Multicriteria Analysis for the Assessment of Flow Release Scenarios from a Hydropower Plant in the Alpine Region

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Abstract

The Alpine region is an area of conflict between the significant demand for hydropower (HP) generation and the protection of landscape and aquatic ecosystems. Decision Support Systems, like multicriteria analysis (MCA), represent suitable tools to support decision-makers and stakeholders in managing the use of water resources in a more sustainable way.

Based on a set of "quality indexes" identified in a previous study, the present paper analyzes the use of MCA in a real case study of HP sustainable management in Aosta Valley, one of the most important Italian regions for HP production. The Simple Additive Weighting (SAW) methodology was applied to quantify the flow to be released by an existing HP plant, in order to balance production needs and watercourse environmental conditions protection considering four criteria (Energy, Environment & Fishing, Landscape, and Economy). The decisional process was developed within a collaborative and participatory framework, involving key stakeholders in every decision-making step, and the obtained results were officially adopted by the Regional Government. In the paper, some innovative aspects of the case study are presented and discussed, like the elaboration of reactive indicators related to the watercourse discharge, progressively updated with the stakeholders along the process, and the definition of "real-time" alternatives, relating the flow releases to the natural discharges in the watercourse. Finally, some weaknesses of this MCA approach are identified and suggestions for improvements in future experimentations are proposed.

Keywords:

Multicriteria analysis · Alpine sustainable hydropower · Water resources management · Environmental flows · Environmental indicators · Stakeholders involvement

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1 Introduction

The Alpine regions represent an area of conflict between the economic demand for high hydropower (HP) generation and the protection of the aquatic ecosystems and landscapes. HP has a long tradition in Europe and it currently remains the largest source of renewable electricity in the continent, with a total installed capacity of 249 GW in 2017 (IHA 2018). However, HP can generate severe negative pressures on the ecological status of river systems and on the preservation of landscapes and natural sceneries. For example, interruption of longitudinal river continuity, changes in river morphology, and reduction of flow velocity can cause degradation and loss of habitats and/or changes in the structure of fish populations (Platform Water Management in the Alps 2011; CIPRA 2013). Moreover, this complex and fragile scenario is further affected by climate change, since glaciers reduction and shift of rainfalls in cold seasons are modifying the hydrological balance of Alpine rivers (Gingrich et al. 2009).

The necessity to integrate sustainable development in the hydropower sector, in the framework of climate changes, highlights a strong need to provide the public authorities responsible for water resources management with adequate Decision Support Systems (DSSs), which can help them to better understand complex system interactions (Ciolli et al. 2015). Among the different DSSs, multi-criteria evaluation techniques allow the implementation of extended integrated evaluations (Paneque Salgado et al. 2009), including competing objectives in the same framework (Steele et al. 2009).

Multicriteria analysis (MCA) refers to a set of techniques which are used to compare and rank different decision alternatives through multiple evaluation criteria (Hajkowicz and Collins 2007), including different relevant stakeholders in the assessment in order to consider multiple opinions and stakes (Paneque Salgado et al. 2009). Over the last decades, several MCA methods have been applied for decision problems concerning planning, management or assessment of renewable energy projects, including HP. Vassoney et al. (2017) carried out a review of the state of the art of MCA applications to sustainable HP production and related decision-making problems, covering the period 2000-2015, highlighting an increasing trend over time of this method application in different parts of the world. In particular, based on a critical review of the scientific literature, the study identified the most important elements to be considered as "quality indexes" of an MCA application.

The present paper describes and analyzes the application of MCA to a real case study of HP sustainable management in Aosta Valley, one of the most important regions in Italy for HP production. The Regional River Strategic Plan (Piano di Tutela delle Acque – PTA), issued in compliance with the requirements of the European Water Framework Directive (EC 2000) and national laws, prescribes the release of a minimum instream flow (MIF) from HP plant dams. The MIF must be quantified using a basic hydrological formulation or an experimental approach (hereafter named "experimentation") which requires the application of MCA to assess the plant compatibility with the environmental conditions of the watercourse (Girardi et al. 2011).

In the case study, MCA was adopted to quantify the instream flow to be released by an existing HP plant and it was carried out by applying all the set of "quality indexes" identified by Vassoney et al. (2017), in order to test their practical applicability. Some innovative aspects of this case study are presented and discussed, like the involvement of all the stakeholders throughout every step of the process and the definition of new indicators, strictly related to the watercourse discharge, elaborated *ad hoc* and progressively updated along the process. Due to the positive outcomes resulting from its application in the case study, this procedure will be formally included as the official assessment method in the Regional River Strategic Plan. To our knowledge, this is the first application of such an MCA procedure leading to the definition of a legally binding environmental flow release scenario for a hydropower plant and to the formal adoption of this assessment process in the institutional water licensing procedure.

2 Materials and methods

2.1 The case study site

MCA was applied to a small HP plant located in Aosta Valley (Italy), whose water intake is located at 1479 m a.s.l. on the Graines torrent, a small Alpine watercourse with a watershed of about 20 km^2 and a mean annual discharge of less than 1 m^3/s (Figure 1).

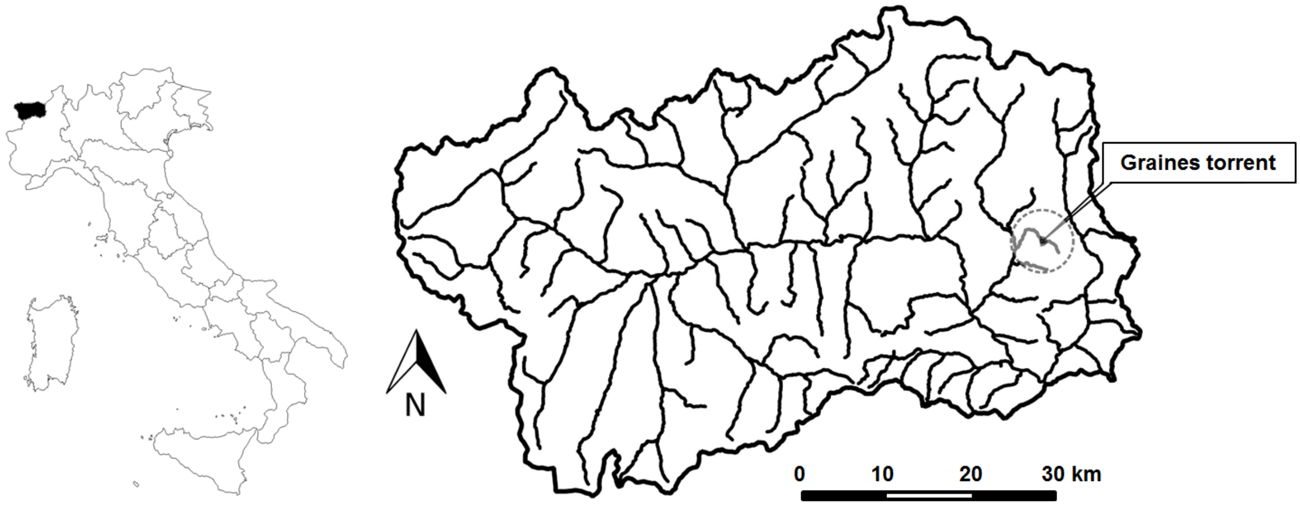

Fig. 1 Location of the HP plant

The HP plant is a run-of-the-river water abstraction with a total head of 125 m, a mean annual discharge of 462 l/s and an average annual nominal power of 566 kW. Its water license was issued in 2010, but, since no discharge data were available, the MIF was quantified using a basic hydrological formulation, with a high level of inaccuracy, which led to the interruption of the HP plant withdrawal for about six months per year. Therefore, in 2012, the HP company (Idroelettrica Brusson s.r.l.) and the Regional Authority (Regione Autonoma Valle d'Aosta) agreed upon starting an experimentation phase for the definition of environmental flows through the application of MCA, involving all the main institutional stakeholders.

A six-year hydrological monitoring program (2012-2018) was then implemented by the HP company in order to support the experimentation process, providing a sufficiently consistent and updated flow data series.

2.2 MCA methodology

A variety of different MCA techniques has been developed since the 1960s, such as AHP (Analytic Hierarchy Process), PROMETHEE (Preference Ranking Organisation Method for Enrichment Evaluation), etc. (Figueira et al. 2005). In recent years, several MCA methodologies have also been applied to complex problems concerning hydropower and water resources management (e.g. Köhler et al. 2019; Garrote 2017; Grilli et al. 2017; Srdjevic and Srdjevic 2014; Kucukali 2011; Supriyasilp et al 2009), in order to add structure, transparency and rigor to the decision-making processes (Šantl and Steinman 2015).

There are no preferable MCA methodologies for all kinds of decision-making situations: researchers and decision-makers are required to choose the method that they consider to be the most appropriate for the specific investigated problem (Alipour 2015). The MCA methodology used in this study is the Simple Additive Weighting (SAW), a linear additive method described by Hwang and Yoon (1981). It was chosen because it is one of the simplest techniques, widely used for decision-making problems and very popular also to practitioners (Zanakis et al. 1998). Therefore, it was not too complex to be explained to (and accepted by) the policy-makers and the stakeholders involved in the decision-making process.

The principle behind this technique is the additive utility assumption, since alternatives are ranked on the basis of their weighted sum performance. The mathematic formulation of the method is described by equation (1):

$$V(A_i) = \sum_{j=1}^{M} w_j \cdot g_j(A_i) \qquad (1)$$

where $V(A_i)$ is the final ranking performance for alternative A_i; M is the number of criteria; w_j is the weight of criterion *j*, expressing its importance; and $g_j(A_i)$ is the score of alternative A_i with respect to criterion *j* (Carriço et al. 2014). All the criteria in the problem should be both measurable and comparable (i.e. expressed in the same unit). Therefore, when SAW is applied to a multi-dimensional decision-making problem, all the scales of the criteria need to be normalized and equation (1) is applied to the transformed data (Shakouri et al. 2014).

2.3 Criteria, indicators and alternatives

A typical MCA problem is characterized by a number N of alternatives, i.e. the different options that may contribute to the achievement of the objectives of the decisional problem. The alternatives (A_i, for *i* = 1, …, N) should be evaluated in terms of a number M of decision criteria (g_j, for *j* = 1, …, M). Each criterion is associated with a weight (w_j, for *j* = 1, …, M) expressing its relative importance: in general, the higher the weight, the more important the criterion is assumed to be. The weights are usually normalized, so that their sum is equal to one (Triantaphyllou and Baig 2005). Hence, the problem can be represented by an N×M matrix (Figure 2), in which each element e_{ij} indicates the score of the alternative A_i when it is evaluated in terms of the criterion g_j, i.e. e_{ij} denotes how well the alternative A_i meets the criterion g_j (Carriço et al. 2014).

	g_1	g_2	…	g_M	Criteria
	w_1	w_2	…	w_M	Weights
Alternatives					
A_1	e_{11}	e_{12}	…	e_{1M}	
A_2	e_{21}	e_{22}	…	e_{2M}	
…	…	…	…	…	
A_N	e_{N1}	e_{N2}	…	e_{NM}	

Fig. 2 Decision matrix of a typical MCA problem characterized by N alternatives ($\boldsymbol{A_i}$) and M decision criteria ($\boldsymbol{g_j}$). Each element $\boldsymbol{e_{ij}}$ indicates the score of alternative $\boldsymbol{A_i}$ when it is evaluated in terms of criterion $\boldsymbol{g_j}$

In several decision-making problems criteria are split in different sub-criteria, often called indicators, to convey more specific information. In this case, a weight assessment should be made by stakeholders for both criteria and indicators. Hence, in the SAW methodology, the final weight for each indicator can be obtained by multiplying its weight by the weight of the corresponding criterion. Looking at the decision matrix (Figure 2), the same considerations can be done if the elements g_j are the indicators and the weights w_j their final weights. Besides, in this case, each element e_{ij} is the score of alternative A_i when it is evaluated by the indicator g_j.

Vassoney et al. (2017) outlined as a significant shortcoming the fact that criteria and indicators are often defined by experts, without considering different stakeholders' opinions and interests. Therefore, in the case study, stakeholders were involved from the very beginning of the MCA preparation, throughout its implementation, review and validation along a six-year period. Each of the seven indicators defined, tested and revised by the stakeholders along the MCA process had to comply with the following requirements:

- alignment to the normative framework;
- effective reactiveness, i.e. causal relationship between the indicator and the different alternatives;
- compliance with the specific context and stakeholder's needs and interests;
- solidity and transparency of the elaboration technique and availability of the dataset;
- possibility to be transferred to different contexts and at different scales.

2.4 Utility functions and data elaboration

When the decision-making problem is multi-dimensional (thus combining different units), a normalization process is necessary to compare various indicators. This procedure transforms the indicators scores into dimensionless values, so that the indicators become comparable to each other (Mammoliti Mochet et al. 2012). The normalization process was done by building, for each indicator, a utility function, i.e. a mathematical function assigning to each indicator score a corresponding dimensionless value ranging between 0 and 1. In this study, the utility functions for each indicator were elaborated by the stakeholders during the MCA process. The SAW method was implemented by using the SESAMO SHARE software (SHARE project 2012), which directly normalized the indicators scores through the corresponding utility functions.

2.5 Sensitivity analysis of the results

Every decisional process is influenced by uncertainty and subjectivity, since different stakeholders focus their attention on different aspects. Even in MCA some phases, in particular the allocation of weights to criteria and indicators, are strongly subjective and different choices can significantly influence the final result (Mammoliti Mochet et al. 2012). Sensitivity analysis is commonly used to test how variations in the model parameters (usually weights allocation) can affect MCA results, i.e. how much the alternatives ranking can vary after the change of one or more input parameters (Steele et al. 2009). Furthermore, it can give an indication about how robust (i.e. insensitive to changes in parameters) the optimal alternative according to MCA is and how this optimal alternative can change in different circumstances (Pannell 1997). In the present study, the sensitivity analysis was carried out by repeating the calculations with the SESAMO software, changing the weights of criteria and indicators.

3 Results

The experimentation process started with the identification of key institutional stakeholders. The Regional Water Authority (Regione Autonoma Valle d'Aosta – Gestione Demanio Idrico), institution coordinating the decision-making process, organized a series of meetings of the "Technical Assessment Board" (TAB) involving the following actors: HP company, Regional Agency for Environment Protection (ARPA Valle d'Aosta), Regional Fisheries Consortium (Consorzio Pesca), Regional Landscape Protection Service, Regional environmental assessment and air quality protection Service, Regional flora, fauna, hunting and fishing Service. The MCA process was implemented, reviewed and yearly validated along the period 2012-2017 and stakeholders were actively involved in a total of 31 TAB meetings.

3.1 Alternatives definition and decisional tree organization

In addition to the basic release scenario quantified through a hydrological formulation ("reference alternative", ALT 0), some initial alternatives based on the first results of the hydrological monitoring at the HP plant were defined in order to be assessed within the MCA process. Each release scenario was specifically proposed by a single member of the TAB and oriented at maximizing the stakeholder's interests. In a later phase, some mediation alternatives were agreed upon by all the stakeholders: these were called "real-time" alternatives, since they foresaw, for each month, a basic flow value to be left in the river downstream of the dam, incremented by an additional release quantified in real-time, varying on hourly basis, calculated as a percentage of the flow rate measured upstream of the dam, with values ranging from 12.5 to 30%.

A final set of nine alternatives was compared using MCA (Table 1 and Online Resource 1 - Table S1).

Table 1 Short description of the final set of alternatives used in the case study and compared through MCA

	ALTERNATIVES	BRIEF DESCRIPTION
INITIAL ALTERNATIVES	ALT 0	"Reference alternative": basic MIF release quantified using the hydrological formulation defined by the River Strategic Plan; fixed monthly values ranging from 90 l/s to 450 l/s
	ALT 1	Proposed by the HP company: fixed flow release throughout the year (= 100 l/s)
	ALT 2	Proposed by the Regional Fisheries Consortium and Regional Environmental Services: based on the MesoHABSIM application on the affected watercourse, thus considering the environmental requirements of fish communities (Vezza et al. 2012; Parasiewicz et al. 2013); fixed monthly values ranging from 70 l/s to 300 l/s
	ALT 3	Proposed by the Regional Landscape Protection Service: based on landscape protection goals; flow release = 70 l/s + monthly % of the natural flow rate upstream of the dam, except for July, August and September (fixed monthly values = 250, 200, 100 l/s respectively with additional %)
	ALT 4	Modified version of ALT 3: the month of June is divided into two halves (with different additional release %); fixed monthly values for July, August and September without additional % and increased for July and August (= 300 and 250 l/s respectively)
REAL-TIME ALTERNATIVES	ALT 5	Total flow release = 70 l/s + 12.5% of the natural flow rate upstream of the dam
	ALT 6	Total flow release = 70 l/s + 15%
	ALT 7	Total flow release = 70 l/s + 20%
	ALT 8	Total flow release = 70 l/s + 30%

Four criteria were selected by the stakeholders: Energy, Environment & Fishing, Landscape, and Economy. One or more indicators were then associated with each criterion (see paragraph 3.2 for related description). Figure 3 shows the decisional tree, i.e. the schematic structure in which the

MCA elements were organized hierarchically: criteria are the "branches" of the MCA tree while indicators represent the "leaves".

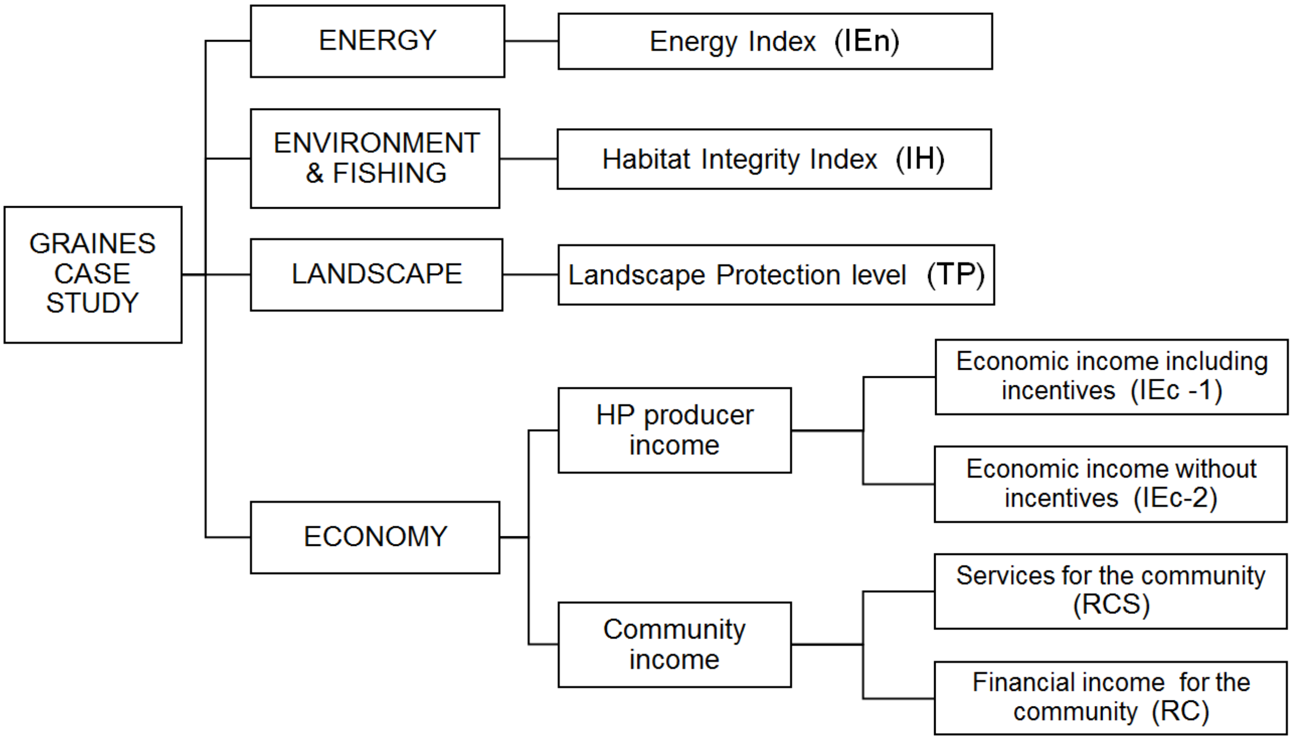

Fig. 3 Case study decisional tree: criteria (in capital letters) and indicators represent the "branches" and the "leaves", respectively

3.2 Indicators description

Indicators selection and review was a delicate and crucial aspect of the MCA process, which continued throughout the experimentation as a result of the cooperation among the different stakeholders involved in the TAB. The seven indicators defined for the case study are described below; a summary of their main features and the considered utility functions are presented in Online Resource 2 (Table S2 and Figure S2). It has to be outlined that all the indicators are strictly related to the watercourse discharge (withdrawn and released at the dam), which represents the key parameter of the whole process for which a specific monitoring program was implemented.

The indicator associated with the Energy criterion, i.e. "Energy Index" (IEn), was defined by the HP company. It quantifies the production losses due to flow releases through the following formula (3):

$$IEn = E_i/E_0 \quad (3)$$

where IEn is the Energy Index [-], E_i is the energy [kWh] produced by applying the i-th alternative, and E_0 is the energy production according to the average annual nominal power of the HP plant [kWh].

For the Environment & Fishing criterion, instead, an eco-hydromorphological indicator, i.e. "Habitat Integrity Index" (IH), was adopted (Vassoney et al. 2019). IH index quantifies the availability of suitable habitats for fish through the MesoHABSIM application in the watercourse for the different release scenarios. It is calculated through the following formula (4):

$$IH = \min(ISH, ITH) \quad (4)$$

where IH is the Habitat Integrity Index [-], ISH is the index of stream habitat spatial availability, representing the alteration of spatial amount of habitat available for fish when the HP withdrawal is present compared to reference conditions (i.e. before the HP plant construction), and ITH is the index of stream habitat temporal availability, assessing the temporal change of stress periods duration for fish. Details for its application, which requires specific surveys of representative stream stretches at different discharges, are described in Vezza et al. (2014, 2017).

The "Landscape Protection level" (TP) was the indicator associated with the Landscape criterion, assessing how the landscape perception changes according to flow releases through the following formula (5):

$$TP = CF + RF + VEF \quad (5)$$

where CF [-] is the Constraint Factor, calculated on the basis of national and regional landscape protection constraints and of the watercourse stream visibility, RF is the Release Factor, based on water flow releases downstream of the dam, and VEF is the Visual Elements Factor (SPARE project 2017). VEF is calculated by landscape experts by visualizing a set of photos of the downstream stretch, periodically taken by a fixed camera, and identifying the flow alteration due to HP withdrawal (e.g. presence of turbulence, ratio of dry to wet streambed, etc.).

Finally, the Economy criterion was divided into two sub-criteria, representing the HP company economic income ("HP producer income") and the community income due to services and fees paid by the HP company according to national and regional rules ("Community income"). For each of them, two indicators were defined. The indicators associated with the first sub-criterion, i.e. "Economic income including incentives" (IEc-1) and "Economic income without incentives" (IEc-2), were proposed by the HP company. They are based on the same index, i.e. the "Economic Index" (IEc), but differentiated considering a higher energy price for the first 15 years of operation (due to national incentives given to plants producing renewable energy). IEc quantifies the economic losses due to water flow releases through the following formula (6):

$$IEc = \frac{E_i \cdot €_{en} - C_i}{E_0 \cdot €_{en} - C_0} \quad (6)$$

where E_i is the energy produced by applying the i-th alternative [kWh], E_0 is the energy production according to the average power output of the HP plant [kWh], $€_{en}$ is the energy sale price [€/kWh], C_i and C_0 represent the HP plant management and maintenance costs related to the i-th alternative and to E_0, respectively [€]. The costs C_0 and C_i include, for instance, management costs, maintenance costs, fees, royalties, etc., which generally vary according to HP energy production.

Finally, the TAB members defined two indicators associated with the sub-criterion "Community income", i.e. "Services for the community" (RCS) and "Financial income for the community" (RC). RCS estimates the quality and amount of services offered by the HP company to the community living in the area affected by the withdrawal (e.g. environmental analyses in the affected watercourse, maintenance of hydraulic works and routes in the area, etc.). The indicator score is calculated on the basis of the previously described "Economic Index", through the transformation given by the utility function shown in Figure S2e (Online Resource 2). It is based on the fact that a higher income for the HP company is directly associated with a larger income for the local community, in terms of services offered by the HP producer. RC indicator quantifies the economic income for the community living in the area affected by the withdrawal, due to different fees and royalties paid by the HP producer. Some of these fees represent a percentage of hydroelectricity production and trade and thus they are directly dependent on the water flow releases. This indicator score is calculated again on the basis of the "Economic Index", through the following formula (7), under the assumption that a higher income for the HP company is directly associated with a larger financial return for the local community:

$$RC = IEc^2 \quad (7).$$

3.3 Weights allocation, sensitivity analyses and final results

The first set of weights decided by the stakeholders was based on an equal distribution among the four criteria (0.25 each), in order to have a first overall assessment of the system. Weights assignment for the indicators involved only the Economy criterion, having the other criteria only one indicator each (hence, the indicator weight was equal to 1). Firstly, the TAB members established together the weights allocation between the two sub-criteria: 0.10 was assigned to "HP producer income" and 0.90 to "Community income", since water and river are a public resource that has to be protected with a greater weight over private HP stakes, which are also represented by the Energy criterion.

Moreover, the weights of the two indicators of the sub-criterion "HP producer income" were proposed by the HP company, which assigned a weight of 0.80 to IEc-1 and 0.20 to IEc-2, since the former is referred to the initial concession period, when national incentives guarantee a higher energy price. Instead, the weights of the two indicators of the sub-criterion "Community income" were agreed upon by all the stakeholders: a significantly higher weight (0.95) was assigned to RC to highlight the importance of economic incomes for local municipalities.

The MCA results obtained with the SESAMO SHARE software with this initial set of weights are shown in Figure 4a. It can be noticed that the alternative with the highest total performance (the optimal alternative) was ALT 3 (i.e. the first one proposed by the Landscape regional service), while the alternative with the lowest performance was ALT 1 (i.e. the fixed releases scenario proposed by the HP company).

Sensitivity analyses, aimed at testing the robustness of the method, were carried out by repeating the calculations with the SESAMO SHARE software by alternately increasing/decreasing the weights of criteria and indicators. Results showed no significant variations of the alternatives ranking (i.e. criteria weights had to be modified by at least 32% to change the optimal alternative – ALT3; on the contrary, any modification of economic indicators weights had no consequences on the final ranking of the alternatives), confirming the stability and robustness of the MCA framework.

Afterwards, a new set of weights was defined for the four criteria: 0.25 to Energy, 0.30 to both Environment & Fishing and Landscape, and 0.15 to Economy. The higher weight assigned to Environment & Fishing was justified by the fact that this criterion takes into account two stakeholders' interests, i.e. the environmental heritage affected by the HP plant and the effects of the withdrawal on fishing activities. Moreover, the corresponding indicator is particularly reactive and reliable in associating a habitat loss to a flow rate variation due to the HP withdrawal. For Landscape, instead, the higher weight was related to the protection needs of both landscape heritage and tourist activities in the area, which could be affected by the withdrawal in a natural context. Lastly, the TAB decided to highlight the importance of HP production, as it is a renewable energy source contributing to regional, national and European strategy for CO_2 emissions reduction, by assigning a higher weight to Energy than to Economy.

With the new set of weights, the final MCA results shown in Figure 4b were obtained: even in this case the optimal and the worst alternatives were the same as in Figure 4a (i.e. ALT 3 and ALT 1, respectively). However, with the new set of weights, the total performances of the worst alternatives were slightly lower than in the previous case (e.g. 0.464 for ALT 1, 0.488 for ALT 5, etc.), while the performance of the best alternatives resulted slightly higher (e.g. 0.584 for ALT 3, or 0.578 for

ALT 0). Overall, with the new set of weights, the mean variation of the total performances was about 2.9% and the ranking remained almost the same, with very similar scores of the different alternatives in both cases.

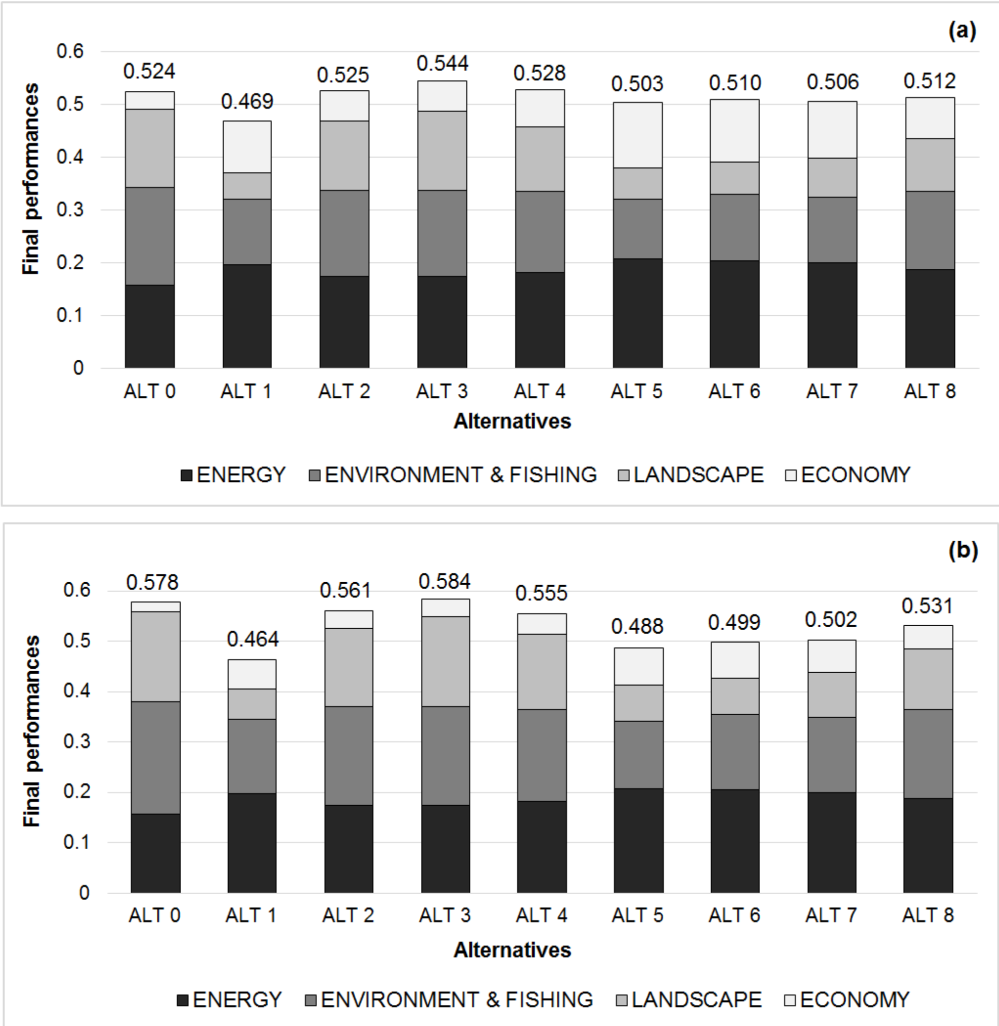

Fig. 4 Alternatives ranking obtained for the Graines case study (**a**) with the initial set of weights, and (**b**) with the final set of weights. Each alternative is divided into four parts representing the different criteria. The numbers at the top of the bars are the final performances of each alternative

On the basis of these MCA results, several discussions among the stakeholders involved in the TAB were then carried out in order to make a final decision on the flow release alternative to be adopted. Indeed, the main purpose of MCA application is to identify the better solution of the decision-making problem based not only on final ranking performances but also by putting in evidence different inter-relations among management choices (Paneque Salgado et al. 2009). As noticed in Figures 4a and 4b, the four alternatives with higher performances (ALT 0, 2, 3 and 4) have fully comparable scores. Among these alternatives, ALT 0 and ALT 3 strongly affected energy production, thus resulting the least advantageous for the HP company. On the contrary, ALT 2 and ALT 4, even if characterized by lower MCA performances, represented the two most feasible scenarios in terms of effective implementation, balancing both river ecosystem and landscape requirements with HP production needs. Finally, ALT 4 was agreed upon by the TAB members as the best mediation solution and it was officially endorsed in February 2018 as the release scenario to be guaranteed by the HP company. This alternative foresaw a basic release of 70 l/s and an additional flow release defined in real-time as a percentage (variable from 12.5 to 25%) of the monitored discharge available upstream of the water intake, while in summer months fixed flow releases had to be guaranteed to ensure a viable river landscape for tourists.

In 2018, the nine flow release alternatives were also *ex-post* validated using a wider discharge dataset coming from the ongoing hydrological monitoring program: this analysis, carried out in order to test MCA results reliability, showed that actual scores were very similar to the simulated ones and the final ranking of alternatives remained unvaried.

4 Discussion

The MCA process described in this paper was the first experimentation carried out in Aosta Valley whose results, shared among all the involved stakeholders, were effectively implemented, validated and then officially prescribed as a compulsory requirement of the HP plant water license.

One of the innovative aspects of this case study was the definition and implementation of releases quantified in real-time, based on monitored river discharges, which allowed a more sustainable HP plant management adapted to the availability of the water resource, particularly variable in a mountain context affected by climate changes.

A central characteristic of this MCA application was the involvement of the main concerned stakeholders from the very beginning of the decision-making process, in the attempt to apply a *bottom-up* approach (even if local communities were not directly involved). The final decision was supported by a long experimental process, based on several meetings, discussions and continuous improvements (e.g. the elaboration of new indicators), with the final aim of finding a management alternative which best supported the stakes of all the concerned actors. Besides, this selected release alternative was actually implemented and endorsed by the Regional Government.

Furthermore, the definition of "real-time" alternatives, which determine the flow releases according to the natural discharges available upstream of the dam, allows distributing the negative and positive effects of the withdrawal/releases among the different stakeholders in a more balanced way, respecting all normative requirements. This choice obviously required the presence of a reliable hydrological monitoring system, which was installed at the HP dam and intake at the beginning of the experimentation, with an informative screen showing real-time values of the natural flow upstream of the dam, flow releases and produced energy. The entire system is fully accessible and supports other direct controls carried out by the Regional Water Authority to verify the HP company compliance with water license compulsory requirements (Vassoney et al. 2019).

Another important result of this case study was the choice of reactive and affordable indicators, related to the watercourse discharge, based on the normative framework and bibliographic research. The same set of indicators has been proposed for its formal adoption within the ongoing Regional River Strategic Plan update and is being tested in other river contexts in the region.

Besides, the analyses implemented during the case study showed that the perception of an efficient water resource use is different for the different involved stakeholders, i.e. the same amount of released flow rate can correspond to very different satisfaction levels. This can be noticed by analyzing the normalized indicators scores for each alternative (Online Resource 1 - Figure S1): Energy Index (IEn) has almost always higher values (from 0.63 to 0.83) and fewer fluctuations than other indicators, while Landscape Protection Level (TP) and Habitat Integrity Index (IH) have more variable scores (from 0.202 to 0.597 and from 0.45 to 0.74, respectively). This is not only due to different indicators configuration and utility functions but mainly to the fact that releases consequences on energy production and economic incomes are much more evident than the outcomes on landscape and environment. For instance, a decrease of 10 l/s can significantly raise energy and economy indicators score, while the same release amount will not be quantified by the landscape indicator. The MCA approach adopted in this case study tried to compensate this intrinsic diversity of indicators by varying the weights of the related criteria (see paragraph 3.3).

It has also to be outlined that, for some indicators, a threshold value was set, denoting the classes in which the indicator score should have remained in order to comply with the normative requirements (i.e. High and Good status classes, for environmental and landscape indicators). For instance, during the discussions for the decisive selection of the optimal alternative, the TAB members immediately excluded the alternatives with IH values lower than 0.6, which is the normative threshold in the regional water planning for reaching the Good status class for the watercourse. However, this means that the variability range of the indicators for which a threshold was set is narrower (limited to two classes, i.e. from 0.6 to 1) in order to keep the stakeholders' satisfaction level high enough, while energy and economic indicators, not being characterized by a threshold of minimum required stakeholders' satisfaction, have a larger variability range (i.e. from 0 to 1).

Finally, despite the efforts of all the involved actors for an exhaustive MCA application, some weaknesses in the case study have to be outlined. In particular, the redundancy of Energy and Economy criteria is evident, being the economic incomes necessarily linked to the HP plant energy production. However, both criteria need to be considered in the MCA framework: energy return represents the regional stake in contributing to the national and European strategy for CO_2 emissions reduction, while economic incomes represent both the HP company interests and the local community incomes (fees and services provided by the HP owner). In the final phase of the experimentation, this drawback was corrected by assigning a lower weight to Energy and Economy criteria. Nevertheless, in future experimentations, a revision should be carried out in order to identify economic indicators less dependent on HP production as well as additional Energy indicators quantifying the HP plant contribution to the renewable energy objectives.

Furthermore, other two important criteria should be introduced in the MCA structure in future experimentations, i.e. Tourism and Agriculture, in order to consider, when needed, the effects of the withdrawal on touristic and recreational activities in the watercourse and on irrigation. Specific indicators associated with these criteria are being developed in collaboration with the related stakeholders.

A final remark concerns the difficulty in explaining the method and the necessary information to actors without a technical background. The SAW methodology is quite simple also for practitioners, but the whole assessing approach appears much more complex than it usually is for decision-makers. In particular, the strategic need of continuous discharge data collection, in order to ensure transparency and improve the quality of the overall assessment methodology, requires a clear explanation to all the stakeholders.

5 Conclusions

In this paper, a real case study of MCA application for sustainable HP management in the Alpine area, aimed at defining an optimal flow release scenario from a small HP plant in Aosta Valley, was presented and analyzed. The experimentation was carried out over a six-year period (from 2012 to 2017), taking into account different interests affected by the HP withdrawal (energy production, economic incomes, landscape protection, environment and sport fishing) and involving the corresponding stakeholders in a set of meetings from the beginning of the decision-making process.

Different water releases alternatives were assessed through MCA in order to find a compromise among protection of river ecosystems, landscape safeguard and HP production needs. The selected alternative was based on a minimum base-flow to be ensured for each month and on a percentage of additional flow release to be added in real-time. This case study approach is the first complete decision-making process fully carried out in Aosta Valley and concluded by the Regional Government official approval, ratifying the TAB results.

The “quality indexes” identified in a previous study for a suitable MCA application (Vassoney et al. 2017) were entirely taken into account, i.e. (1) the management problem is fully clarified; (2) the actors involved in the decision-making process are listed; (3) the adopted MCA methodology is described, including criteria, indicators and alternatives features; (4) sensitivity analyses have been implemented; (5) MCA results have been presented and an *ex-post* evaluation of their real impacts has been positively performed; (6) official endorsement of the selected scenario is highlighted.

Even if some drawbacks were still noticed, this case study showed several innovative aspects, like the elaboration of new reactive indicators related to the watercourse discharge and the definition of “real-time” alternatives, which allow sharing withdrawal effects among the different stakeholders in a more balanced way.

Due to the positive results of this first experimentation, which showed an increased quality of the decision-making process and the satisfaction of the involved stakeholders, the same approach is being used in other similar contexts in the region. Therefore, further necessary analyses are being performed in order to better improve the whole procedure. After testing the MCA approach in simpler case studies, future applicative research could also focus on multicriteria analysis application to assess HP sustainability on a larger scale level, for example, to identify the optimum management of a system of withdrawals located in an entire watershed.

Conflict of Interest: The authors declare that they have no conflict of interest.

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