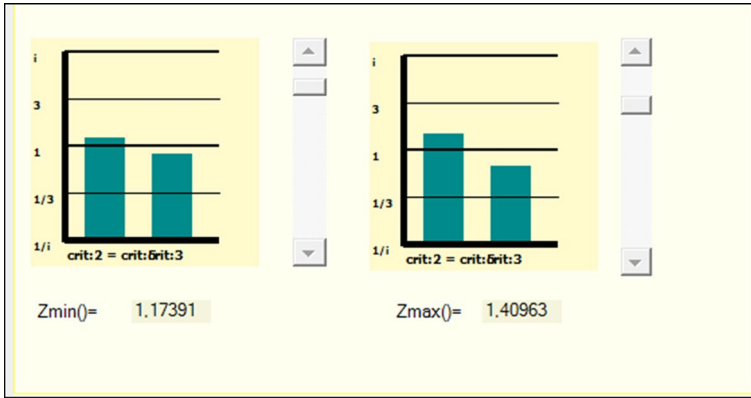
The WAP technique is implemented using the relevant WAP software to estimate the criteria weights  $p_j$  in the following steps:

- The DM ranks the  $n$  points of view (or criteria under the points of view) into  $s$  classes ( $s \leq n$ ), from the most important to the less important.
- 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  $Z_r$  (Eq. 3):

$$Z_r = \frac{p_r}{p_{r+1}}, \tag{3}$$

where:  $r=1, 2, \dots, s-1$  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 ratio of relative importance  $Z_r$  is not required to be determined with strict precision, but it is required to be articulated in the range format  $[Z_{min_r}, Z_{max_r}]$ , where the value of  $Z_r$  may vary. The WAP software offers scroll bars to assist the visualisation of index  $Z_r$ . The DM uses the scroll bars to define the range of the index  $Z_r$ , thus to define  $Z_{min_r}$  and  $Z_{max_r}$  (Fig. 3).



**Fig. 3** Identification of the minimum ( $Z_{min}$ ) and maximum ( $Z_{max}$ ) ratio of relative importance of two successive points of view/criteria using the double bars graph in the WAP software

- The above preference information, when elicited for all points of view/criteria, corresponds to infinite weights vectors, which are bordered into a  $n$ -dimensional hyper-polyhedron. Linear Programming (LP) techniques are employed in order to estimate the minimum and maximum values of the weights. The following  $2n$  optimisation problems describe the estimation of the weight vectors for the maximisation and minimisation of the criteria weights:

$$\min p_j \ \& \ \max p_j, \quad \text{where } j = 1, 2, \dots, n$$

s.t.  $p_q - p_{q+1} = 0$ , if  $g_{q+1}$  is followed by  $g_q$  and  $g_{q+1}$  belongs to the same importance class ( $r$ ) as  $g_q$  or  $p_q - p_{q+1} \geq Z_{min,r}$ ,  $p_q - p_{q+1} \leq Z_{max,r}$ , if  $g_q$  is followed by  $g_{q+1}$ ,  $g_q$  belongs to most important class ( $r$ ) and  $g_{q+1}$  belongs to less important class ( $r + 1$ ), for every  $q = 1, 2, \dots, n - 1$   $0 \leq p_j \leq 1$  and  $\sum_{j=1}^n p_j = 1$ .

- After the estimation of the maximum and minimum values of the weights, the mean value of the weight of each point of view/criterion is extracted. This leads to the approximation of the barycentre of the above-mentioned hyper-polyhedron. If the values of the weight vector, which represents the barycenter, are found satisfactory and the robustness is fair, then the weight vector of the barycenter can be used in the additive value model (Eq. 2).

### 2.4.3 Robustness analysis

Robustness analysis for the estimated criteria weights is important, because it helps to evaluate how stable the DM's preferences are regarding the relative importance of the criteria. In the proposed MCDA framework, the level of robustness of the estimated criteria weights can be evaluated using two indices.

- The first is the indices  $\mu_j$ , which represent the range between the maximum and minimum values of the estimated weights  $p_j$  for each criterion  $C_j$  (Eq. 4).

$$\mu_j = (\max p_j - \min p_j), \tag{4}$$

where:  $j = 1, 2, \dots, n$ .

- The second is the index ASI (Average Stability Index) (Grigoroudis and Siskos 2002), which represents the normalised standard deviation of the criteria weights values corresponding to the vertices of the above-mentioned hyper-polyhedron, which is created by the ranges of all criteria weights (Eq. 5). A value of ASI close to 1 means that the DM’s preference model is almost totally robust.

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

where  $n$  is the number of the criteria and  $v$  is the number of post-optimal solutions which are corresponding to the vertices of the hyper-polyhedron.

If the robustness analysis shows that the estimated preference model does not have satisfactory robustness, a set of feedback actions can be triggered, in order to introduce new preference information by the DM. For example, this may lead to changing the criteria modelling, the criteria ranking or the ratios of the criteria relative importance.

### 2.5 Evaluation of alternatives

Using the estimated marginal value functions (see Sect. 2.4.1) and the estimated criteria weights (see Sects. 2.4.2, 2.4.3) the final additive value model (Eq. 2) can be constructed. The marginal value on each criterion and the global value for each alternative are estimated according to the assessed additive value model. Then, the agricultural management alternatives can be ranked in descending order based on their global values. The alternative with the highest global value is recommended for selection by the DM.

## 3 Demonstration example and 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. It should be noted that the demonstration example is not an exhaustive study for the elaboration of river basin measures, rather than a showcase of the previously mentioned methodology.



### 3.1 Brief overview and environmental analysis of the study area

The local River Basin Management Plan (SSW 2014) and relevant publications (Panagopoulos et al. 2014; Psomas et al. 2017; Stefanidis et al. 2018) provide a detailed insight into the environmental status and challenges in Pinios river basin. In addition, they support with data the DPSIR and WELF nexus analysis of the river basin.

The Pinios river basin (~10,600 km<sup>2</sup>) lies in central Greece and its central part is covered by a large fertile plain, where cotton, winter wheat, maize and alfalfa are mainly cultivated. Cotton is a major export product which is used in textile industry, while wheat and maize are used (with or without processing) for food. Alfalfa and maize are used as feed for animals, which are intensively bred in the river basin to meet the needs of the local meat and dairy industry. Biomass from agricultural residues, such as those of cotton and maize, have been studied for their potential to produce bio-energy in local plants.

The average annual rainfall and reference evapotranspiration are approximately 700 mm and 1400 mm respectively, while the observed average annual streamflow at the catchment outlet is approximately 80 m<sup>3</sup>/s. Irrigated agriculture takes up approximately 90% of the total water use and approximately 50% of the total agricultural land. Taking into account the official and unauthorised abstractions from illegal boreholes, the primary water source is by far groundwater. Overexploitation of groundwater has led to high energy costs for pumping from high groundwater depths and it has increased the vulnerability of coastal aquifers to seawater intrusion. Surface water is mainly abstracted from the reservoirs of Plastiras and Smokovo, as well as from the restored lake of Karla. Plastiras and Smokovo are multi-purpose reservoirs which also meet the needs for hydropower production, tourism and recreation. Irrigation infrastructure includes collective systems with open trenches and canals, which are responsible for very high conveyance losses (30–50%). The conveyance efficiency of the urban distribution network is also very low, as losses reach up to 40%.

Since the 1980s, payments to the farmers under the Common Agricultural Policy (CAP) have led to intensive farming of subsidised crops. As a result, the use of fertilisers and pesticides has grown rapidly causing problems with diffuse pollution. Today, the plain of Thessaly is officially characterized as a Nitrate Vulnerable Zone (NVZ). The ecological status of most water bodies in the area is below good condition. In addition, the organic content of the soils has depleted, while erosion of the hillslopes has increased.

Moreover, a major challenge related to agriculture is the hydromorphological alteration of the natural riverine system. Dams, levees, irrigation infrastructure and pumping have changed the natural conditions of water flow and sediment transport. The complete dry-up of various downstream river segments is a frequent phenomenon in summer months.

**Table 1** Conventional agricultural management practices

Crop	Annual irrigation (mm)	Annual fertilization	
		(kg N/ha)	(kg P/ha)
Cotton	570	195	31
Maize	620	214	48
Alfalfa	740	0	46
Winter wheat	40	131	16

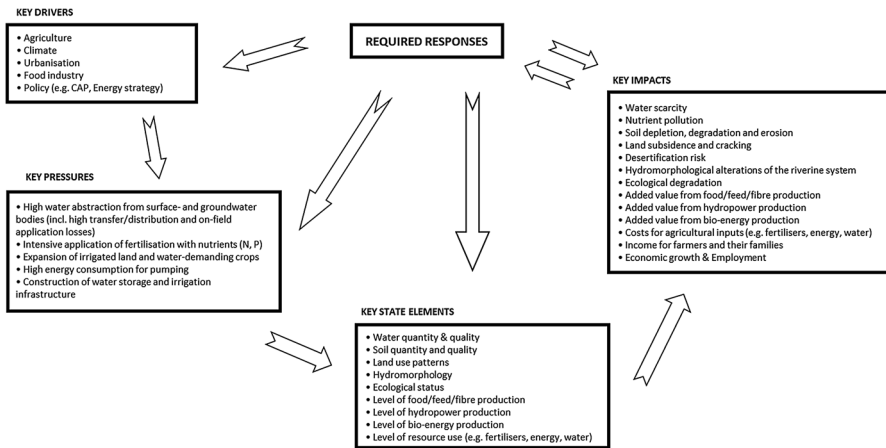
**Table 2** Presentation of alternatives for agricultural management

Alternative	Description	Crops to be applied
Baseline (REF)	Conventional farming	Cotton, maize, alfalfa, winter wheat
Deficit irrigation (DI)	– 30% in irrigation doses	Cotton, maize, alfalfa
Reduced fertilisation (RF)	– 30% in fertilization doses	Cotton, maize, alfalfa
Combined deficit irrigation and reduced fertilisation (DIRF)	– 30% in irrigation and fertilization doses	Cotton, maize, alfalfa
Precision agriculture (PA)	Automated irrigation and fertilization doses	Cotton

### 3.2 Setting up the decision problem from MCDA perspective: towards construction of the Decision Performance Table

Taking into account previous research and stakeholder processes in the region (Makropoulos and Mimikou 2012; Panagopoulos et al. 2014; Psomas et al. 2016), the baseline conditions for agricultural management practices (Table 1) and a number of responses (Table 2) have been developed. The selected responses/alternatives target at key pressures identified from the environmental analysis (Fig. 4), such as high water abstraction and intensive application of fertilisers. The alternatives focus on increased resource efficiency at the farm level.

The performance of the above alternatives is evaluated using six points of view, including Investment needs, Agricultural inputs, Water quantity and quality, Energy (water-related), Land/Soil and Food/Feed/Fiber. Each point of view is further elaborated using 1–3 criteria, which are closely related in terms of content, and 11 criteria on total. The selected points of view and criteria take into account attributes related to different types of costs and WELF nexus elements. It should be highlighted that most of the criteria represent expected key impacts, which were identified in the environmental analysis (Fig. 4). Impacts are good indicators in planning, because they allow ex ante evaluation of the performance of suggested alternatives. Thus, any potential negative impacts during the implementation of a measure may be captured and addressed pro-actively. The organisation of the individual criteria in points of view is needed for cognitive reasons, because it helps the DM to make more meaningful comparisons. Generally, it is recommended to present to the DM for assessment no more than six or seven



**Fig. 4** Environmental analysis of the Pinios river basin combining DPSIR model with WELF nexus perspective

criteria in each subset, or possibly a few more if visual information is also provided (Pomerol and Barba-Romero 2000).

The five alternatives for agricultural management (Table 2) constitute hydro-environmental scenarios which may be simulated using a properly calibrated and validated SWAT model of the Pinios river basin (Psomas et al. 2016). Remote sensing and image interpretation techniques were used to derive land use information from multispectral high spatial resolution data (Landsat 8/OLI-TRS, 30 m). Relevant administrative and environmental datasets for the Pinios river basin were collected from various sources, such as the Greek Ministry of Environment and Energy, the Public Power Corporation, the National Institute of Geology and Mineral Exploration, the National Institute of Soil Mapping and Classification, Eurostat and previous studies conducted in the Pinios river basin (Psomas et al. 2016). Furthermore, expert judgements took stock of the extensive stakeholder dialogue, which was organised in Pinios river basin during the research project i-adapt (2011–2012). The i-adapt project was focused on innovative approaches to halt desertification in Pinios river basin (Makropoulos and Mimikou 2012; Panagopoulos et al. 2014). The outputs of the SWAT model over the 20-year simulation period were averaged and then combined with the other sources of information. Proxy values for the selected criteria were estimated.

The evaluation of the performance of the alternatives on the selected criteria lead to the construction of the decision performance table (Table 3). The recommendation which is requested in this specific demonstration example is to select the best alternative, based on the DM's preferences (choice problem).

### 3.3 Estimation of the evaluation model for the alternative agricultural management practices

After the construction of the decision performance table, preference modelling is required to establish a value system. For the purposes of this demonstration

**Table 3** Decision performance table

Points of view	Investment needs	Value of agricultural inputs	Impacts on water quantity and quality				Impacts on (water-related) energy				Impacts on land/soil	Impacts on food/feed/fiber
Criteria	Additional annual equivalent cost for capital, operation and maintenance of equipment (10 <sup>6</sup> €/year) (min)	Average annual cost of fertilisation with N (10 <sup>6</sup> €/year) (min)	Average annual cost of electricity consumption for pumping irrigation water (10 <sup>6</sup> €/year) (min)	Average annual total freshwater use/renewable freshwater resources (%) (min)	Average annual irrigation abstraction from groundwater/renewable groundwater resources (min)	Average annual load of nitrates percolating in groundwater (kg/ha/year) (min)	Average annual value of hydro-power production from local dams (10 <sup>6</sup> €/year) (max)	Average annual value of potential bioethanol production from local maize residues (10 <sup>6</sup> €/year) (max)	Average annual value of potential biogas production from local cotton residue (10 <sup>6</sup> €/year) (max)	Average annual value of potential biogas production from local cotton residue (10 <sup>6</sup> €/year) (max)	Average annual erosion intensity (kg/ha/year) (min)	Average annual value of crop production (10 <sup>6</sup> €/year) (max)
Alternative actions	Performance of alternatives on criteria											
REF	0.0	127.7	31.7	55.4	1.91	24.2	5.8	6.0	4.2	1350	406.6	
DI	0.0	127.7	23.2	36.8	1.61	23.6	5.0	5.5	3.8	1336	382.6	
RF	0.0	108.6	31.7	55.5	1.91	18.2	5.8	5.7	4.2	1350	402.2	
DIRF	0.0	108.6	23.2	36.8	1.61	17.9	5.0	5.4	3.8	1336	380.5	
PA	19.9	112.7	32.5	57.5	1.32	14.3	6.1	6.0	4.3	1344	410.4	

example, a senior expert on hydrology, integrated water resources management and agriculture, with very good knowledge of the Pinios river basin from previous research and stakeholder processes, has been called to role-play the DM (“fictitious DM”). Physical interaction with the DM is central for this part of the methodology, which leads to the establishment of the DM’s value system. The decision analysts have prepared structured questionnaires and they have used them to interview the DM, while he/she is guided to use the competent software of MIIDAS or WAP. This allows a dialogue with the DM, which helps to clarify ambiguities and solve misconceptions related to the content of the questions or the process. At each step, the DM is asked to confirm his/her choices, else to repeat the step and provide updated information. The process is terminated when the DM feels that the constructed value system is fully compliant with his perceptions and the robustness of the value system is found satisfactory. Overall, the decision analysts have elicited the required preference information, which is described in Sect. 2.4, to estimate marginal value functions and weights for all criteria.

### 3.3.1 Estimation of marginal value functions using the MIIDAS system

The DM is interviewed using a dedicated structured questionnaire, while he/she is guided to use the proposed methodological frame and the software MIIDAS. The marginal value functions were estimated with both techniques presented in Sect. 2.4.1., according to the criteria nature and the DM’s preferences. Initially, the decision analysts make an introduction to the DM regarding the process that is going to be followed throughout the interview. The DM is asked to confirm that he/she understands and agrees with the process. Afterwards, a sequence of questions follows, where each of them is focused on one criterion and the indicator which represents the criterion. The questions are carefully formulated to provide all necessary information about the content, the units, the physical constraints, the regulatory limits and thresholds and the baseline value of the indicator. It should be noted, also, that the indicator values of the alternatives are not labelled after the name of the alternatives, but with generic names (e.g. alternative #1). It is assumed that the DM is kept unbiased, if he/she is not aware of which management practice is behind each alternative.

The analysis of the DM’s preferences has led to linear marginal value functions for nine out of eleven criteria and non-linear marginal value functions for two criteria. The selection of mostly linear marginal utility functions, which vary between a minimum and a maximum value, is also mentioned in relevant literature about MAVT/MAUT applications in agricultural resources management. The use of more complex non-linear preference models is rare (Dantsis et al. 2010; Hayashi 2000). In this specific example, the use of non-linear preference models was applied for two indicators related to water quantity. Both indicators have predefined levels, which distinguish more sustainable from less sustainable water management.

The first indicator is the average annual ratio of irrigation abstraction from groundwater to renewable groundwater resources. When this ratio exceeds 1, then the irrigation abstractions from groundwater become unsustainable, because water is abstracted from permanent resources. The DM did not want the groundwater

body to be over-exploited, so his/her preference fell rapidly for values greater than 1. However, the DM also took into account that the groundwater body is already over-exploited in the baseline scenario and sustainable conditions cannot be restored by any alternative. Thus, he was willing to show additional preference for alternatives, which may reduce the level of non-sustainable conditions, compared to the baseline. The above led to the identification of a sigmoid general form for the marginal value function of the above-mentioned min criterion, using the MIIDAS system. It also led to the identification of the following points  $(g_{jk}, u_j(g_k))$  of the marginal value function: (0, 1.0), (1, 0.9), (1.3, 0.5), (1.4, 0.4) (1.8, 0.1). The utilisation of the MIIDAS visual tools enabled the construction of the marginal value function and the estimation of the a, b and c parameters of the  $u_j(a, b, c; g_j)$  function, so as the sigmoid function passes through the above mentioned five points.

The second indicator is the percentage of the average annual total freshwater use to the renewable freshwater resources in the river basin. Based on the local river basin management plan, when this indicator exceeds 30%, water stress is moderate. Also, when it exceeds 50%, water stress is severe (Psomas et al. 2017). The DM showed a high preference for indicator values lower than 30%, but his preference started to decline sharply above this point. For indicator values exceeding 50% the preference was minimised. However, taking into account that the indicator is above 50% in the baseline scenario, the DM showed some additional preference for alternative that were at least closer to 50%. The criterion was broken down into six ranges, namely [0, 16.67], [16.67, 33.33], [33.33, 50], [50, 66.67], [66.67, 83.33], [83.33, 100], which were ranked in the positions (1, 2, 3, 4, 5, 6) respectively. After the ranking, using the MIIDAS system, a sigmoid general form of the value function was identified following (Eq. 6):

$$u(g) = \begin{cases} a_1 - b_1 e^{c_1 g}, & 0 \leq g < 30 \\ a_2 + b_2 e^{c_2 g}, & 30 \leq g < 100 \end{cases} \quad (6)$$

Afterwards, the DM was asked to identify the mid-value point for the total range of the criterion [0, 100]. In this case, the corresponding mid-value point was (33, 0.50). Then the DM was asked to identify the mid-value points for the intervals [0, 33] and [33, 100]. The corresponding mid-value points were (30, 0.75) and (43, 0.25). The solution of the system of equations of  $u(0)=1$ ,  $u(100)=0$ ,  $u(33)=0.5$ ,  $u(30)=0.75$  and  $u(43)=0.25$  led to the estimation of the parameters  $a_1=0.750$ ,  $b_1=0.276$ ,  $c_1=-0.1$ ,  $a_2=-0.336$ ,  $b_2=-6.176$ ,  $c_2=-0.291$  and the assessment of the marginal value function.

The elicited marginal value functions are shown indicatively for four criteria (Fig. 5). It should be highlighted that the information of the marginal value functions is site-specific and person-specific, so it may not be transferred in another context.

### 3.3.2 Estimation of criteria weights using the WAP technique—robustness analysis

The DM is interviewed using a dedicated structured questionnaire, while he/she is guided to use the WAP method software. Initially, the decision analysts make an introduction to the DM, regarding the process that is going to be followed throughout

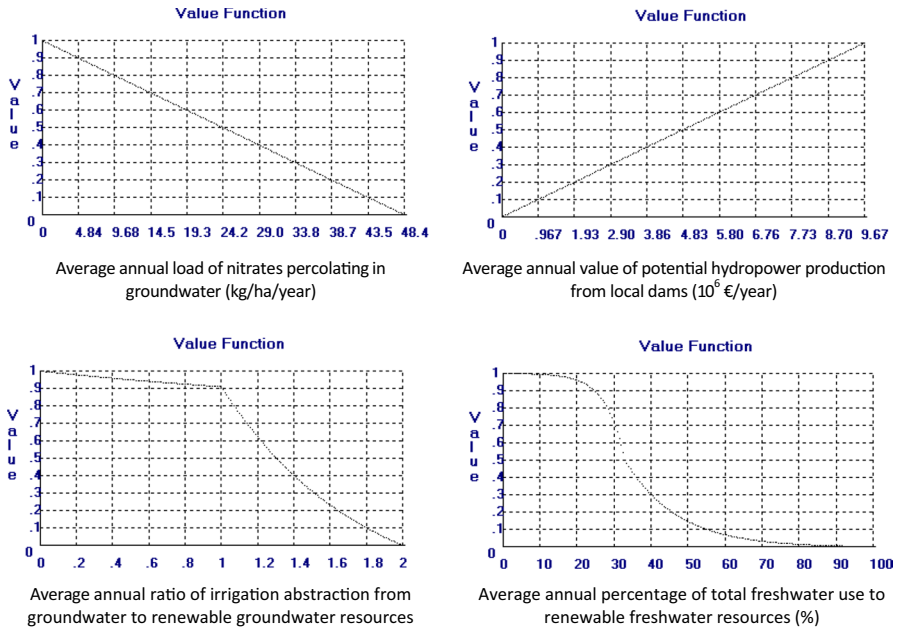


Fig. 5 Marginal value functions drawn by the DM (indicative)

the interview. The DM is asked to confirm that he/she understands and agrees with the process. The DM is asked to express his/her preferences about the importance of the points of view and criteria in various ways: ranking, pairwise comparisons of consecutive attributes in ranking, relative importance of consecutive attributes in terms of range of ratios. The adopted approach is hierarchical, starting with the estimation of the weights for the points of view and concluding with the estimation of the weights for the criteria. Robustness analysis for the weights is performed at each step (see Sect. 2.4.3).

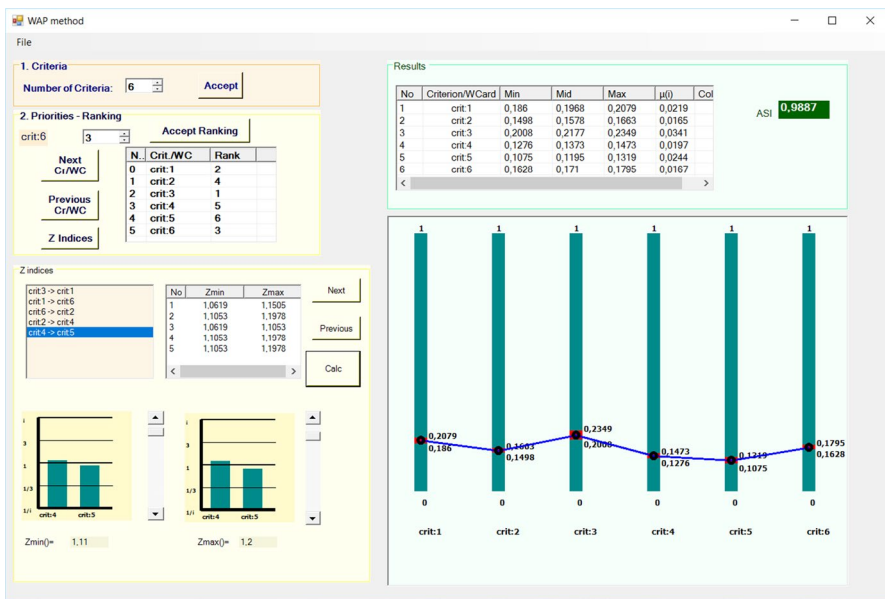
In the first step, the relative importance of the six main points of view was estimated. Table 4 includes the ranking of the main points of view, the ranges of the  $Z_r$  indices, the estimated weights barycentre and the minimum and maximum weights estimated by post-optimality analysis. In addition, it includes the values of indices  $\mu_j$  and ASI. Based on their values, the estimated value system is considered very robust. Figure 6 illustrates the interface of the WAP method software, where the above step was implemented.

In the second step, the relative importance of the criteria under each point of view has been estimated in a similar way as above. In specific, the WAP method has been implemented separately for the group of criteria included in the Water Quantity and Quality (Table 5) and Energy (Table 6) points of view. For the two criteria included in the Agricultural inputs point of view, the DM has judged the same importance. The rest points of view have only one criterion, thus the weight of the point of view is set equal to the weight of the criterion. Based on the values of indices  $\mu_j$  and ASI the estimated value system is considered very robust.



**Table 4** Estimation of weights and robustness analysis for the main points of view

Ranking	Main points of view	$[Z_{min}, Z_{max}]$	Weights BC	Weights min	Weights max	Index $\mu_j$
1	Impacts on water quantity and quality	[1.06, 1.15]	0.218	0.201	0.235	0.034
2	Investment needs	[1.11, 1.20]	0.197	0.181	0.207	0.026
3	Impacts on food/feed/fiber production	[1.06, 1.11]	0.171	0.163	0.180	0.017
4	Value of agricultural inputs	[1.05, 1.20]	0.158	0.150	0.169	0.019
5	Impacts on energy (water-related)	[1.05, 1.20]	0.137	0.128	0.147	0.019
6	Impacts on land/soil		0.120	0.108	0.140	0.032
Average Stability Index (ASI)						0.989



**Fig. 6** Interface of the WAP method software

The aggregation of the estimated weights for the points of view (first step) and the estimated weights for the intra-relative importance of the criteria within each point of view (second step) results in the estimation of the final criteria weights vector.

### 3.3.3 Evaluation of alternatives

Using the estimated marginal value functions and the estimated criteria weights the marginal and global values of the agricultural management alternatives are

**Table 5** Estimation of weights and robustness analysis for water quantity and quality criteria

Ranking	Criteria	$[Z_{\min}, Z_{\max}]$	Weights BC	Weights min	Weights max	Index $\mu_j$
1	Average annual irrigation abstraction from groundwater/renewable groundwater resources	[1.05, 1.152]	0.370	0.363	0.377	0.014
2	Average annual load of nitrates percolating in groundwater	[1.062, 1.105]	0.328	0.323	0.332	0.009
3	Average annual total freshwater use/renewable freshwater resources		0.303	0.296	0.309	0.013
	Average Stability Index (ASI)					0.996

**Table 6** Estimation of weights and robustness analysis for Energy criteria

Ranking	Criteria	$[Z_{min}, Z_{max}]$	Weights BC	Weights min	Weights max	Index $\mu_j$
1	Average annual value of potential bioethanol production from local maize residues	[1.0, 1.0]	0.351	0.349	0.353	0.004
1	Average annual value of potential bioethanol production from local maize residues	[1.05, 1.20]	0.351	0.349	0.353	0.004
3	Average annual value of potential hydropower production from local dams		0.299	0.295	0.303	0.008
	Average Stability Index (ASI)					0.997

estimated (Table 7). Based on their global values, the alternatives are ranked in descending order. In this demonstration example, the alternative which is recommended for selection is the combined deficit irrigation (−30%) and reduced fertilization (−30%) for cotton, maize and alfalfa. This alternative has the highest global value among the rest.

## 4 Discussion

### 4.1 Strengths and weaknesses of the proposed methodological framework

One of the strong points of the proposed methodological framework is the link between the MCDA framework and the framework for environmental analysis. The paper explains in detail the merits of combining DPSIR with WELF nexus and how specific elements of the environmental analysis can support the formulation of the decision problem. These include the identification of the responses/alternatives to the environmental challenge, the identification of relevant points of view and the identification of competent criteria to evaluate the alternatives, especially if the indicators representing the criteria are linked to the impacts of the responses/alternatives. Nevertheless, the DPSIR model has various shortcomings, which should be known to its users (Marttunen et al. 2017). For example, it can be difficult to decide if an agent is a driver or a pressure or even an impact, in cases where an impact initiates a new cycle of causal effects. In the context of the MCDA framework, when selecting D–P–S–I–R agents as criteria, the consistency of the family of criteria has to be examined (requirements for exhaustiveness, non-redundancy and monotonicity), to eliminate the risk double-counting the same effect.

In general, the proposed MCDA framework, which combines the compensatory approach of MAVT/MAUT with the WAP method, shows significant advantages. For example, the framework allows the independent evaluation of each alternative from the other alternatives. Hence, adding or deleting alternatives does not change the estimated weights or marginal value functions for the criteria. This makes the framework flexible and suitable for a high number of alternatives. In addition, the framework is also suitable for decision problems with a limited set of alternative actions. In the demonstration example the alternatives were only five. In this case, an alternative method, based on disaggregation–aggregation approach, would not be appropriate, since the number of alternatives is not satisfactory to build a reference set and estimate the additive value model. If there was a considerable number of alternatives, then a disaggregation–aggregation approach could be followed also.

The framework is also relatively strong in handling inclusions or exclusions of criteria. The adoption of a hierarchical structure, which starts with defining the points of view and grouping the criteria in subsets of criteria, contributes to the following. When one criterion is added or deleted under one point of view, then only the criteria weights for the respective criteria under that specific point of view have to be re-estimated. Since the criteria weights express the relative importance of each criterion compared to the rest, if there were no points of view, then all criteria weights would have to be re-estimated. Grouping the criteria under points of view

**Table 7** Estimation of marginal and global values for the evaluation of agricultural management alternatives

Points of view	Investment needs	Value of agricultural inputs	Impacts on water quantity and quality	Impacts on (water-related) energy				Impacts on land/soil	Impacts on food/feed/fiber	
Weights for points of view	0.199	0.158	0.218	0.147	0.120	0.171				
Criteria	Additional annual equivalent cost for capital, operation and maintenance of equipment (10 <sup>6</sup> €/year) (min)	Average annual cost of fertilisation with N (10 <sup>6</sup> €/year) (min)	Average annual electricity consumption for pumping irrigation water (10 <sup>6</sup> €/year) (min)	Average annual irrigation abstraction from groundwater/renewable groundwater resources (min)	Average annual load of nitrates in ground-water (kg/ha/year) (min)	Average annual potential hydro-power production from local dams (10 <sup>6</sup> €/year) (max)	Average annual value of potential bioethanol production from local maize residues (10 <sup>6</sup> €/year) (max)	Average annual erosion intensity (kg/ha/year) (min)	Average annual value of crop production (10 <sup>6</sup> €/year) (max)	
Intra-relative weights	1.000	0.500	0.500	0.370	0.328	0.299	0.351	1.000	1.000	
Weights for criteria	0.199	0.079	0.079	0.080	0.071	0.044	0.052	0.120	0.171	
Alternative actions	Marginal values	Global values								
REF	1.000	0.499	0.599	0.023	0.499	0.601	0.601	0.599	0.801	0.626
DI	1.000	0.499	0.706	0.224	0.511	0.518	0.551	0.603	0.754	0.654
RF	1.000	0.574	0.599	0.023	0.623	0.601	0.571	0.599	0.792	0.638
DIRF	1.000	0.574	0.706	0.224	0.629	0.518	0.541	0.603	0.750	0.667
PA	0.253	0.558	0.589	0.483	0.704	0.601	0.615	0.601	0.808	0.536

is also advantageous for cognitive reasons. This approach helps the DM to make more meaningful comparisons between less attributes each time, while the alternative was to put the DM in the position to assess all criteria in the family at one stage. In the demonstration example there were 11 criteria in total. However, each subset included only up to 3 criteria, which required to be compared and assessed each time by the DM.

The utilisation of the WAP method for the estimation of the criteria weights provided the following advantages to the overall MCDA framework. Firstly, it provided a structured approach for the estimation of the criteria-relevant importance. Secondly, it required limited and easily extracted information on preferences by the DM. Thirdly, the application of visual tools made its application more intuitive and spontaneous. Fourthly, the application of linear programming techniques to extract weight ranges from minimum to maximum values, rather than unique weight values, led to improved quantification of uncertainty. This may support the performance of robustness and sensitivity analysis.

However, it should be noted that the engagement of stakeholders and DMs, as well as the processes for preference elicitation, are data-demanding, time-consuming and strenuous on cognitive terms. Hence, from this aspect, the proposed approach has rather high requirements in learning effort and implementation time. The utilisation of the MAVT/MAUT techniques for the construction of the marginal value functions requires very good knowledge by the DM both on the decision problem and on the selected points of view and criteria. In the demonstration example, the selected points of view and criteria were practical and well-documented, referring to costs/values or scientific/technical/regulatory information, and the DM had a long record of work in the examined river basin. Thus, the criteria were comprehensive to the DM, based on his/her academic and technical experience. Therefore, in that case, the construction of the marginal value functions was moderately difficult.

It should be highlighted that the methodology is also compatible with multiple DMs (or organisations represented by DMs). In this case, the preferences from different DMs should be analysed and aggregated using collaborative decision support approaches in the MCDA context. However, this discussion is related to group decision making, which is out of the scope of the current paper.

Additionally, it should be noted that before reaching the final stage of the decision making, which involves the DM's participation, numerous other decisions have been made in the previous stages. For example, the decision analysts may have examined various studies, or they may have engaged various experts and stakeholders to devise various alternatives, before pre-selecting those that are fit for further analysis. In addition, they may have pre-selected the points of view, the criteria and the indicators which are fit for the evaluation. Therefore, there is a whole pyramid of decisions, which are taken during the planning process and the formulation phase of the decision problem, long before the DM is mobilised to make the final decision. Hence, the final decision by the DM is also indirectly affected by the value systems and decisions of many other groups and individuals. In water resources planning the relevant stakeholders could include local residents, farmers, local authorities, water companies, water associations, regional planners, environmental agencies or environmentalists.

Finally, a key shortcoming of the proposed approach is the assumption of full compensation among the different criteria, which means that lower performance on some criteria can be offset by higher performance on other criteria. Due to the aggregation of all criteria in one unique additive value model, there is no possibility to introduce veto thresholds for one alternative. As a result, the proposed framework enforces a weak sustainability concept.

#### **4.2 Discussion of results from demonstration example—insights into the WELF nexus trade-offs**

In the demonstration example from Pinios river basin, the alternative which was selected for recommendation, based on the preferences of the selected DM, was combined deficit irrigation (−30%) and reduced fertilization (−30%) for cotton, maize and alfalfa (DIRF). This agricultural management alternative shows a very good performance on criteria related to investment needs, value of agricultural inputs, water quantity and quality, and land/soil. For the above points of view, it is the best or the second best option among the rest. The aggregated weighting of the above points of view is almost 0.7. Thus, despite its lower performance on criteria related to value of food/feed/fiber production and value of (water-related) energy production, this alternative prevails on global value. In conclusion, this alternative showcases a key trade-off in the river basin. If the DM wants to improve the environmental status and save costs for agricultural inputs, compared to the baseline, then he/she will have to sacrifice part of the value gained from crop and energy production. The estimated saving of costs is 27.6 million € per year (with aggregated weight of importance: 0.158), whereas the estimated loss of value is 26.9 million € per year (with aggregated weight of importance: 0.318).

Deficit irrigation (−30%) for cotton, maize and alfalfa (DI) shows very similar performance with DIRF, with two major exceptions. These are the cost of fertilization and the load of nitrates percolating into the groundwater (with aggregated weight of importance: 0.150), where DIRF is more effective. Reduced fertilization (−30%) for cotton, maize and alfalfa (RF) does not prevail on any criterion against the rest alternatives.

Finally, precision agriculture for cotton (PA) has a very mixed performance on the various criteria. PA has the highest or very high performance in reducing pollution with nitrates, costs of fertilisers and soil erosion, while it increases the natural recharge to groundwater bodies and the value of (water-related) energy and food/feed/fiber production in the river basin. It should be noted that water availability in the baseline does not suffice to meet the water requirements of all crops, so the river basin is in severe water stress. Although PA achieves initial water savings in the cotton fields, the additional water becomes gradually available for the irrigation of all water-stressed crops in the region. In general, water saving measures have to be combined with additional measures (e.g. incentive water pricing, strict monitoring and control of abstractions) to ensure real environmental progress on a regional scale (Psomas et al. 2017). PA has a low performance on criteria related to reduction of water stress and cost of electricity for pumping. Furthermore, its major weak point is



the extremely low performance on investment needs. PA requires the installation of closed pipe networks and drip irrigation systems, which makes it a relatively expensive alternative. On this criterion PA has a marginal value of 0.253, whereas the best alternative has a marginal value of 1. In conclusion, the evaluation of PA showcases another key trade-off in the river basin. If the DM wants to improve the environmental status and increase the value gained from crop and energy production, compared to the baseline, then he/she will have to compromise with higher investment costs for infrastructure.

Based on the above, it is suggested to examine a new alternative with reduced area of application for PA. For example, PA could be used not in all cotton fields, but only in those with the highest environmental issues. In general, more complex alternatives could be devised and evaluated taking into account the detailed spatial distribution of challenges and the detailed spatial performance of measures. In this way, effective and efficient spatial combinations of methods could be explored (Panagopoulos et al. 2014).

### 4.3 Sources of uncertainty and sensitivity analysis

The paper has focused on the quantification of uncertainty in the DM's value system, which is a major source of uncertainty in MCDA frameworks. Generally, this type of uncertainty may be related to criteria ranking, relative importance of criteria or evaluation of criteria performance. The performance of sensitivity analysis may support the understanding on how the variations of the criteria weights, within the estimated ranges, affect the ranking of the recommended alternatives.

In addition, the decision-making process in the above agricultural water management problem may have to address other sources of uncertainty, originating from the nature of the variables used as criteria and from the process for their estimation/modelling. For example, hydrological and climatic inputs in the river basin, land use patterns and water allocation strategies show variance over time. Furthermore, the prices of agricultural and energy commodities show high volatility across the years. As a result, modelling all the above processes and estimating the performance of the alternatives on the criteria introduces assumptions, which add up to the total uncertainty. When the performance of the alternatives on the criteria is characterised by uncertainty, then probabilistic, stochastic or fuzzy techniques and methods could be utilised. Moreover, sensitivity analysis could be conducted to identify the most sensitive variables in the whole decision process and to explore the robustness of the final recommendation against the changes of these variables.

## 5 Conclusions

Agricultural water management in the context of WELF nexus is associated with multiple, conflicting and incommensurable objectives. Similarly to other decision problems from the environmental domain, such problems are suitable candidates for MCDA approaches. An MCDA framework with significant relative merits is

the combination of MAVT/MAUT approach, for the estimation of marginal value functions using the MIIDAS system, with the WAP method, for the estimation of points of view and criteria weights using the WAP software. MAVT/MAUT is a traditional approach, while WAP is a newly-established method. This is the first application of this combination in an environmental problem.

It is recommended to use the framework, after a proper environmental analysis has been conducted. The combination of the DPSIR model, which ensures structured causal analysis of socio-economic activities and environmental challenges, with the WELF nexus model, which ensures cross-sectoral, multi-dimensional and integrated systemic thinking, constitutes a robust framework for environmental analysis, provided that caution is taken to address the shortcoming related to DPSIR. Strict formulation of the decision problem from environmental and MCDA perspective may enhance the adoption of common language and common understanding between the communities of environmental and operational researchers. Literature mentions that MCDA applications in the environmental field often lack proper formulation of the decision problem, understanding of underlying method assumptions and justification for the approach selection. This paper emphasises the need to close the gap between environmental science and operational research, while it provides an integrated framework bridging environmental analysis with MCDA.

Overall, improved environmental analysis and prioritisation of measures for water management may lead to more robust, effective and efficient portfolios of measures on river basin scale. Ex ante evaluation of environmental impacts, taking stock of hydro-environmental modelling and relevant impact indicators, supports the above target. Future work in nexus management problems may focus on extending the nexus interactions towards other fields and incorporating more types of uncertainty into the decision variables. Furthermore, group decision making approaches and social choice theory (Arrow 1963, 1967) would be explored for the engagement of multiple DMs and the analysis of the perspectives of different stakeholders.

A demonstration example was set up in the context of this paper for the Pinios river basin, which suffers from water scarcity and nutrient pollution. Five alternatives for more efficient on-field resource management were examined. Combined deficit irrigation and reduced fertilization had the best overall performance, taking into account the preferences of the selected DM on a consistent family of criteria, including perspectives about costs and WELF nexus. Precision agriculture is very effective in improving environmental conditions and sustaining yields and revenues related to agriculture and energy, but a huge shortcoming is its application cost. Therefore, it is suggested to be examined in areas with severe environmental challenges, after detailed spatial planning.

**Acknowledgements** We would like to thank the unknown reviewers for their useful comments on this publication. We would also like to thank Dr. Panagiotis Zervas and Vasiliki Dagalaki for their support with background data related to Pinios river basin modelling. Parts of this research were conducted under the project 'Nomoteleia' (Scientific Responsible: M. Mimikou). 'Nomoteleia' (<http://nomoteleia.eu/>) was partly funded by the General Secretariat of Research & Technology of the Greek Ministry of Education, Research and Religious Affairs (ARISTEIA I project).

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