Multi-criteria decision-making (MCDM) for the sustainable management of water withdrawals in Alpine watercourses

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Multi-criteria decision-making (MCDM) for the sustainable management of water withdrawals in Alpine watercourses

By

Erica Vassoney

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Supervisors:
Prof. Claudio Comoglio, Supervisor
Dott. Andrea Mammoliti Mochet, External Co-Supervisor

Politecnico di Torino
2022

Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

Erica Vassoney
2022

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Abstract

Alpine watercourses are subject to conflicting interests, related to the increasing number of water withdrawals and the need for protecting aquatic ecosystems and natural sceneries. Moreover, the impacts of climate change on water resources availability will further intensify conflicts among different water users. To face these complex water management problems, new approaches, based on a participatory framework, are required to support decision-makers in achieving more sustainable solutions. Multi-attribute decision-making (MADM) methods can be used for this purpose.

The aim of this thesis is to refine the innovative methodological framework adopted in Aosta Valley (northwest Italy) for the overall assessment of water withdrawal sustainability. The region is located in the middle of the Alps and most of its watercourses are significantly impacted by water withdrawals, mainly for hydropower generation and agricultural irrigation. Therefore, an experimental approach, based on the application of MADM and actively involving key stakeholders, has been developed to identify the optimal scenario of ecological flows to be released downstream of a withdrawal dam. The aim is to achieve a decision that represents the best mediation among river environment and landscape protection and the other water users' interests.

The main improvements presented in this thesis were aimed at increasing the representativeness of the different stakes involved in each decision-making process. The revised MADM decision tree usually includes four criteria (Energy, Environment & fishing, Landscape, and Economy), each quantified by one or more indicators. All the revised indicators are directly related to the watercourse discharge. Moreover, they are reactive, representative, and based on the normative framework.

In particular, the thesis focuses on two indicators. The Index of river Habitat integrity (IH), derived from the MesoHABSIM (Mesohabitat Simulation Model) methodology, quantifies the effects of water withdrawals on river ecosystems and fish communities. This index has especially allowed overcoming the limitations of the previous indicators derived from the European Water Framework Directive, which were scarcely reactive to hydrological alterations. On the contrary, the new indicator Landscape Protection Level (LPL) has been developed to assess the effects of water withdrawals on the river landscape. The reactiveness and representativeness of both indicators are demonstrated by presenting the results of some real case studies, involving existing hydropower plants.

Furthermore, the effectiveness of the MADM technique used in Aosta Valley is evaluated by comparing the results and the methodological approach of different MADM methods, applied to the same real case study. The implemented analyses (including correlation tests and sensitivity analyses) and the feedback of some involved stakeholders show the robustness and feasibility of the method adopted in the region.

In the last part of the thesis, an overview of the decision-making processes concluded and ongoing in Aosta Valley is presented, highlighting the general satisfaction with the revised methodological approach. Indeed, decision-makers and stakeholders have noticed an improvement in the decision-making quality. Therefore, the methodology has been formally adopted in the institutional water withdrawal licensing procedure for the definition of ecological flows. It is thus currently applied to several real case studies over the regional territory, both *ex-ante* and *ex-post*, involving different types of water withdrawals.

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Chapter 1

Introduction

1.1 Brief overview on surface water resources use in the Alpine area

The Alps are often defined as the “water tower of Europe”, since they represent a huge water reservoir providing freshwater for large parts of the continent [14]. Many important European watercourses have their headwaters here, including the four major Alpine rivers, i.e., the Danube, the Rhine, the Rhône, and the Po [15]. Via river systems, their discharge reaches lower-lying areas where mountain water is used for multiple purposes, from drinking water and food production to industrial development [14, 16].

Another element that contributes to the hydrological importance of the Alps is the runoff deriving from the melting of snow and glaciers over the summer months, when precipitation is less frequent in the lowlands. This runoff not only provides significant volumes of water, but it also ensures more regular discharge regimes, reducing hydrological variability downstream [10]. This highlights the strong relationship between the Alps and the surrounding areas: runoff characteristics in the lowlands are influenced by hydrological changes upstream and the Alps are affected by decisions taken downstream [15].

Table 1.1 demonstrates the hydrological importance of the Alps, by comparing the proportion of expected discharge based on catchment size and the measured actual discharge. With a mean contribution varying between 26% (for the Danube

Table 1.1 Contribution of the Alps to total discharge of the four major Alpine watercourses (from [10])

	Rhine	Rhône	Po	Danube
Mean contribution of the Alps to total discharge (%)	34	41	53	26
Areal proportion of total Alpine region (%)	15	23	35	10
Disproportional influence of the Alpine region	2–3	1–8	1–5	2–6

River) and 53% (for the Po River) of the total discharge, the Alpine region provides up to 2–6 times more water than may be expected based only on the catchment area. Therefore, the disproportional runoff contributions of the Alpine regions have a significant impact on a larger scale, affecting hydrological patterns in downstream European river systems [10].

Furthermore, Alpine watercourses host many different habitats and species, making the Alps one of the most important biodiversity hotspots in the world [16]. In fact, natural Alpine freshwaters are highly dynamic systems. Through a large amount of solid transport, hydromorphological processes enable a periodic restoration of habitats [17], thus creating optimal ecological conditions for the growth and conservation of biological communities [16]. At the same time, natural habitats are crucial for the protection and maintenance of water resources. For these reasons, careful management of Alpine watersheds should have the highest priority [14].

However, during the last 150 years, most of the Alpine watercourses have been extensively modified by several adaptations to human needs, like canalizations, removals, weirs, abstractions, etc. In particular, for flood protection purposes and hydropower generation, natural rivers and streams were affected by longitudinal and transverse structures, even at high altitudes, thus impacting habitat quality and biodiversity [17]. Therefore, today, the remaining pristine reference rivers have become extremely rare in the area [18]. It is estimated that only about 10% of Alpine watercourses can be considered ecologically intact, i.e., not affected by pollution, over-engineered, or compromised in terms of their flow regimes [15].

Water is used for different purposes. Withdrawals are mainly licensed for agricultural irrigation, drinking water, energy production, and other industrial purposes (including snowmaking) [19]. Moreover, increasing importance is attributed to "non-consumptive uses", e.g., recreational activities, preservation of ecological aspects, and river landscape services [15]. This growing demand of Alpine water resources, exacerbated by the threat of climate change, may lead to social conflicts at different levels.

Focus on hydropower production

Hydropower (HP) has a long tradition in Europe and it remains a leading source of renewable energy in the continent, with a total installed capacity of 254 GW in 2020 [20] and more than 21000 HP plants in operation [21]. In particular, in the Alps, HP generation has been the most important source of electricity since the beginning of the 20th century [16]. The reason is related to the typical characteristics of the area, i.e., steep slopes combined with high precipitation, which make HP production an important socio-economic factor for Alpine countries [17]. Moreover, among the strategies for reducing greenhouse gas emissions, HP plays a crucial role since it is considered an almost emission-free form of electricity generation and it strongly contributes to the stabilization of the European energy grid by means of storage power stations [22]. This feature is becoming particularly important with the growing use of intermittent, weather-dependent, renewable energy sources, like wind and solar energy [19]. For these reasons, during the 20th century, HP facilities have become increasingly widespread in the Alps [21] and applications for new, generally small-scale, HP plants are still rising [23].

However, despite its clear benefits, HP can generate significant negative impacts on aquatic ecology and ecosystems. Hydromorphological alterations due to HP production (e.g., interruption of the longitudinal river continuity, changes in river morphology, hydro-peaking, reduction of flow velocity, alterations in the transport of sediments, etc.) deeply alter natural habitats, leading to a considerable loss of biodiversity [22, 24]. Furthermore, HP generation can also be responsible for the transformation of characteristic landscapes and natural sceneries [22]. These pressures are not only caused by large dams and reservoirs, but also by small HP plants, whose wide distribution originates cumulative effects impacting a significant number of Alpine watercourses [23].

In fact, the most significant share of hydroelectricity in the Alps, i.e., about 86%, is generated by large facilities (with capacities higher than 10 MW), representing only 10% of the total number of HP plants [21]. The remaining share of about 14% is produced by many thousands of small and micro-HP stations, which affect most of the Alpine watercourses [16]. Therefore, river stretches that are still in natural conditions (i.e., having a high ecological status) are becoming more and more important in the Alps, since they are increasingly rare [17]. Hence, regional-based planning is considered necessary when deciding about new small HP projects to avoid, in particular, the deterioration of high-status watercourses [25], in line with the requirements of the European Water Framework Directive (WFD) [26].

Ecological flows

Anthropogenic alterations of the natural flow regime in Alpine rivers affected by water withdrawals represent an important issue causing several negative effects on the aquatic environment [17]. Indeed, the hydrological regime has fundamental importance for the structure and functioning of river ecosystems [27, 28].

The definition and maintenance of ecological flows downstream of water withdrawal sites are essential in achieving the environmental objectives of the European WFD on the protection and conservation of river ecosystems [26]. The concept of "ecological flows" has evolved over time, from the traditional view of a minimum amount of water to face the degradation of aquatic ecosystems caused by the overuse of water (often defined as "minimum instream flow") to a more holistic understanding [29]. In the European Guidance on ecological flows [29], this term is described as "*the amount of water required for the aquatic ecosystem to continue to thrive and provide the services we rely upon*". This concept includes not only the minimum required amount of water but also the variation of flow over time [17].

In the European Union and in Switzerland, licenses for water withdrawal from watercourses include ecological flow requirements [22]. Consequently, they limit the amount of water that can be abstracted for anthropogenic uses (e.g., hydropower generation or agricultural irrigation), resulting in economic losses. However, nowadays, there is a large awareness of the importance of sustainable development principles, i.e., using resources for human needs while preserving the natural environment [17]. Nevertheless, since the practical implementation of the European legislation is often difficult, national and regional frameworks should include means and strategies to ensure the effective implementation of ecological flows [29].

In Italy, for example, new methodological guidelines for water withdrawal planning, monitoring, and assessment have been defined, ensuring the achievement of the environmental quality objectives defined by the WFD for surface water bodies [30, 31]. One of the proposed methods is the MesoHABSIM (Mesohabitat Simulation Model) methodology [32, 33], which quantifies fish habitat availability based on the flow rate and local morphological conditions of the river. More information about this methodology will be provided in Chapter 3 (section 3.2.3).

Climate change impacts on water resources

Alpine watercourses are particularly vulnerable to various impacts, including climate change [14]. The effects of global warming on river hydrology are already evident. Alpine glaciers have lost almost 50% of their area since the 1850s [34] and many of them are projected to disappear by the end of the century [35]. Moreover, the mean monthly snow depth between November and May is decreasing at an average rate of 8.4% per decade [34]. The consequence is a variation of the seasonal runoff distribution, in particular in snow-dominated or glacier-fed high mountain basins. Changes have already been observed in most Alpine catchments, with an increase in winter runoff and a reduction in summer runoff, but this development will probably intensify in the future [19].

These hydrological alterations have consequences for freshwater ecosystems and habitats. For example, connectivity between water bodies usually decreases, with a resulting possible loss of biodiversity [15]. Furthermore, the increase in temperature and its effect on water availability will significantly affect the different uses of water resources in the Alpine region [35]. For instance, the demand of water for agricultural irrigation will probably intensify due to the decrease in summer precipitation. Besides, to compensate for the decline in snowfall in the winter months, water is already increasingly used for snowmaking in the skiing areas [19]. As concerns HP production, it has recently increased due to the melting glaciers, but a reduction is projected in several Alpine countries by the end of the century, when glacier volumes will be significantly lower [34]. The effects of the shift in runoff seasonality will be mainly evident on run-of-river HP plants, while the role of storage power schemes to stabilize power grids will probably intensify [19]. Furthermore, despite the increase in water withdrawal demands from surface water bodies for different purposes, ecological flow regulations must always be met for Alpine rivers.

Therefore, the effects of climate change will probably intensify conflicts among different water users in the future [36].

Management of conflicting water uses

New approaches, based on cooperation and including the different concerned interests, are necessary to deal with conflicts over the use and management of water in the Alps [36]. In particular, improving the dialogue among stakeholders is highly recommended [17], not only at the catchment level but also for regional and cross-border water management [36]. Furthermore, integrative and participatory planning approaches will become particularly important for the development of Alpine river basins, considering the different needs for water use [37]. Any decision-making process should involve all relevant actors, allowing enough time for mutual understanding of problems and to develop shared strategies for water management [38]. New measures should also be agreed upon to balance water demand and availability [36].

Moreover, there is currently a growing awareness of the extreme importance of strategies that focus on the conservation of ecosystems to avoid irreversible impacts [39]. Therefore, river stretches that are still largely in natural state must be attentively considered by decision-makers since they are becoming increasingly rare in the Alpine area [15]. Protection of their pristine aquatic ecosystems should be improved, even enforcing existing conservation legislation, to safeguard their unique biodiversity [36].

To face these challenging issues, common guidelines and support for decision-making are more and more necessary [22]. Besides, local strategies, tailored to specific regional features, should also be developed for common management of surface water resources, reducing water-related conflicts [17, 40].

1.2 Multi-criteria decision-making (MCDM) for water conflict management

A methodological approach that can be adopted for water conflict management in the field of surface water uses is multi-criteria decision-making (MCDM) [41].

MCDM refers to a set of techniques that take into account multiple evaluation criteria, related to different objectives and stakeholders, to support decision-makers in solving complex problems [42]. In particular, MCDM methods provide a framework in which the whole assessment process is carried out [43]. They also have the potential to improve transparency and analytic rigor of decisions [4].

Due to its intrinsic features, MCDM has been applied to a variety of environmental problems [44]. Different MCDM methods have also been frequently used in the field of water resources management, generally characterized by multiple, conflicting interests [45]. Indeed, MCDM allows the active involvement of the concerned stakeholders in the assessment [43], providing a common language for discussing and learning about the problem [46]. The inclusion of stakeholders represents a departure from traditional top-down approaches, which have frequently shown their limits. It allows different actors to work closely with the decision-makers, thus providing additional information and having direct input into resource management [47].

Furthermore, MCDM is recognized as a suitable tool to deal with the complexities of conflict resolution, typical of regional water resources planning [48]. By informing stakeholders about the implications of resource use and the involved interests, in fact, it increases mutual trust, thus reducing resistance and conflicts among different water users [47]. Moreover, it also contributes to identifying shared solutions looking beyond short-term considerations [43].

1.3 Water withdrawals in Aosta Valley

Aosta Valley is a small region located in northwest Italy, in the middle of the Alps, with a surface of about 3260 km^2. It is characterized by a completely mountainous territory, more than 60% of which is located above 2000 m a.s.l. [49]. The region is crossed by Dora Baltea River, one of the major tributaries of the Po River, with a mean annual discharge of 110 m^3/s (Figure 1.1).

In the last century, the region has been strongly affected by river exploitation to support economic growth and urban expansion. In particular, hundreds of HP plants have been built in a river network already altered by agricultural withdrawals and, more recently, by hydraulic structures for flood protection. These anthropogenic alterations have frequently deteriorated the ecological assets of watercourses. More-

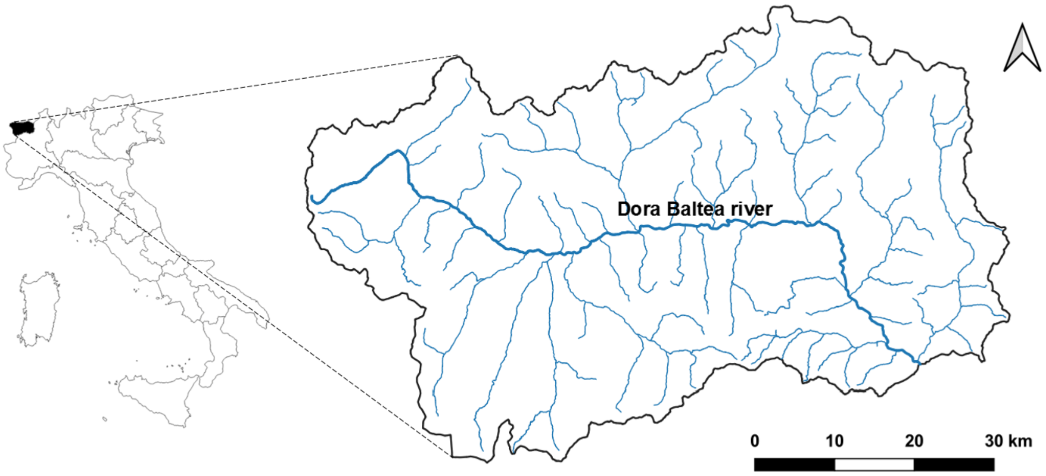


Fig. 1.1 Location of Aosta Valley in northwest Italy, within the Alps, and main regional hydrography network (i.e., Dora Baltea River, highlighted with a thicker line, and its main tributaries) (adapted from [1])

over, the presence of various water users with different interests (e.g., HP production, irrigation, angling, landscape protection, water tourism, environmental conservation) has increased water-related conflicts [50].

Aosta Valley is one of the most important Italian regions for HP production [51]. Figure 1.2 illustrates the trend of HP river exploitation in the regional territory from 1911 to 2010. The red line represents the cumulative installed HP capacity. It shows two evident phases of growth of the number of HP plants, i.e., from the late 1910s to the late 1920s and from the mid-1940s to the early 1960s. Over these periods, a relatively low number of HP plants, but characterized by a high average capacity, was installed. These HP plants still represent a significant share of the capacity currently installed in the region. The trend of HP exploitation in Aosta Valley reached its peak in the late 1960s. In June 1962, in fact, the cumulative installed capacity was 87.6% of the cumulative capacity in 2011, with 33 installed plants out of the 178 plants in operation in 2011 [2].

The black line in Figure 1.2 represents the average installed capacity, calculated over ten years until 1981 and then over five years. It highlights the strong decrease in the average size of the HP plants installed since the late 1960s, despite the significant rise in the number of installed plants. In particular, both in the early and the late 1990s, the number of small-scale HP plants has drastically increased due to the introduction in Italy of financial incentives for renewable energy sources. Indeed,

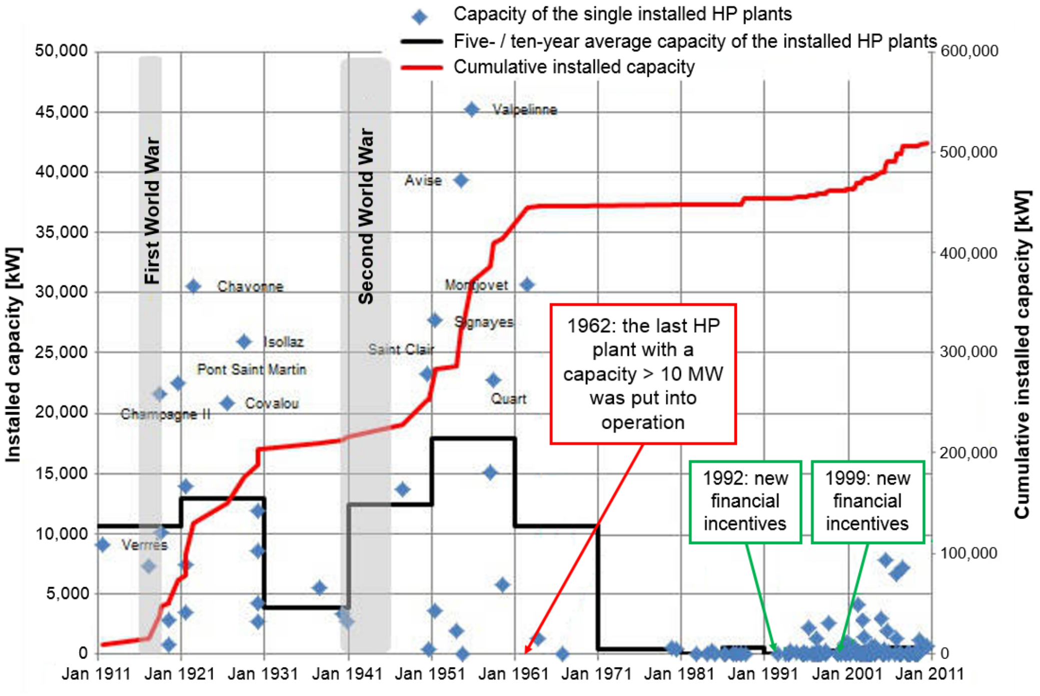


Fig. 1.2 Single (blue markers), cumulative (red line), and average (black line) capacity of the hydropower plants installed in Aosta Valley over the period 1911-2010 (from [2])

these incentives ensure important economic revenue even to small-scale HP plants, whose contribution to the total energy production is often negligible [23]. Therefore, since the early 1990s, the growth of the total installed capacity in Aosta Valley has been proportionally low compared to the increase in the number of HP plants. However, the overall exploitation of regional watercourses for HP production is considerable, generating relevant pressures, and the estimated residual potential is particularly low, especially compared to other Alpine areas [2].

Water withdrawals from watercourses in the Aosta Valley territory, for any purpose, require the application for a license from the Regional Administration. The withdrawal license has usually a thirty-year duration and can be renewed, after this period, if no higher reasons of public interest preclude it [49]. The license sets the conditions for water use based on the current environmental legislation. In particular, as prescribed by the European WFD [26] and based on the European Guidance on ecological flows [29], it requires the release of ecological flows downstream of the withdrawal dam to ensure the protection of aquatic ecosystems in the affected river stretch.

According to the regional River Strategic Plan (*Piano di Tutela delle Acque* – PTA), approved in 2006 [52], ecological flows in Aosta Valley can be defined either using a simple hydrological formulation or through an experimental approach based on the application of multi-attribute decision-making (MADM) methods (a category of MCDM methods). Recently, this decision-making approach is being adopted in several case studies in the region to assess the sustainability of different types of water withdrawals, mainly HP plants, but also agricultural and industrial withdrawals. These decision-making processes involve the main concerned stakeholders to identify a sustainable balance among their different interests. The main stakes are represented in the MADM framework by the different criteria (usually, four criteria are considered, i.e., Energy, Environment & fishing, Landscape, and Economy), each quantified by indicators based on the watercourse discharge.

1.4 Aim and outline of the thesis

The strong necessity and, at the same time, the difficulty in integrating environmental and landscape protection and socio-economic interests in a sustainable way have been recognized by the European Union and in Switzerland. Indeed, national and regional guidelines have been developed to provide a methodological approach to support decision-making processes (e.g., [53, 54, 29]. However, a concrete and shared methodology for the evaluation of watercourses exploitation is still missing [4].

Under the above scenario, the aim of this thesis is to present the innovative methodological framework, based on MADM, adopted in Aosta Valley to support decision-making processes for the overall assessment of water withdrawal sustainability. The methodology has been refined during the PhD, in collaboration with the main Regional Services involved in the decision-making processes, identifying the information necessary to perform the MADM assessment, testing different MADM methods, and including reactive indicators. These improvements are presented in the following Chapters, illustrating how the refined methodological approach is used over the regional territory to identify, for each release or renewal of a withdrawal license, the most appropriate scenario of ecological flows to be implemented downstream of the withdrawal dam. The aim is to consider the interests of the main concerned stakeholders, who are involved in the decision-making process, and the related sets of laws, achieving a decision that balances river environment and landscape protection with water use needs.

Although several studies have focused on the use of MADM to solve decision problems concerning the use of surface water resources, real applications with legal binding results are rare, especially on a regional scale. On the contrary, the methodological framework presented in this dissertation has been formally adopted in the institutional water licensing procedure for the definition of ecological flow scenarios in Aosta Valley. Furthermore, each decision-making process is based on the actual collaboration among the involved stakeholders, representing both public and private interests.

The dissertation is organized into seven Chapters. After this Introduction, Chapter 2 illustrates the main features of MCDM, focusing on the MADM model, based on the results of a literature review concerning the application of different MADM methods. Since the number of collected studies specifically related to water withdrawal management was relatively low, the review has been extended to decision-making problems concerning surface water resources management, including water use, flood protection, and water protection.

Chapter 3 describes the methodological approach used in Aosta Valley to assess water withdrawal sustainability, explaining how the initial MADM framework has been improved through the integration of the MesoHABSIM methodology to quantify the impacts of withdrawals on river ecosystems and fish communities. The results of the implementation of the resulting MADM procedure in a real case study, involving a single HP plant, are also discussed.

Chapter 4 introduces the new indicator, named Landscape Protection Level (LPL), developed in Aosta Valley and included in the MADM framework to assess the effects of water withdrawals on the river landscape in the bypassed watercourse stretch. Moreover, the results of the indicator obtained in four real case studies, concerning different watercourses and HP plants, are examined.

Chapter 5 assesses the effectiveness of the MADM method adopted in Aosta Valley based on the comparison with other MADM techniques widely used in the literature, considering a real case study of HP management in the region and including the revised indicators described in the previous Chapters.

Chapter 6 presents an overview of the applications of the revised procedure, both concluded and ongoing, to a wide range of different water withdrawals over the Aosta Valley territory. Furthermore, the Chapter deals with the satisfaction of the stakeholders involved in the different decision-making processes with the improved procedure, based on their feedback.

Finally, Chapter 7 summarizes the main achievements, suggesting future research directions to overcome the remaining limitations of the proposed methodological framework and to extend its application.

1.5 Scientific contributions

Parts of this work are also discussed in the following publications:

- Vassoney, E., Mammoliti Mochet, A., Rocco, R., Maddalena, R., Vezza, P., and Comoglio, C. (2019). Integrating Meso-Scale Habitat Modelling in the Multicriteria Analysis (MCA) Process for the Assessment of Hydropower Sustainability. *Water* 11, 640. doi:10.3390/w11040640

- Vassoney, E., Mammoliti Mochet, A., and Comoglio, C. (2020). Multicriteria Analysis for the Assessment of Flow Release Scenarios from a Hydropower Plant in the Alpine Region. *Water Resources Management* 34, 637–651. doi:10.1007/s11269-019-02459-6

- Vassoney, E., Mammoliti Mochet, A., Bozzo, M., Maddalena, R., Martinet, D., Paternoster, C., Quiriconi, C., Rocco, R., and Comoglio, C. (2021a). Definition of an indicator assessing the impact of a dam on the downstream river landscape. *Ecological Indicators* 129, 107941. doi:10.1016/j.ecolind.2021.107941

- Vassoney, E., Mammoliti Mochet, A., Desiderio, E., Negro, G., Pilloni, M. G., and Comoglio, C. (2021b). Comparing Multi-Criteria Decision-Making Methods for the Assessment of Flow Release Scenarios From Small Hydropower Plants in the Alpine Area. *Frontiers in Environmental Science* 9, 104. doi:10.3389/fenvs.2021.635100

Chapter 2

Multi-criteria decision-making: basic concepts and literature review in the field of water resources management

2.1 Introduction

The majority of human problems, from the most common to the most complex political decisions, have a multi-criteria nature and require identifying trade-offs among different objectives [55]. When purchasing an object, for example, we usually want to minimize the price, but also maximize other aspects, like quality and aesthetics. Environmental problems are also characterized by conflicting objectives, due to the presence of multiple purposes and stakeholders with different interests [42]. Therefore, the use of Decision Support Systems (DSSs), i.e., systems which help with some aspects of decision-making, is strongly required [56].

Among DSSs, multi-criteria decision-making (MCDM) has been recognized as an important tool in addressing environmental problems with conflicting objectives, since it allows evaluating the different aspects from multiple perspectives [57]. As defined by Belton and Stewart [3], MCDM is "*an umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter*". This definition highlights three main features of MCDM, i.e., the formal approach, the presence of multiple criteria, and the involvement of individuals or groups in the decision-making [42].

The basic concepts of MCDM were explicitly considered for the first time in the 1960s [58]. In the following years, many researchers have focused on multi-criteria decision theory and new, more complex, methods have been developed, with an increasing trend of MCDM applications to a wide range of problems which continues today [43]. MCDM methods are used as structuring tools that add auditability, transparency, and rigor to the decision-making process [4]. They help the involved actors to better understand the decision problem and to improve the quality of the decisions [59]. Moreover, the structure of MCDM processes facilitates a collaborative planning and decision-making environment, allowing the involvement and participation of multiple experts and stakeholders [42].

Compared to other methodologies (like cost-benefit analysis), MCDM methods do not aim at identifying an absolute best solution but creating a set of relations among the different actions to provide better information to the actors involved in the decision-making process [43]. In fact, usually, there is not an alternative optimizing all the considered criteria at the same time. Therefore, the solution of an MCDM problem should be a compromise, which not only depends on the objective data collected for the considered criteria but also on the preference structure defined by the decision-maker(s) [9]. This characteristic does not reduce the efficiency of MCDM methods: on the contrary, it increases their flexibility and consistency with the involved actors' requests [60].

The aim of this Chapter is to illustrate the main features of MCDM, focusing on the use of multi-attribute decision-making (MADM) methods. The analysis was based on a critical review of more than 300 scientific articles, providing a global overview of the MADM applications in the field of surface water resources management and discussing their potential strengths and shortcomings. It has to be highlighted that the number of collected studies specifically referring to the topic of this dissertation, i.e., water withdrawals, was relatively low. For this reason, the review has been extended to decision-making problems concerning surface water resources management, thus including studies related to water use (e.g., for HP production, irrigation, drinking water, recreational uses), flood protection, and water protection (e.g., measures to face climate change effects, pollution reduction, and restoration of watercourses).

The Chapter is organized as follows: a description of the basic concepts of MCDM is provided in section 2.2, presenting different classifications of the MCDM methods and describing the main elements of the multi-attribute decision-making model. In section 2.3, the literature review concerning the application of MADM methods to surface water resources management is presented, analyzing the different contexts and typologies of water-related problems, and investigating the most important technical features of MADM implementation in specific case studies proposed by various authors. Finally, based on the results of the literature review, some concluding considerations are given in section 2.4.

2.2 Multi-criteria decision-making (MCDM) methods

Multi-criteria decision-making (MCDM) can be used as a general term to identify various typologies of problems, whose fundamental characteristic is the multiple criteria nature [3]. Moreover, according to Hwang and Yoon [11], all the MCDM problems have the following common features:

- each problem has multiple attributes and objectives;
- the considered criteria usually conflict with each other;
- the attributes have different units of measurement (sometimes including qualitative measurements);
- the MCDM process identifies one or more alternatives that are the most attractive over all the considered criteria, either designing them or selecting them among a previously defined finite set of alternatives.

According to Belton and Stewart [3], the whole MCDM process can be divided into three key phases, i.e., problem identification and structuring; model building and use; and development of action plans (Figure 2.1). Problem identification and structuring is the opening phase in which, before starting any analysis, the different stakeholders begin to discuss the problem, recognizing the complexity and identifying the decisions that should be made. In the phase of model building and use, formal models of decision-maker preferences, objectives, etc. are developed in order to represent the problem in a more transparent way and support a more

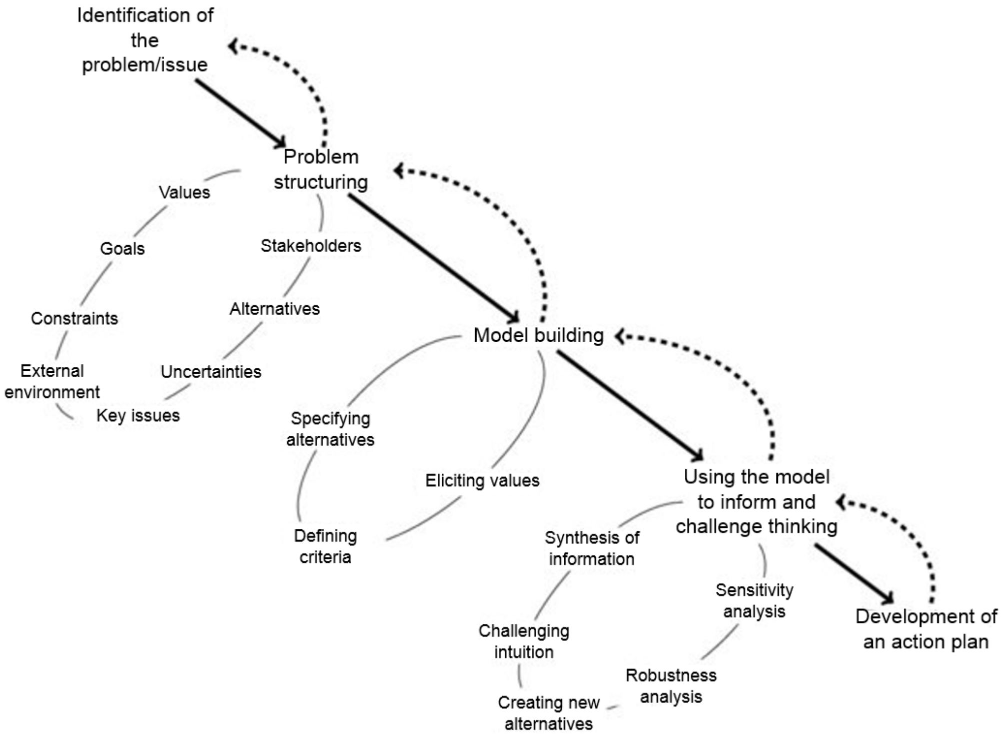


Fig. 2.1 The MCDM process (adapted from [3])

precise evaluation. The concluding phase concerns the development of action plans. In fact, the MCDM methods do not "solve" the decision-making problem. The implementation of the results, i.e., the translation of the technical modeling into specific action plans, is also an important phase of MCDM.

Furthermore, Belton and Stewart [3] defined six different categories of MCDM problems:

- choice problems, in which a simple choice from a set of alternatives is made;
- sorting problems, in which alternatives are sorted into classes or categories (e.g., "definitely acceptable", "possibly acceptable", "definitely unacceptable");
- ranking problems, in which a preference ordering of alternatives, not necessarily complete, is obtained;

- description problems, in which alternatives and their consequences are formally described, so that they can be better understood and evaluated by the decision-maker;
- design problems, in which new decision alternatives are identified or designed to meet the goals revealed through the MCDM process;
- portfolio problems, in which a subset of alternatives is selected based not only on their individual characteristics but also on the way in which they interact.

In order to understand the structure of MCDM models, the definition of some keywords must be provided. In fact, most of these terms do not have a univocal definition and some of them, having a similar meaning, are used interchangeably by many authors [61]). The conceptual differences among some key terms are explained, among the others, by Hwang and Yoon [11] and Romero and Rehman [62]:

- Criterion: a criterion is the basis for evaluation and a measure of effectiveness. The word includes both the concepts of attribute and objective.
- Attribute: an attribute represents a particular feature of the considered problem selected by the decision-maker (e.g., for a car, purchasing cost, horsepower, consumption, etc.). It is usually expressed as a mathematical function of the decision variables.
- Objective: the objective represents the direction of improvement chosen by the decision-maker for an attribute, i.e., maximization or minimization (for example, a car manufacturer may want to minimize the cost and maximize the power).
- Target: a target is a value defined by the decision-maker as an acceptable level of achievement for an attribute.
- Goal: the goal is the expected level of an attribute that the decision-maker aims to achieve. Goal and target are often considered synonyms. Moreover, when they are designed to restrict the alternative set, goals are defined as constraints. These two parameters have the same mathematical structure: the only difference between them is related to the fact that, for goals, the target is aspired by the decision-maker (but it may not be achieved), while constraints represent rigid limits, for example set by law, that must be satisfied.

2.2.1 Strengths and weaknesses of MCDM

MCDM methods have been criticized by some researchers for applying simplistic ideas to complex problems. In reality, the apparently simple MCDM models are included in a wider process of problem structuring and resolution, as represented in Figure 2.1 [3]. During this process, the complex problem is disaggregated into more manageable elements, which are then reorganized and presented to the decision-maker in a more transparent form, easier to understand and to handle [63].

MCDM methods provide a systematic and transparent approach that leads to balanced and justifiable decisions [42, 64]. These properties are necessary to persuade stakeholders to support decisions [56]. Moreover, the data resulting from the technical analysis of the considered problem can be used by the decision-maker to achieve a more informed choice [56].

MCDM also promotes active participation in all the phases of the decision-making process, enabling the involved actors to improve their knowledge about the analyzed problem and recognize the different opinions, finding a meeting point between opposing positions [65, 43]. In fact, MCDM provides a model that facilitates discussion among multiple experts and stakeholders, so that a dialogue process, based on a common language, can be created [66].

Another property of MCDM that makes it an appropriate tool for analyzing complex problems typical of natural resources management is the possibility to handle also qualitative, inaccurate, or uncertain data [44]. Moreover, MCDM methods allow large-scale analyses, involving very large datasets, long time-series, or spatial data [56].

However, some elements of criticism of the MCDM approach have also been highlighted by some researchers. Among the criticized aspects, subjectivity that inevitably affects MCDM methods is often underlined. In fact, subjective information (e.g., weights and preference thresholds) is related to individual perceptions and specific knowledge of the involved actors, which may influence the results [64].

Another criticism concerns the compensatory aggregation methods (e.g., Analytic Hierarchy Process), which allow trade-offs between good performance on one criterion and poor performance on another criterion. For example, in a water supply system, poor performance on water quality could be compensated with good performance on investment cost. Important information is often lost through this type of aggregation and, for some decision problems (e.g., concerning public health), the results could be unacceptable [67].

Furthermore, it has to be highlighted that people involved in the MCDM process, often, are not experts. Therefore, they may be unable to understand more complex techniques and, even if assisted by a facilitator, they may perceive them as “black-box” methodologies [44]. This can compromise the capacity of the decision-maker to follow the process and reduce stakeholders’ acceptance of the MCDM results [64].

Moreover, the implementation of MCDM methods in an entirely participatory decision process (e.g., actively involving citizens or local communities in various phases of the process) may be particularly challenging. The use of these algorithmic models can be difficult especially for environmental problems, involving a broad group of stakeholders with conflicting interests [42].

2.2.2 Classification of MCDM methods

In the last decades, a variety of MCDM methodologies, based on different theoretical assumptions, have been considered in the literature. However, there is not a method that can be considered better than the others in any decision-making situation [44]. Decision-makers and analysts should select the technique that, according to them, is more suitable for their specific decision context [68].

MCDM methods can be classified according to different features. A first classification proposed in the literature considers two general categories: Multi-Objective Decision-Making (MODM) and Multi-Attribute Decision-Making (MADM) methods. The MODM methods are mainly suitable to deal with multi-objective planning problems [42]. They consider a continuous domain with a theoretically infinite number of feasible solutions, defined by the constraints of the problem and by the maximization or minimization of different objective functions [61]. Usually, interactive aggregation algorithms are used to define the set of feasible, non-dominated, solutions [69].

The MADM methods, on the contrary, are usually employed to deal with management problems [70]. In this case, a discrete, usually limited, set of predefined alternatives is evaluated by means of inter- and intra-attribute comparisons, involving explicit or implicit trade-offs [11]. Therefore, MADM is associated with selection

Table 2.1 Comparison of Multi-Objective Decision-Making (MODM) and Multi-Attribute Decision-Making (MADM) approaches (adapted from [11])

	MODM	MADM
Criteria (defined by)	Objectives	Attributes
Objectives	Explicit	Implicit
Attributes	Implicit	Explicit
Constraints	Active	Inactive
Alternatives	Infinite, continuous	Finite, discrete
Use	Design	Selection, evaluation

problems, while MODM is related to design problems. Sometimes, MADM methods are also used for identifying the best compromise action among MODM solutions, based on the decision-maker's preferences [71]. Table 2.1 summarizes the main differences between these two categories of methods highlighted by Hwang and Yoon [11].

Another distinction refers to the level of compensation allowed by the methods: compensatory and non-compensatory techniques can be identified. Compensatory methods (e.g., Simple Additive Weighting (SAW) [72] and Analytical Hierarchy Process (AHP) [73] allow the compensation of poor performances of some criteria by very high performances of other criteria. Thus, the aggregated performance of an alternative may not highlight its weaknesses [74]. On the contrary, in non-compensatory methods (e.g., ELECTRE (ELimination and Choice Translating REality) methods [75]), every single criterion can have a significant impact on the aggregated performance of an alternative [74].

The main difference, however, concerns the theoretical approach used to represent the decision-maker's preference structure. Belton and Stewart [3] classified the MCDM models into three broad categories, or "schools of thought":

1. *Value measurement models*: they are based on the calculation of numerical scores for each criterion, which are then aggregated in order to obtain an overall score for each considered alternative. The overall numerical values of the alternatives reflect a preference order, denoting how much a decision option may be preferred to another one. Multi-Attribute Value Theory (MAVT) and Multi-Attribute Utility Theory (MAUT) [76] are the main methods of this category, but other techniques can also be included, e.g., AHP and SAW [44].

2. *Goal, aspiration, or reference level models*: they require the definition of desirable or satisfactory levels of achievement for each criterion. The process seeks to identify alternatives that are closest to achieve these desirable goals, systematically eliminating the other alternatives. The main methodologies of this category are goal programming [77] and its variants, but other methods, like compromise programming [78], have similar features.

3. *Outranking models*: they focus on pairwise comparisons of alternatives in terms of each criterion. The resulting preference information is aggregated across all the considered criteria in order to identify “incomparabilities” and to assess preferences and indifferences among the alternatives. The ELECTRE family of methods and PROMETHEE (Preference Ranking Organization METhod for Enrichment Evaluation) [79] are the two most famous outranking approaches.

Polatidis et al. [44] also considered an additional group with “other methods”, including, for example, Novel Approach to Imprecise Assessment and Decision Environment (NAIADE) [80] and Stochastic Multiobjective Acceptability Analysis (SMAA) [81].

To conclude this subsection, the use of fuzzy set theory in preference modeling has to be mentioned, since it is extensively applied in MCDM to deal with uncertainties [58]. This concept should not be classified as a “separate school of preference modeling”: it is rather a tool that can be applied in any of the MCDM models considered in this Chapter [3]. The fuzzy set theory was introduced by Zadeh [82] and used in MCDM for the first time by Bellman and Zadeh [83]. This theory is employed, for example, in the development of outranking relations [58], in the interval rating of alternatives expressed through triangular fuzzy numbers (e.g., [84]), or in the estimation of scores or weights of criteria through linguistic variables which are then converted into fuzzy numbers (e.g., [85, 86]).

2.2.3 Multi-attribute decision-making (MADM) approach

As explained in section 2.2.2, MADM methods are characterized by a finite number of predetermined alternatives, denoted as $A = \{A_i \mid i = 1, \ldots, m\}$, evaluated in terms of a discrete number n of criteria, represented as $C = \{C_j \mid j = 1, \ldots, n\}$. Both benefit criteria (for which higher values are preferable) and cost criteria (to be minimized) can be considered [11]. Furthermore, each criterion is associated with a weight, expressing its relative importance: usually, higher weights are assigned to criteria that are considered more important [87]. The weights, denoted as $W = \{w_j \mid j = 1,\dots,n\}$, are generally normalized, so that their sum is equal to one [88].

The MADM problem can be concisely represented by an $m \times n$ matrix, as shown in Table 2.2. Each element x_{ij} of the decision matrix indicates the score of the alternative A_i when it is evaluated in terms of the criterion C_j [11]. These scores can generally be expressed both in quantitative and qualitative terms [61].

Table 2.2 Decision matrix of a MADM problem characterized by m alternatives (A_i) and n criteria (C_j), associated with a weight w_j. Each element x_{ij} indicates the score of A_i with respect to C_j

	C_1	C_2	...	C_n
	w_1	w_2	...	w_n
A_1	x_{11}	x_{12}	...	x_{1n}
A_2	x_{21}	x_{22}	...	x_{2n}
...	...	...	...	...
A_m	x_{m1}	x_{m2}	...	x_{mn}

The main steps of the MADM process, adapted from Hajkowicz and Collins [45], are described in the following paragraphs.

Mathematical formulation of the problem

This first step is extremely important for the achievement of a good decision [67]. Clear goals have to be defined, as well as an appropriate set of evaluation attributes, taking into account the opinions of the various stakeholders. Selected criteria should be complete but non-redundant, relevant to the decision problem, and meaningful (i.e., facilitating stakeholders' and decision-makers' understanding of the effects of alternatives) [45, 67]. A set of feasible alternatives has also to be identified. Each alternative should be clearly described, highlighting how it may contribute to the achievement of the decision problem [67]. The result of this first phase is a mathematical formulation of the problem, represented by the decision matrix [89].

Evaluation of the scores for the decision matrix

In the second phase, each alternative is evaluated according to the different criteria in order to obtain the values x_{ij} that are introduced in the decision matrix. This activity should be carried out by a competent team, including the analyst and experts on the considered topics [67].

Moreover, the elements of the decision matrix may be either cardinal or ordinal. In fact, some MADM methods can handle both quantitative and qualitative information [45]. This is an advantage when dealing with real-world decision problems, especially concerning environmental management, which are frequently characterized by incomplete or uncertain data. In these cases, qualitative data, sourced from expert judgments or experiential knowledge, can be used [42].

Transformation of attributes

The criteria considered in a MADM problem are almost always characterized by different scales and measurement units [45]. Moreover, as explained in the previous paragraph, both quantitative and qualitative information can be included in the decision matrix. For these reasons, some MADM methods require a transformation of attributes in order to obtain comparable values [87].

Qualitative data expressed in linguistic terms, for example, are usually converted into interval scales to allow their comparison with quantitative values [67]. The presence of non-homogeneous measurement units in the decision matrix, on the contrary, is often managed through a normalization of the attributes. This procedure generally transforms the scores into dimensionless values, characterized by the same scale [45].

Normalization is not always necessary, but it is required by some methods (e.g., SAW) to allow the aggregation of different attributes for the calculation of the overall performance of each alternative [11]. Different normalization methods exist in the literature: some of the most common techniques are briefly described below.

Vector normalization: it divides each element of the decision matrix by the norm of the corresponding column vector to calculate the normalized scores r_{ij}.

For benefit criteria:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{2.1}$$

For cost criteria:

$$r_{ij} = 1 - \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{2.2}$$

Through this normalization, which is generally used in the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [11], all the criteria have dimensionless units. However, the obtained measurement scales do not have the same length, since the minimum and the maximum values are not equal for all the criteria. Therefore, a direct comparison among the attributes may be still difficult [11].

Linear normalization: it divides each value of a criterion by its maximum value $x_{max,j}$.

For benefit criteria:

$$r_{ij} = \frac{x_{ij}}{x_{max,j}} \tag{2.3}$$

For cost criteria:

$$r_{ij} = 1 - \frac{x_{ij}}{x_{max,j}} \tag{2.4}$$

In this case, $0 \leq r_{ij} \leq 1$, with higher values representing better outcomes, and the relative order of magnitude of the attribute values is unvaried [11].

Linear max-min normalization: it uses the distance of each attribute relative to the minimum value $x_{min,j}$ (or to the maximum value, for cost criteria).

For benefit criteria:

$$r_{ij} = \frac{x_{ij} - x_{min,j}}{x_{max,j} - x_{min,j}} \tag{2.5}$$

For cost criteria:

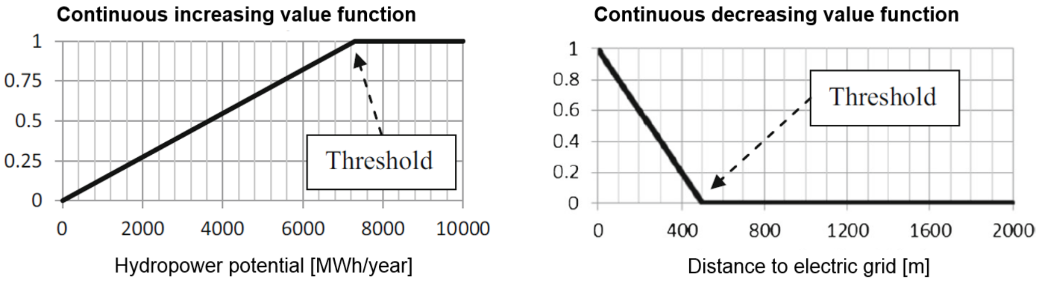


Fig. 2.2 Examples of value functions with different shapes (adapted from [4])

$$r_{ij} = \frac{x_{max,j} - x_{ij}}{x_{max,j} - x_{min,j}} \tag{2.6}$$

Therefore, the scale of measurement of the normalized values varies exactly between 0 (for the worst outcome) and 1 (for the best outcome) for each criterion [90].

Normalization through value functions: value functions are mathematical representations of human judgments [91]. They can be characterized by different shapes, according to the stakeholders' preferences towards different values of a criterion (Figure 2.2). Value functions transform the scores of criteria into dimensionless values, representing the degree to which a decision objective is achieved. The dimensionless values vary between 0 and 1, where 1 corresponds to a perfect achievement of the objective [91].

Allocation of weights

In any decision problem, the considered criteria have rarely the same importance according to the decision-maker. Therefore, most MADM methods require the definition of a set of weights expressing the relative importance of each criterion [45].

Weight assignment is a critical phase of MADM implementation because it is characterized by a high level of subjectivity and it directly influences the results of the analysis [67]. According to some authors, this is the most difficult task of the MADM approach [64]. Thus, it has to be carried out in a rational and transparent way, in order to achieve reliable model results [92].

A variety of weighting methods have been proposed in the literature. They can be divided into two main categories: subjective weighting methods and objective weighting methods [64]. Subjective methods determine criteria weights based on the preferences or judgments of the decision-makers. They are the most used for MADM problems concerning water resources management [64], even if they are often time-consuming [92]. Examples of subjective weighting methods are direct rating, pairwise comparison, and Simos' method. Objective methods, on the contrary, determine criteria weights based on the analysis of the initial data by means of mathematical models [64]. These methods do not consider decision-makers' preferences and, therefore, they are particularly applicable when reliable subjective weights cannot be obtained [93]. Examples of objective weighting methods are Entropy method, mean weight, and Criteria Importance Through Inter-criteria Correlation (CRITIC). Moreover, a further category can be considered, concerning the "combination weighting methods", i.e., hybrid weighting techniques based on the integration of subjective and objective weight assignment [67]. Some well-known weighting methods are illustrated in Appendix A.

Furthermore, when the decision-making problem is organized in a hierarchical structure, as in the example shown in Figure 2.3, the assignment of weights is required at the different levels of the decision tree [3]. In this case, relative and cumulative weights have to be defined. Usually, above all for complex models characterized by different levels, it is easier to begin the definition of weights by assessing *relative weights* within families of criteria, i.e., criteria having the same parent. The weights within each family should be normalized so that their sum is equal to 1. Afterward, the *cumulative weight* of each criterion can be calculated as the product of its relative weight by the relative weights of its parents until the top of the decision tree. The sum of the cumulative weights of all the bottom-level criteria (i.e., the leaves of the tree, highlighted in red in Figure 2.3) is equal to 1 [3].

Aggregation procedure

In the next step, the scores of the different criteria (normalized, when required) are aggregated, using the set of weights and, in some methods, other parameters (e.g., the thresholds), to obtain an overall performance score or rank for each alternative [45]. Each MADM method uses a different aggregation procedure, which represents its "hallmark" [69]. However, there is not a method that is considered the best for

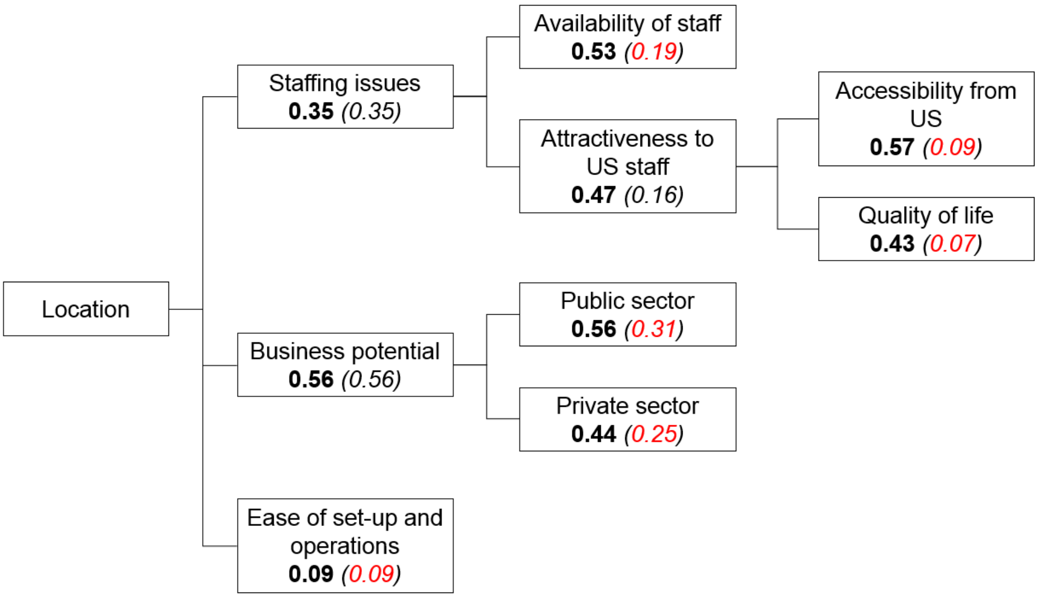


Fig. 2.3 Example of problem structured as a multi-level decision tree: relative weights are in bold type, cumulative weights in italics. The cumulative weights highlighted in red correspond to the bottom-level criteria (adapted from [3])

all decision-making problems: according to the decision context, some techniques may be more appropriate than others [44]. Furthermore, applying different methods to the same problem can produce different results [44, 89], even if some studies have demonstrated that, generally, the changes are not significant when the decision problem has been appropriately structured [45].

Therefore, the main issue in this phase concerns the selection of a suitable MADM technique. The choice depends on the specific decision context, i.e., in particular, on the typology of the decision problem, the available data, the expertise and preferences of the analyst and the other involved actors [67]. Moreover, it has to be considered that, according to the MADM method, a different type of result may be achieved. For example, several methods provide an overall performance score for each alternative (e.g., the methods based on value measurement), while other methods only result in an ordinal ranking of the alternatives (e.g., ELECTRE III). Besides, some other methods allow the allocation of the alternatives to different categories: they are thus used for classification problems (e.g., ELECTRE TRI).

As explained in section 2.2.2, the main methodological approaches can be classified into three categories. The methods based on *value measurement* (e.g., MAVT, MAUT, and SAW) attempt to obtain a true value for each alternative, representing the preferences of the decision-maker, by aggregating the value functions of each considered criterion, according to their relative importance. The preferred alternative is the one that maximizes the multi-attribute value function $f(\vec{a})$, where $\vec{a}$ represents the vector of the attributes. An advantage of these methods is the transformation of the multi-attribute problem into a problem with a single attribute, easier to be analyzed [61].

The MADM methods that can be included among *goal, aspiration, or reference level models* (e.g., compromise programming and TOPSIS) are based on the definition of an "ideal", but non-feasible, solution, i.e., an alternative where all the attributes achieve their optimal value. Then, the considered alternatives are ranked according to their distance from the ideal solution, measured through an aggregating index. The preferred alternative is the closest to the ideal solution [94].

The *outranking methods* (e.g., ELECTRE and PROMETHEE), on the contrary, are based on the concept of outranking and concordance/discordance analysis [61]. The considered alternatives are pairwise compared to identify their outranking relation, denoted as S, which means "at least as good as". Considering two alternatives A_1 and A_2, the following outranking relations may occur [58]:

- $A_1\ S\ A_2$ and not $A_2\ S\ A_1$: $A_1\ P\ A_2$, i.e., A_1 is strictly preferred to A_2;
- $A_2\ S\ A_1$ and not $A_1\ S\ A_2$: $A_1\ P^-\ A_2$, i.e., A_2 is strictly preferred to A_1 or A_1 is inversely preferred to A_2;
- $A_1\ S\ A_2$ and $A_2\ S\ A_1$: $A_1\ I\ A_2$, i.e., A_1 is indifferent to A_2;
- Not $A_1\ S\ A_2$ and not $A_2\ S\ A_1$: $A_1\ R\ A_2$, i.e., A_1 is incomparable to A_2.

The outranking relations are then used to define, according to the MADM method, the concordance and discordance indexes, which allow obtaining the ranking of the alternatives [61]. A characteristic of the outranking methods is that they are usually non-compensatory, i.e., the high performance of one criterion cannot completely compensate for a poor performance of another criterion. This feature could be more appropriate for some decision problems [44].

The most popular MADM methods are described in Appendix B.

Sensitivity analysis

Once preliminary conclusions are achieved, an analysis should be carried out to investigate their robustness or sensitivity to changes in some features of the MADM model. Sensitivity analysis may be performed, for example, to evaluate the influence of missing information or to offer a different perspective on the problem [3]. However, more frequently, it is used to assess the effects of uncertainty and subjectivity, usually associated with any decision process, by testing the consistency of MADM results after a variation in the input parameters and/or in the decision-maker's preferences [69].

A technical sensitivity analysis assesses which input data have a critical influence on the overall evaluation, i.e., whether a slight variation, for example, in a criterion weight can affect the MADM results [3]. The input parameters more frequently considered in sensitivity analysis are criteria weights (e.g., [95, 96]). However, there are different other features of the MADM model that can be analyzed [97], such as the scores of alternatives (e.g., [98]), the number of criteria or alternatives (i.e., a criterion or an alternative can be added or removed, e.g., [99]), the values assigned to the thresholds required by some MADM methods (like ELECTRE III, e.g., [100]), or other technical parameters.

This information is very useful in making a decision because it can give an indication of how robust (i.e., insensitive to changes in parameters) the alternative with the higher overall performance is and how it can change in different circumstances [97]. If this alternative is robust, the decision-maker will be more confident in adopting or recommending it. Otherwise, sensitivity analysis will support the decision-maker in understanding whether this alternative can be implemented or in deciding which other alternative would be more appropriate [97].

Final decision

The MADM process is not only characterized by the technical modeling and analytical features: it also concerns the support provided to the implementation of results [3]. In fact, the MADM model does not make the final decision [45], but it provides information that helps the decision-maker to better understand the problem and to achieve a decision of higher quality [59].

Therefore, in the final phase of the decision-making process, the results of the implemented method, including sensitivity analysis, are presented by the analyst to the decision-maker. Usually, visualization tools are employed for this purpose, to improve the comprehensibility and facilitate the final evaluation of the decision-maker [67]. Indeed, to achieve the final decision of any MADM process, human judgment is generally required to consider relevant issues that could not be properly included in the technical model [45].

2.3 Literature review in the field of surface water resources management

Over the last decades, numerous studies have used different MADM methods to face decision-making problems concerning water resources management. One of the reasons is that water policy is usually guided by multiple, often conflicting, objectives [45]. Moreover, most of these decision-making processes involve several stakeholders with different interests, thus increasing the complexity of the problem [89]. Therefore, the use of a MADM method, providing an integrated approach that brings a rigorous structure and transparency to the decision model, can be a useful approach to support decision-makers in water management [4].

The review presented in this Chapter aims at providing a global overview of the studies applying MADM to solve decision-making problems concerning surface water resources management. More than 300 papers selected among the academic articles present in *Scopus* and *Web of Science* databases and published from 1980 to the beginning of 2021 have been critically analyzed to show the development and the state of the art of MADM use in this field. The analyzed results illustrate how researchers have applied different methods in their studies to solve different problems, in various contexts. Moreover, based on these results, the potential strengths and shortcomings of MADM application for water resources management are discussed.

This review is not meant to be exhaustive and some choices have been made to limit the number of articles to be analyzed, since numerous MADM studies are being published over the last years. However, the reviewed papers cover a wide range of water management decision-making problems and MADM techniques, both classical and novel.

2.3.1 Selection and analysis of papers

The selection of papers to be analyzed was carried out using the *Scopus* and *Web of Science* databases, considering the keywords ("multi-criteria" OR "multi criteria") AND "water resources management". The literature search was completed on January 27, 2021 and yielded almost 1200 articles published from 1973 to 2021.

By reading the abstract of all these papers, the final sample of studies to be further analyzed was defined. For simplicity, only scientific articles concerning surface water management and urban water systems, written in English, were selected. Studies focusing, for example, on groundwater management, wastewater treatment or desalinisation plants, or whose main topic was not related to water resources (e.g., the focus was on agriculture sustainability, desertification, erosion risk, etc.) were excluded from the analysis. Moreover, it was decided to focus on MADM, thus ignoring papers applying multi-objective optimization, except when its results were evaluated through a MADM method. Review articles were also excluded, as well as articles whose full paper resulted unavailable in the above databases or from other online sources.

This procedure resulted in a total of 312 collected articles. Each full paper was analyzed based on a set of review criteria in order to understand the purpose of the MADM application, the context, and the way in which the research was carried out. In addition to a short summary of the study, the following review criteria were considered:

- the location of the case study, highlighting the concerned country;
- the context and spatial scale in which the case study was carried out (e.g., a river basin, a city, a watercourse, etc.);
- the purpose category, highlighting the objective for which MADM was applied: 18 categories, representing the main topics covered by the selected papers, were identified;
- the water uses considered in the study (e.g., agricultural irrigation, domestic or industrial water use, hydropower generation, etc., when applicable);
- the MADM method(s) and the weighting technique(s) used (when specified) – information about the use of multi-objective optimization, correlation coeffi-

cients to compare the results of different MADM methods, and/or aggregation techniques was also collected;

- the number and typology of considered alternatives, highlighting the studies in which an index was developed with the support of MADM or a spatial analysis was performed by coupling the Geographic Information System (GIS) with MADM methods;
- the application of sensitivity analysis, indicating the parameters that were varied to test the robustness of the obtained results.

In order to analyze in detail the above review criteria and to allow a subsequent comparison of all the selected papers, a spreadsheet was used. A row was compiled for each paper during its critical reading by entering in each cell the information related to the corresponding criterion.

2.3.2 Results of the review

General findings

The 312 selected papers were published in the period between 1980 and the beginning of 2021. An increasing **trend over time** of MADM applications in water resources management was noticed, as represented in Figure 2.4. For simplicity, the figure does not show the period before 1992, because only 1 selected paper was published before this year (in 1980). Moreover, the 9 papers corresponding to 2021 are not represented in the graph since the literature search was completed in January 2021 and, therefore, this number could not be considered representative. The figure highlights that the use of MADM methods in the investigated field became more and more frequent from the early 2000s, with more than 20 studies per year from 2017 (42 studies in 2019 alone).

A rising trend over time was usually detected also considering the case studies carried out in each continent (Figure 2.5). The most significant increase was noticed in Asia, where more than 20 studies took place both in 2019 and in 2020. Furthermore, 8 out of the 9 papers published in 2021 (not represented in the figure) referred to an Asian location. Moreover, even if there is not an increasing trend over the last

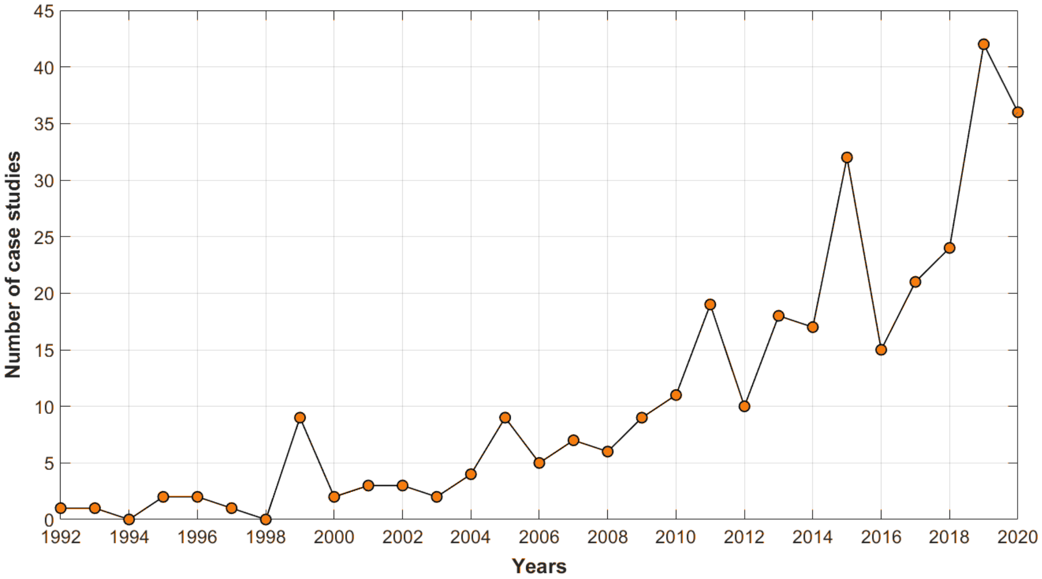


Fig. 2.4 Trend of the application of MADM methods to water resources management between 1992 and 2020

years in North America and Oceania, most of the articles presenting a case study located in these continents were published from 2005.

The **geographic distribution** of the analyzed case studies is represented in Figure 2.6. It can be noticed that they concern different areas of the world, but their distribution is highly uneven across the continents. In fact, the majority of case studies were located in Asia (47.9% of the 334 considered case studies), above all in Iran (55 case studies), China (33), and India (16), but a consistent part of the sample also concerned the European territory (25.4%). On the contrary, Africa (7.5%), North America (6.6%), South America (5.7%), and Oceania (5.1%) were much less represented.

It has to be highlighted that this geographic analysis was not based on the authors' affiliation, but on the locations of the case studies presented in the selected articles. Therefore, for papers describing multiple case studies set in different countries (e.g., [101–103]), each location was considered individually and represented on the map. Moreover, 2 articles referred to a study carried out at the European level ([104, 105]) and another one presented a global assessment ([91]), while in 8 papers the location of the study was not specified (e.g., Rajasekaram et al. [106] and Lopes et al. [107] illustrated a hypothetical case study, whereas Behzadian and Kapelan [108] referred to "*a northern European city*"). These case studies could not be represented in Figure

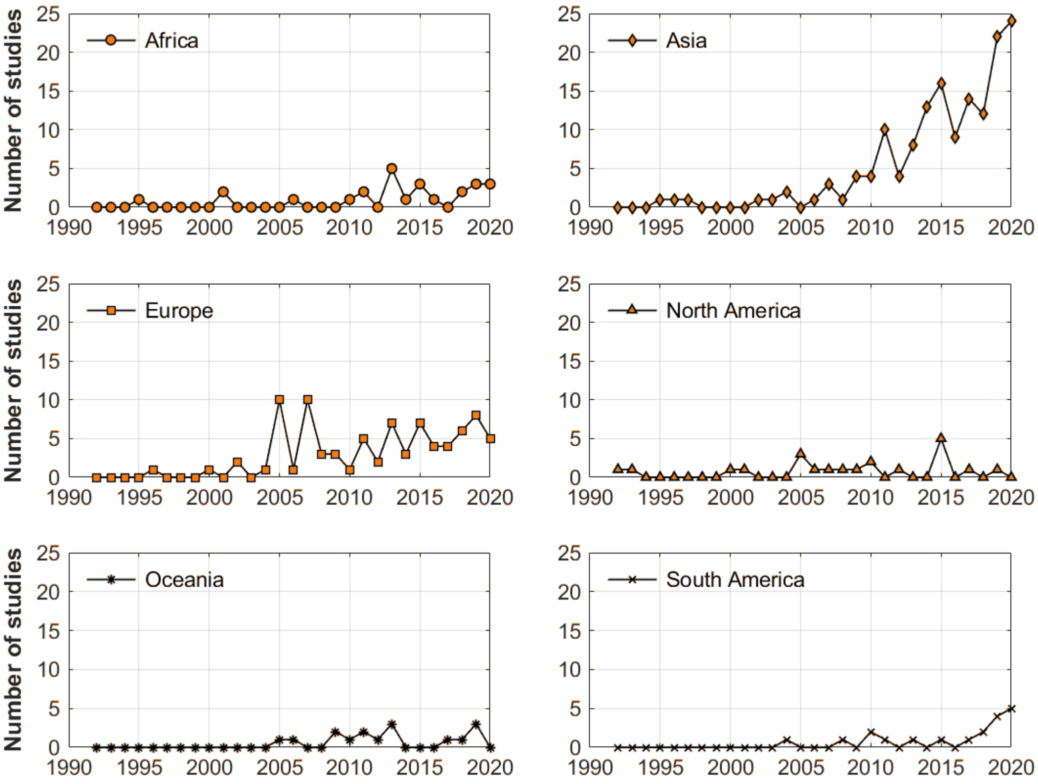


Fig. 2.5 Trend of MADM application between 1992 and 2020 for each continent

2.6, but they were taken into account to calculate the total number (i.e., 334 case studies).

As concerns the **context and spatial scale** of the case studies analyzed in the sample, most of them referred to a watershed (38.3% of the 334 considered case studies) (e.g., [109, 110]), including 5 transboundary river catchments and 5 lake basins, while 2.1% of the studies considered a sub-basin (e.g., [111]). Other research activities performed at a large spatial scale concerned a region (8.7% of the case studies, e.g., [13]), a province (2.7%, e.g., [112]) or a district (2.1%, e.g., [113]), and 6.3% of the case studies were carried out at national level (e.g., [114]). Other studies referred to a narrower scale, such as a city or an urban area (10.8%, e.g., [115]), a dam (4.5%, e.g., [68]) or a reservoir system (3.0%, e.g., [116]), a water distribution system (2.7%, e.g., [117]), or an irrigation area (2.7%, e.g., [102]). A watercourse (2.4%) or a river stretch (1.5%) were also frequently considered (e.g., [118, 119]), as well as a lake (1.8%, e.g., [120]) or a marine area (1.5%, e.g., [121]).

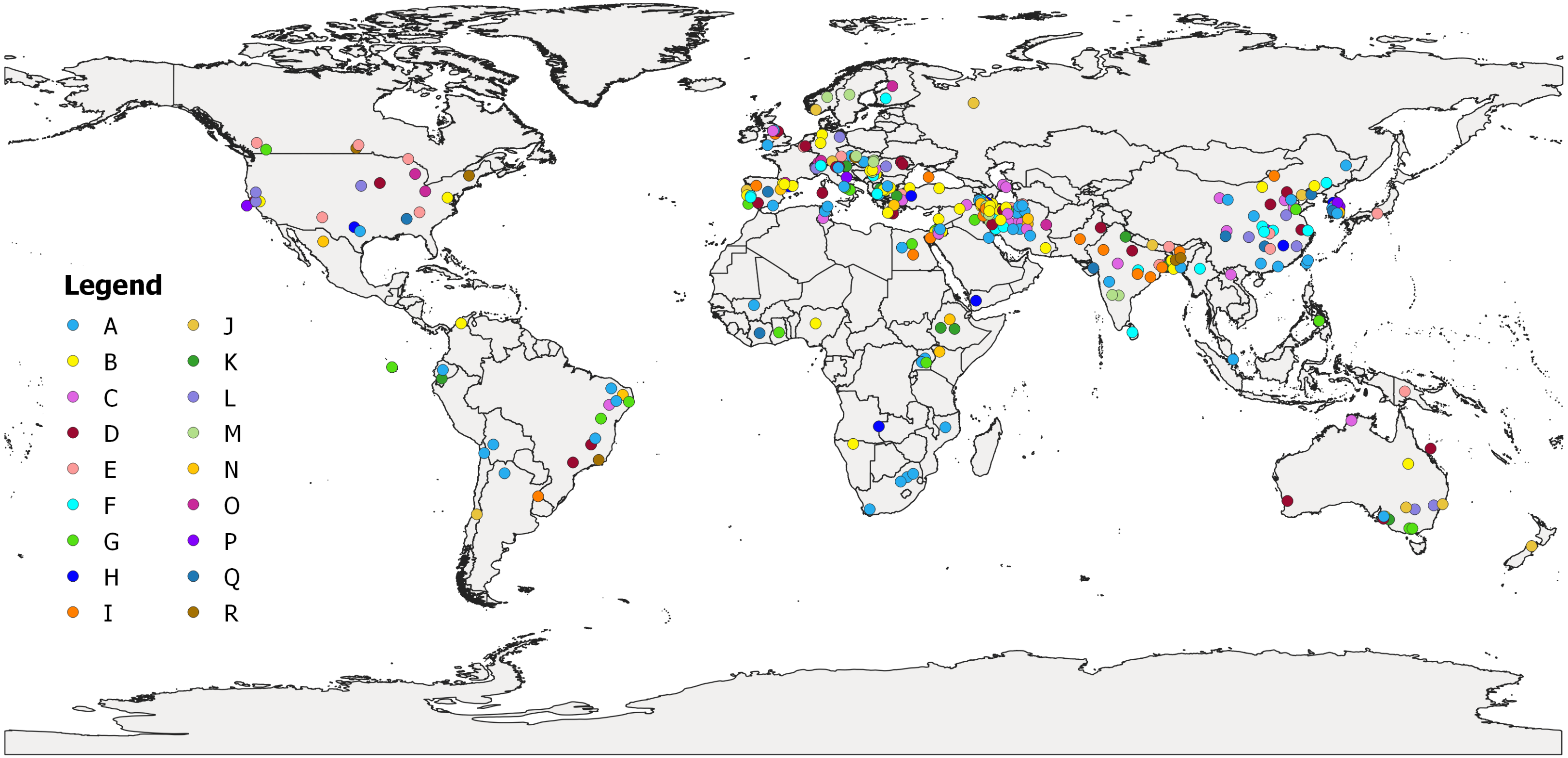


Fig. 2.6 Geographic distribution of the analyzed case studies. Letters indicate the different purpose categories, listed on page 36. Studies at European or global level or not specifying the location are not represented (©*EuroGeographics for the administrative boundaries*)

Main purposes of the studies

The diversity of methodological approaches identified within the sample of analyzed articles demonstrated that MADM methods are applied to a broad range of decision-making problems concerning water resources management. In this review, eighteen categories, representing the main purposes for which MADM techniques were used in the selected studies, have been identified:

A) Evaluation of different water management strategies (16.7% of the sample), including different studies considering alternative strategies, for example, to solve water-related conflicts (e.g., [122]), for the integrated water resources management in a watershed (e.g., [123, 124]), to develop long-term policy scenarios (e.g., [125]), etc.;

B) Selection of projects/technologies for water supply (12.8%), including studies ranking different water supply projects (e.g., [126]), alternative drinking water sources (e.g., [127]), or evaluating various alternatives for providing additional water supply to a city (e.g., [128]);

C) Water allocation to different users/areas (9.3%), including studies ranking water allocation alternatives among different areas (e.g., [106]), or analyzing the reuse of reclaimed water for different sectors (e.g., [13]);

D) Water quality assessment/improvement (9.0%), including studies performing a spatial assessment of surface water quality in a watershed (e.g., [129]), ranking water quality management options (e.g., [130]), or establishing a water quality monitoring system (e.g., [131]);

E) Flood control (7.7%), including studies assessing the spatial distribution of flood hazard in a river basin (e.g., [132]) or ranking different flood management alternatives (e.g., [133]);

F) Operation of reservoirs (7.7%), including studies evaluating different alternatives for the regulation of a lake (e.g., [41]) or for the real-time operation of a reservoir system (e.g., [134]), or comparing different algorithms used to optimize the reservoir operation (e.g., [135]);

G) Management of water distribution systems (7.1%), including studies ranking alternative operating rules (e.g., [136, 137]) or different intervention strategies (e.g., [67]) for a water supply system;

H) Water management scenarios for climate change adaptation (5.4%), including studies assessing adaptation options to climate change for agricultural water management (e.g., [138]), different water use sectors (e.g., [139]), or wetland conservation (e.g., [140]);

I) Location of water supply structures (5.1%), including studies ranking different possible locations for a reservoir (e.g., [141]) or for rainwater harvesting structures (e.g., [142]);

J) Balance of various ecosystem services provided by surface waters (4.8%), including studies assessing the angling and swimming value of different rivers (e.g., [143]), different payment and non-payment alternatives for ecosystem services in a watershed (e.g., [144]), or the recreational water use potential of a river basin (e.g., [145]);

K) Identification of areas for the implementation of water management practices (4.5%), including studies identifying potentially irrigable areas (e.g., [146]) or suitable sites for green stormwater management infrastructures (e.g., [147]);

L) Water ecology (4.5%), including studies assessing the habitat conditions for a river species (e.g., [148]) or assessing river health (e.g., [149]);

M) Selection of water resources projects (3.8%), including studies evaluating different projects, not focusing on water supply (as for category B), but, for example, considering different typologies of hydropower plants (e.g., [150]), alternative systems of reservoirs in a river basin (e.g., [151]), or various water resources projects designed for meeting long-range goals (e.g., [152]);

N) Water shortage risk assessment/mitigation (3.8%), including studies performing a spatial assessment of water shortage vulnerability (e.g., [153]) or prioritizing different measures to mitigate water shortage risk (e.g., [154]);

O) River and wetland restoration (2.9%), including studies ranking alternative river restoration strategies (e.g., [118]) or prioritizing sites for wetland restoration (e.g., [155]);

P) Assessment of water resources vulnerability (2.6%), including studies evaluating the vulnerability of an urban water system (e.g., [156]), the hydrologic vulnerability of a river basin (e.g., [98]), or the vulnerability to climate change for different water sectors at national level (e.g., [157]);

Q) Evaluation of water management sustainability (2.6%), including studies assessing the Sustainable Water-supply Index for a river basin (e.g., [158]) or evaluating the sustainable use of urban water (e.g., [159]);

R) Selection of watercourse engineering measures (2.6%), including studies assessing different hydraulic structures for river management (e.g., [160, 119]).

The purpose categories related to the considered case studies are represented with different colors in Figure 2.6. It has to be highlighted that some papers were classified into more than one purpose category, sometimes even when a single case study was described (e.g., [101, 161, 96]). In these cases, however, only one color was used on the map.

Figure 2.7 shows the number of papers referring to each continent for the different purpose categories. It can be noticed that, while in Africa and South America the studies focused mainly on the evaluation of different water management strategies (category A), in Oceania and North America one of the main subjects was water quality (category D), as well as the balance of various ecosystem services (category J) in Oceania, flood control (category E) and water ecology (category L) in North America. Only Asia and Europe are represented by at least one case study in all the eighteen purpose categories. In addition to the evaluation of different water management strategies, most of the case studies in these two continents focused on the selection of projects and technologies for water supply (category B) and, in Asia, on the assessment of water allocation to different users or areas (category C). Operation of reservoirs (category F) was also a frequent purpose in these continents, as well as water quality and, in Asia, flood control.

With regards to the **water uses** considered in the analyzed studies, most of the papers concerned agricultural irrigation (53.8% of the sample, e.g., [162, 103]). Several studies also referred to industrial water use (22.4%, e.g., [163]), urban water supply (21.5%, e.g., [164]), or hydropower production (17.9%, e.g., [134]). Water use for drinking (14.7%, e.g., [165]) and domestic (11.5%, e.g., [86]) purposes, recreational activities and tourism (12.8%, e.g., [100]), or commercial fishing (8.0%,

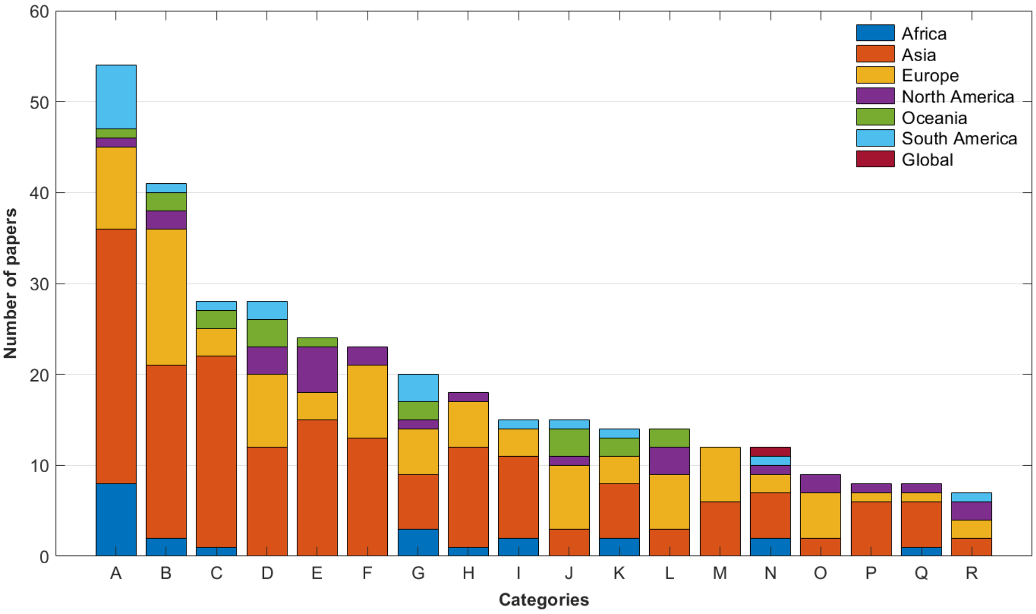


Fig. 2.7 Number of papers referring to each continent for the different purpose categories (listed on page 36)

e.g., [166]) were also mentioned in various papers. Moreover, different articles referred to regional water supply (7.1%, e.g., [126]), environmental water supply (7.1%, e.g., [167]), navigation (4.2%, e.g., [149]), irrigation of urban green areas (3.8%, e.g., [168]), or recreational fishing (3.5%, e.g., [143]).

MADM methods and alternatives

Different typologies of MADM **methods** were used in the analyzed articles. Figure 2.8 shows how frequently the most popular methodologies have been mentioned in the selected sample. The figure discriminates the use of classical and fuzzy methods for the ranking of the alternatives. It also highlights the application of some methods for criteria weighting.

The most applied MADM technique (33.7% of the sample) is AHP, which was frequently employed to weight the considered criteria, combined with another MADM technique, often Weighted Linear Combination (WLC), used for the final assessment. This result is in line with the outcomes of a previous review in the field of hydropower planning and management [169]) and a more recent review concerning water resources decision-making [89]): they both observed that AHP is

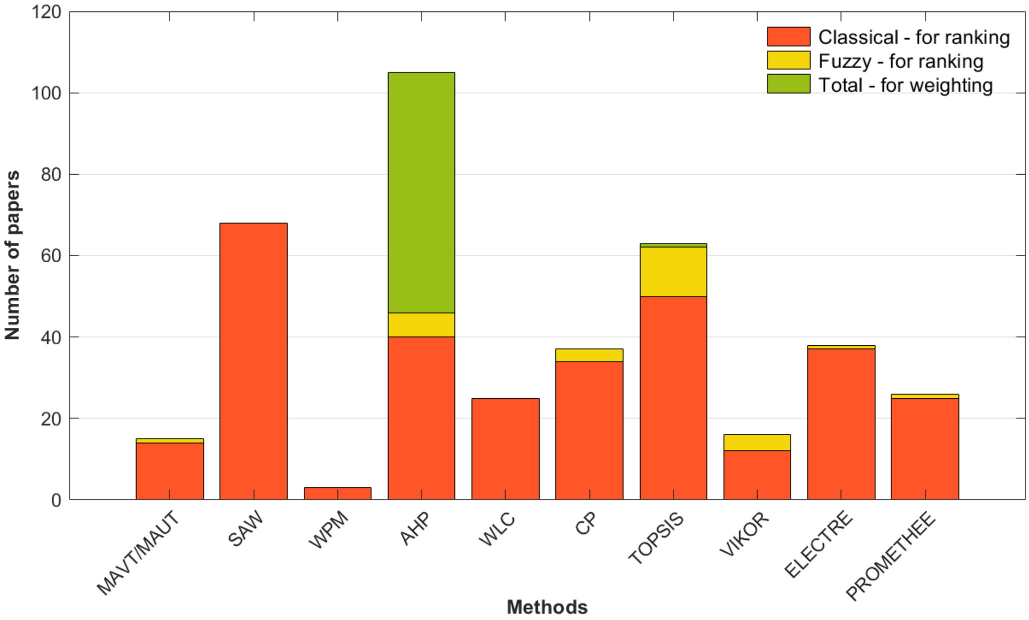


Fig. 2.8 Number of papers employing different MADM methods for water resources management: Multi-Attribute Value and Utility Theories (MAVT/MAUT), Simple Additive Weighting (SAW), Weighted Product Method (WPM), Analytic Hierarchy Process (AHP), Weighted Linear Combination (WLC), Compromise Programming (CP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), VIKOR method, ELECTRE family, and PROMETHEE family

the most commonly used MADM method. Zolghadr-Asli et al. [89] also noticed that its application continues to increase over time, probably due to its relatively simple approach, requiring low computational efforts and directly involving the decision-maker(s) through subjective assessments.

According to the present review, SAW and TOPSIS are other methods among the most used (21.8% and 20.2%, respectively). TOPSIS was also employed in a fuzzy environment in various studies (12 papers) and as a weighting technique (only in 1 paper). Furthermore, two families of outranking methods, i.e., ELECTRE (including ELECTRE I, ELECTRE II, ELECTRE III, ELECTRE IV, and ELECTRE TRI) and PROMETHEE (including PROMETHEE I and PROMETHEE II), were used in several studies (12.2% and 8.3%, respectively), as well as Compromise Programming (11.9%) and Weighted Linear Combination in a GIS environment (8.0%). Fewer applications, on the contrary, concern VIKOR (5.1%), MAVT/MAUT (5.1%), and Weighted Product Method (only 3 papers).

However, other methods not represented in Figure 2.8 were mentioned in 110 papers, such as ANP (Analytic Network Process), NAIADE (Novel Approach to Imprecise Assessment and Decision Environments), or WASPAS (Weighted Aggregated Sum Product Assessment), only employed in a few studies, or novel techniques presented in a specific article (e.g., [170, 165]) or based on the use of a particular software (e.g., [68, 171]). Overall, MADM applications in a fuzzy environment concerned 17.9% of the selected papers. They were used to address complex water-related problems characterized by high levels of uncertainty and the imprecise nature of stakeholders' judgments ([172, 154]). Moreover, 20.2% of the sample described a spatial assessment carried out in GIS.

It has to be highlighted that in several articles (42.0% of the sample) two or more MADM techniques were compared or applied together (e.g., [173, 174]). Moreover, even if studies focusing on the use of multi-objective optimization have been excluded from the sample, 7.7% of the selected articles employed an optimization model to identify a set of Pareto-optimal solutions from which the best compromise solution was chosen by means of one or more MADM methods. Finally, only in 5 papers the considered MADM methodology was not specified.

Table 2.3 summarizes the main MADM methods adopted in the selected studies according to the different purpose categories. Table 2.4, on the contrary, shows, for each purpose category, the overall number of fuzzy MADM methods identified in the sample, the number of articles using GIS, and the number of studies employing a multi-objective optimization model in addition to MADM methods.

As concerns the assignment of **weights** to criteria, subjective weighting methods, based on the preferences of decision-makers, were the most frequently employed in the analyzed studies (75.0% of the sample). In particular, direct rating was the most used method (34.9%), followed by AHP (17.6%). Other popular subjective weighting techniques identified in the selected papers were: pairwise comparison (3.2%), Delphi method (3.2%), ranking of criteria (1.9%), Simos' procedure (1.9%), Swing method (1.3%), and Fuzzy AHP (1.3%). Moreover, some MADM methods used to rank the considered alternatives, such as AHP, already include in their framework a procedure that allows the calculation of weights based on the opinions of decision-makers [89]): hence, the studies employing these MADM methods have been considered among the papers using subjective weighting techniques.

Table 2.3 Main MADM methods used in the analyzed articles according to the different purpose categories (letters refer to the purpose categories listed on page 36; w = use of the method for the assignment of weights to criteria; f = fuzzy method)

Purpose category	MAVT/ MAUT	SAW	WPM	AHP	WLC	CP	TOPSIS	VIKOR	ELECTRE family	PROMETHEE family
A	2	16	0	19 (5 w)	0	9	14	0	8	3
B	2	14	1	13 (3 f, 6 w)	1	5	10 (5 f, 1 w)	4 (1 f)	4 (1 f)	3 (1 f)
C	1	3	1	12 (4 f, 2 w)	1	4	3 (1 f)	1 (1 f)	3	1
D	1	7	0	5 (4 w)	5	1	4	1	0	2
E	0	6	0	9 (7 w)	3	4 (1 f)	10 (3 f)	5	5	1
F	1	5	0	5 (2 w)	0	3	7	0	2	2
G	0	4	0	7 (3 w)	0	2	4	0	5	3
H	1	5	0	5 (2 w)	0	1	3	1	2	1
I	0	1	0	11 (1 f, 9 w)	7	1	1	1	0	1
J	2	5	0	0	0	0	0	0	0	0
K	0	1	0	10 (7 w)	8	0	1	0	0	0
L	1	2	0	6 (4 w)	0	3	2	0	1	2
M	3	1	0	1	0	5 (1 f)	2 (1 f)	1 (1 f)	5	1
N	0	3	1	6 (1 f, 5 w)	1	0	0	0	0	1
O	3	1	0	1 (1 w)	2	0	0	1	0	0
P	0	3	0	0	0	0	5 (1 f)	2 (1 f)	0	0
Q	0	1	0	3 (3 w)	0	0	2 (1 f)	0	0	1
R	0	2	0	0	0	2 (1 f)	2	0	0	3

Table 2.4 Number of articles using fuzzy MADM methods, GIS, and multi-objective optimization, according to the different purpose categories listed on page 36

Purpose category	Fuzzy MADM methods (total)	Use of GIS	Use of multi-objective optimization
A	3	3	1
B	11	1	2
C	7	1	5
D	5	10	3
E	7	10	2
F	2	0	11
G	5	1	1
H	3	0	2
I	2	11	0
J	1	5	0
K	1	11	0
L	0	2	1
M	4	1	1
N	4	5	0
O	0	3	0
P	2	2	0
Q	1	2	0
R	1	0	0

On the contrary, only 28.2% of the selected articles used objective weighting methods, where the weights are obtained through a mathematical procedure. The most frequent method was Mean Weight, i.e., equal weights were assigned to all the criteria (16.0% of the sample). This technique was usually adopted in addition to other, often subjective, weighting methods and the results were compared in a sensitivity analysis (e.g., [175, 176]). Another common objective weighting method adopted in several analyzed articles was the Entropy method (7.1% of the sample), while CRITIC and Fuzzy TOPSIS were used only in 1 paper each.

Other less popular weighting methods were mentioned in 41 articles. Furthermore, in several papers, different weighting methods were employed and the results obtained by considering the different sets of weights were compared (e.g., [138]). Finally, the considered weighting technique was not specified in 20 articles.

The number and typology of **alternatives** considered in each case study were also monitored during the analysis of the collected sample. The number of alternatives usually varies between 3 and 10 (59.0% of the sample): the median value is 7, while the most frequent value is 5 (14.1% of the sample). However, some authors only considered 2 alternatives (6 articles, e.g., de Lange and Kleynhans [125], who analyzed two long-term water resources management strategies, or Heidari [150], who proposed two schemes of hydropower projects), or even more than 100 (13 articles, e.g., Prado and Novo [177], who classified 182 sub-basins, or Pourshahabi et al. [178], who ranked 150 Pareto-optimal solutions). Moreover, in 4.8% of the selected papers, the number of alternatives was not specified (e.g., [179, 180]), whereas in 15.7% of the sample a specific set of alternatives was not considered, for example because GIS was coupled with MADM methods to produce a map (e.g., [142, 146]).

As concerns the typology, the considered alternatives were frequently represented by a set of management strategies (35.6% of the sample), but also by different projects or engineering measures (15.7%), or various regions (12.5%). Other recurrent types of alternatives were: operational scenarios for a reservoir (5.4%), resource allocation options (4.2%), water uses (3.2%), or watercourses, stretches, and wetlands (2.6%).

Moreover, it has to be highlighted that in 4.2% of the analyzed articles the set of alternatives ranked through one or more MADM methods was a set of Pareto-optimal solutions identified by means of a multi-objective optimization model (e.g., [181, 182]). Furthermore, in several articles, the MADM result was not only the ranking of different alternatives, but a spatial representation obtained by coupling GIS with MADM methods (20.2% of the sample, e.g., [183, 145]), or the development of an index based on the MADM use (4.5%, e.g., [184, 110]). In these cases, a ranking of alternatives was not always presented.

Sensitivity and comparative analyses

In several papers (45.5% of the selected sample), **sensitivity analysis** was carried out to investigate the consistency of the MADM results. Usually, it was applied by varying the weights initially assigned to criteria (39.1% of the sample), for example, considering different schemes of weights allocated through a direct method (e.g., [139, 185]), or even adopting different weighting techniques, as mentioned above (e.g., [141, 147]). In some papers, other parameters were also included in the sensitivity analysis, such as the performance scores of criteria and sub-criteria (4.8%, e.g., [186]), the p-value in Compromise Programming and Goal Programming (4.2%, e.g., [123]), or the thresholds defined for the criteria in ELECTRE and NAIADE (2.6%, e.g., [187]). Less common parameters that were varied to test the robustness of the MADM results were, for example, the normalization functions, the interval scales of the criteria scores, or the aggregation functions (2 papers each). In few studies, the effects of the addition or removal of some criteria (2 papers) or alternatives (1 paper) on the results were also analyzed.

Moreover, in 25.3% of the selected articles, a **comparative analysis** of different MADM methods applied to the same case study was also performed. In some cases (4.5% of the sample), the correlation among the obtained rankings was statistically analyzed by means of correlation tests. The most used was Spearman correlation test (4.2%, e.g., [188, 137]), but Pearson and Kendall correlation tests were also applied (in 2 papers each, e.g., [189] and [190], respectively). Furthermore, some authors employed one or more aggregation methods to combine the rankings obtained with the different MADM techniques (3.8% of the sample). Borda [191] and Copeland [192] methods were usually adopted (3.2%, e.g., [101, 40]; and 1.9%, e.g., [193], respectively). The key features of the correlation tests and aggregation methods mentioned in this paragraph are described in Appendix C.

2.4 Concluding remarks

Over the last decades, studies applying MADM methods to solve problems concerning surface water resources management have significantly increased. The reasons were often related to their potential to provide a deeper understanding of the water problems and the possibility to investigate conflicting points of view [61]. The review of more than 300 scientific papers presented in section 2.3 revealed that case studies were carried out in different areas of the world, but with an uneven distribution among the continents. The highest number of studies was set in Asia: in particular, 23.1% concerned the Middle East (above all Iran), where MADM methods were frequently used to address the water crisis that afflicts this region (e.g., [194]).

Almost all the examined papers described a real case study, whose spatial scale was often a watershed or a region, less frequently an urban area or a smaller spatial scale. A wide range of water-related problems has been considered. The results of the review showed that the evaluation of different water management strategies is the most frequent purpose for the application of MADM, followed by the selection of projects or technologies for water supply. Furthermore, most of the analyzed studies concerned agricultural irrigation, while only a lower number of researchers focused on industrial and urban water use.

Various MADM methods were used in the analyzed papers. Researchers often applied existing, popular, methods: in particular, AHP was the most mentioned, due to its procedural transparency and its suitability for the analysis of complex problems, characterized by multiple criteria [124, 146]). However, novel MADM methods are continuously developed, and several authors of the analyzed studies proposed new techniques to improve the considered decision-making processes (e.g., [195, 165]). Furthermore, spatial analyses were frequently performed by coupling GIS with MADM methods.

A critical aspect of MADM application to water resources management is the possible lack of suitable information, due to the incomplete knowledge of the involved experts or the uncertainty associated with actual environmental problems [61]. For this reason, different studies have adopted fuzzy-based frameworks to address high levels of uncertainty of the data [154]. Moreover, several researchers conducted sensitivity or comparative analyses. However, considering the uncertainties associated with real-world water resources problems, such analyses should always be performed [89].

Another limitation of the analyzed sample is that, although almost all the articles described a real case study, it was usually not specified whether the MADM results were actually adopted to support the real decision-making process. Besides, in some papers, significant features of the MADM application were unspecified (e.g., the MADM technique adopted for the decision problem, the number and typology of the considered alternatives, etc.). In these cases, it was more difficult to fully understand how MADM supported the decision-making process.

In conclusion, MADM can be a suitable decision support tool for water management problems, typically characterized by a multi-dimensional and complex nature. The use of MADM methods often facilitates the resolution of conflicts, allows the participation of stakeholders with different opinions, and improves the transparency of water management decisions [45]. However, applying these methods in an inappropriate way, for example examining the problem from a single perspective or relying exclusively on a subjective weighting technique, can lead to ambiguous results [89]. On the contrary, a comprehensive framework that integrates technical data and environmental, socio-economic, and legislative aspects, including active participation of the concerned actors in the whole process, is required to provide more sustainable management of water resources [169, 61].

Chapter 3

MCDM procedure for the assessment of water withdrawal sustainability in Aosta Valley: integration of meso-scale habitat modeling

3.1 Introduction

Part of the work described in this Chapter has been previously published in the papers [1] and [5].

As illustrated in Chapter 1, the majority of Alpine watercourses are affected by different types of human exploitation [17], generating significant negative pressures on the aquatic ecology and, consequently, an important loss of biodiversity [39, 22]. Moreover, the effects of climate change on water availability will further exacerbate conflicts among different water users [36]. For these reasons, integrated water resources management, analyzing conflicting aspects from multiple perspectives, is strongly required in the Alps [17]. Furthermore, all relevant stakeholders should be involved in decision-making, allowing enough time for mutual understanding of problems, in order to solve water-related conflicts and achieve decisions that ensure environmental protection [38]. A methodological approach that has been widely used to support decision-making problems concerning water resources management is MCDM, as demonstrated in Chapter 2.

In Aosta Valley, where water withdrawals have dramatically increased over the last century, especially for HP production [50], an experimental approach based on the application of MADM is being used to assess their sustainability. The decision-making process involves the main concerned stakeholders for the definition of the ecological flows to be released by withdrawals. The procedure has been formally included in the regional River Strategic Plan (*Piano di Tutela delle Acque* – PTA) [52] and is being applied to several case studies in the region.

Different criteria are considered in the MADM framework, corresponding to the main water users' stakes, quantified by sub-criteria (hereafter named "indicators") based on the watercourse discharge. The criterion "Environment" was initially quantified by biological indicators derived from European legislation, i.e., the Water Framework Directive (WFD) [26]. However, several studies have demonstrated that, although biology in general is strongly affected by hydromorphological pressures, most of the WFD methods developed for the assessment of biological quality elements are either insensitive to main hydrological alterations (e.g., [28, 196, 197]) or respond to a variety of pressures whose individual contribution may be difficult to isolate. For example, the alteration of fish community composition can be associated with a hydromorphological alteration but also with massive restocking, angling, or introduction of alien species [29].

To overcome the above limitations, the MesoHABSIM (Mesohabitat Simulation Model) methodology [32, 33] can be used to assess the effects of water withdrawals on river ecosystems. This meso-scale habitat model quantifies fish habitat availability based on the flow rate and local morphological conditions of the river. In Italy, it is currently proposed by the High Institute for Environmental Protection and Research (ISPRA – *Istituto Superiore per la Protezione e Ricerca Ambientale*) as a reference to evaluate and model the aquatic habitat in rivers. Therefore, in the decision-making procedure developed in Aosta Valley, indexes based on MesoHABSIM have been introduced in the MADM framework, replacing the previous WFD biological indicators.

The aim of this Chapter is to present the methodological approach used in Aosta Valley to support decision-making processes concerning the assessment of water withdrawals. In particular, the integration of the MesoHABSIM model into the MADM framework is described, focusing on the use of MesoHABSIM indexes, instead of WFD biological indicators, to quantify the impacts of withdrawals on river ecosystems and fish communities. The effectiveness of the resulting MADM procedure is analyzed by illustrating and discussing its first implementation in a real case study, involving a single HP plant.

The Chapter is organized as follows: the decision-making procedure developed in Aosta Valley and the MesoHABSIM methodology are described in section 3.2, presenting the criteria and indicators usually considered and explaining how the MesoHABSIM indexes have replaced the previous WFD biological indicators in the MADM framework. In section 3.3, the application of the MADM procedure to a simple case study of hydropower management is illustrated, describing the considered alternatives (i.e., different schemes of ecological flows) and the steps that led to the final decision. A discussion about the main strengths and some weaknesses of the procedure is also included in this section. Finally, some concluding remarks are presented in section 3.4.

3.2 Multi-criteria decision-making and MesoHABSIM in Aosta Valley

To comply with the requirements of the European Water Framework Directive [26] about the maintenance of the hydraulic and ecological continuity of rivers, Italian norms impose the release of a minimum instream flow (MIF) for any surface water withdrawal. The rules for the definition of the MIF are determined locally by the Regional Authority [198].

In Aosta Valley, according to the regional River Strategic Plan (PTA) approved in 2006 [52], the MIF can be quantified through an experimental approach based on MADM. This approach is currently used to define the “ecological flows”, a concept that, as explained in Chapter 1, includes, in addition to the MIF, also the variation of flow over time [17]. The decision-making process is based on the collaboration among different stakeholders, who are involved throughout every step of the method implementation. The aim is to define a participatory framework where the stakes of different water users are taken into account.

3.2.1 MCDM approach for the assessment of water withdrawals

The first step of the decision-making process adopted in Aosta Valley for the assessment of water withdrawal sustainability concerns the official involvement of key stakeholders, representing the main concerned water uses. For this purpose, the Regional Water Authority (*Regione Autonoma Valle d'Aosta – Gestione Demanio Idrico*), coordinating the procedure, institutes a "Technical Assessment Board" (TAB). The TAB includes, in addition to the applicants (usually, members of an HP company) asking for the release or renewal of a water withdrawal license, the representatives of different regional technical bodies, i.e.:

- Regional Agency for the Protection of the Environment (*ARPA Valle d'Aosta*),
- Regional Fisheries Consortium (*Consorzio Pesca*),
- Regional Landscape Protection Service,
- Regional environmental assessment and air quality protection Service, and
- Regional flora, fauna, hunting and fishing Service.

The TAB defines a hydrological monitoring program, which is implemented by the applicants over the whole decision-making process, to provide a reliable and updated flow data series. For this purpose, a continuous monitoring system is generally installed at the withdrawal dam. Usually, at least five years of data are required.

After this preparatory phase, the MADM model is defined, identifying suitable criteria and indicators. A set of alternatives to be evaluated is also developed, generally corresponding to different scenarios of flow release from the withdrawal dam. The initial set of alternatives often includes, in addition to the "reference alternative" (i.e., corresponding to the present situation), some release scenarios proposed by single members of the TAB and oriented at the maximization of their specific interests.

The normalized scores of the alternatives towards the different indicators are then calculated, in order to fill in the decision matrix. Furthermore, a set of weights has to be allocated to criteria and indicators. Usually, for a preliminary evaluation, equal weights are assigned to all the criteria (mean weight method, see Appendix A), whereas the weights of indicators within the same family (i.e., associated with the same criterion) are defined by the members of the TAB (direct rating method).

Once a first ranking of the alternatives is obtained, sensitivity analyses are performed. Based on these results, the initial set of alternatives is refined by including some halfway scenarios, agreed by the involved stakeholders. Moreover, a final set of weights is defined for criteria through direct rating, taking into account the opinions of the different actors and based on arguments that can be explained to external observers and policy-makers.

The final ranking of the alternatives is thus obtained. Based on these results, the alternative that represents the best mediation scenario, supporting the interests of the different concerned actors, is identified by the members of the TAB. Finally, the results of the decision-making process are submitted to the Regional Government for official approval and the selected alternative is implemented in the affected watercourse.

Overall, when discharge data for the considered watercourse are not available before the beginning of the decision-making process, this will take a minimum of five years, necessary to collect a reliable flow data series. During this period, the members of the TAB are actively involved throughout the procedure, which is based on several meetings, discussions, and continuous refinement of the MADM model (e.g., the definition of alternatives, the weighting procedure, etc.). Furthermore, hydrological monitoring is also implemented after the conclusion of the decision-making process, for a total of at least 15 years [199, 29]. If there are significant variations in the watercourse hydrological regime, the ecological flow values should be revised based on the analysis of the collected discharge data. Moreover, the monitoring system also supports direct controls carried out by the Regional Water Authority to verify the compliance of water withdrawal with the license.

MADM method used in Aosta Valley: SHARE MCA

The MADM method usually adopted in Aosta Valley is SHARE MCA [200]. It is a method based on *value measurement* which, similarly to AHP (see Appendix B), requires the definition of a hierarchical structure for the problem. The goal is at the top level and each criterion is detailed by one or more indicators, providing quantitative information about the effects of different alternatives. This hierarchical structure is often named “decision tree”, where criteria and indicators represent the “branches” and the “leaves”, respectively [16].

To normalize the scores of indicators characterized by different measurement units, SHARE MCA requires the definition of a mathematical function for each indicator, transforming the initial scores into dimensionless values varying between 0 and 1 [16]. The normalization functions for new indicators are usually built by the group of experts involved in the decision-making process, based on their expert judgment.

Moreover, the assignment of weights is carried out as described in section 2.2.3 (see Figure 2.3), i.e., starting with the allocation of relative weights within families of criteria at the different levels of the decision tree (namely, the main criteria and each group of indicators having the same parent criterion). The weights within each family are normalized [3]. Generally, in SHARE MCA, weight assignment for each group of indicators is carried out by experts of the corresponding sector, while the allocation of weights to criteria is usually a political phase [16]. Finally, the cumulative weight of each bottom-level indicator is calculated by multiplying its relative weight by the relative weights of its parents.

For each alternative, the method calculates the overall performance score $P(A_i)$ based on a weighted sum:

$$P(A_i) = \sum_{k=1}^{l} w_h \cdot r_{ik} \tag{3.1}$$

where l is the number of bottom-level indicators $I = \{I_h | h = 1, \ldots, l\}$, w_h is the cumulative weight of each indicator, and r_{ik} is the normalized score of alternative A_i with respect to criterion j.

The preferred alternative, for a maximization problem, corresponds to the highest performance value $P(A_i)$. The calculations of SHARE MCA were initially performed by means of the *SESAMO SHARE* software [200]. More recently, an online platform has been developed [201]. It directly calculates the overall performance score of each alternative, based on the normalization functions and the relative weights introduced by the user, graphically representing the ranking of alternatives. Moreover, it also provides a user-friendly tool for the implementation of sensitivity analysis: an

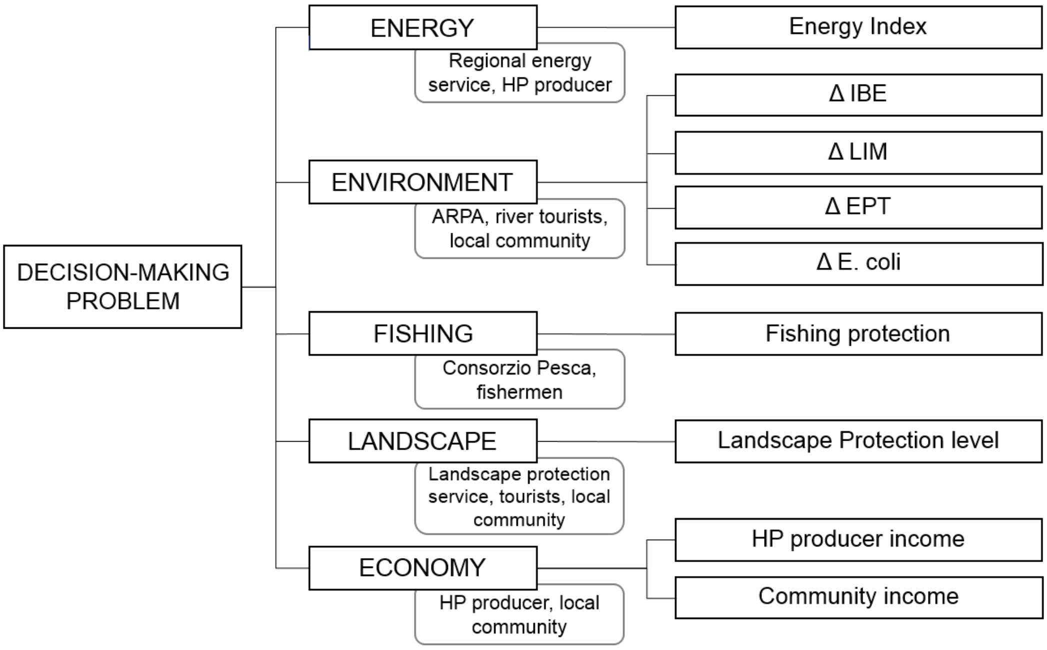


Fig. 3.1 Initial decision tree adopted in Aosta Valley for the assessment of water withdrawal sustainability. For each criterion (in capital letters), the corresponding stakeholders and the indicators (on the right) are shown (Δ = difference between the quality status upstream and downstream of the withdrawal point; IBE = Extended Biotic Index; LIM = Pollution Level of the Macro-descriptors; EPT = Ephemeroptera, Plecoptera, Tricoptera Richness Index; E. coli = Escherichia coli) (from [1])

interactive approach allows the user to visualize the effects of weight variations on the ranking of alternatives.

3.2.2 Criteria and indicators: the initial decision tree

Five criteria were initially considered in the first test applications of the experimental approach in Aosta Valley (since 2009) to assess the sustainability of hydropower diversions. The criteria, i.e., Energy, Environment, Fishing, Landscape, and Economy, were selected because they represent the interests of the main concerned water users.

The decision tree initially considered in Aosta Valley is shown in Figure 3.1. Next to each criterion, the corresponding stakeholders are indicated. Moreover, the figure shows the initial set of indicators considered in the first test case studies.

The indicator Energy Index, associated with the Energy criterion, quantifies the production losses due to the flow releases. For the Fishing criterion, the indicator

Fish and fishing activities protection was defined. It is a hydromorphological proxy indicator, essentially based on expert judgment, assessing the conditions of fish in the watercourse stretch affected by the withdrawal. The indicator Landscape Protection Level, associated with the Landscape criterion, assesses the effects of different flow releases on the river landscape. On the contrary, for the Economy criterion, the indicators HP producer income and Community income were considered: they represent the economic income of the HP company and the income of the local community, respectively, due to the HP plant according to the withdrawn water.

Finally, four indicators were selected to quantify the Environment criterion. Indicators required by the regional environmental regulations, based on the same WFD macro-descriptors, were considered. They are used to assess the effects of water withdrawal on the chemical, physical, microbiological, and biological quality status of the watercourse. Their score is calculated as a difference (Δ) between the quality status upstream and downstream of the withdrawal point. The initial environmental indicators are [200]:

- Δ IBE (Extended Biotic Index): it evaluates the quality status of a watercourse stretch by analyzing the changes in the structure of the communities of benthic macroinvertebrates living in contact with the substrate of the riverbed;
- Δ LIM (Pollution Level of the Macro-descriptors): it describes water quality by evaluating the degree of pollution caused by chemical and microbiological factors. Different parameters are considered, e.g., Dissolved Oxygen (DO), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD_5), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), total phosphorus (P), and *Escherichia coli*;
- Δ EPT (Ephemeroptera, Plecoptera, Tricoptera Richness Index): it estimates water quality based on the variation of the relative abundance of three Orders of river insects, i.e., *Ephemeroptera*, *Plecoptera*, and *Tricoptera*;
- Δ E. coli (Escherichia coli): it assesses water quality based on changes in the concentration of *Escherichia coli* colonies caused by an alteration of the flow rate and load of pollutants deriving from an organic source. It is extracted from the metrics used to calculate the LIM index because it is more sensitive to variations in the concentration of organic matter in the regional hydrographic network.

However, different studies and literature reviews have demonstrated that the WFD biological indicators are not always suitable to quantify the impacts of water withdrawal on the hydromomorphology (e.g., [28, 196, 197]). Several applications in Aosta Valley have also shown that the initial indicators do not respond reliably to variations of flow release alternatives, thus increasing the level of uncertainty in the MADM process. Moreover, classifying a watercourse affected by important hydrological pressures using only biological methods that are not sufficiently sensitive to hydrological alterations may overestimate their ecological status, thus contravening the WFD requirements [29]. The European Guidance on ecological flows [29] invites the Member States to provide suitable metrics, more sensitive to hydrological pressures, "*taking into account the relationship between hydrology, morphology and the biological impacts*".

For these reasons, in Aosta Valley, the application of the MesoHABSIM methodology was considered an efficient alternative to the use of the WFD biological indicators for the quantification of the Environment criterion. Furthermore, since also the indicator initially associated with the Fishing criterion, essentially based on expert judgment, was not sufficiently reliable, the index derived from MesoHABSIM application was adopted to quantify both the criteria Environment and Fishing (as described below, in section 3.2.4). Nevertheless, the environmental quality indexes required by the European WFD are monitored over the decision-making process to ensure at least a good ecological status of the considered watercourse.

3.2.3 MesoHABSIM methodology

The use of a spatial unit of physical habitat suitable for an aquatic community is an accurate metric for the analysis of river restoration actions [33] and instream habitat management in applications like hydropower and water withdrawal mitigation [202]. Therefore, modeling the spatio-temporal variation of physical habitat characteristics (e.g., water depth, flow velocity distribution, substrate composition, etc.) can be used to predict the distribution and abundance of aquatic species, assess environmental flows, and plan river restoration measures [203].

In recent years, the use of mesohabitat scale and multivariate habitat suitability models (e.g., MesoHABSIM) has increased, overcoming the traditional habitat models (e.g., PHABSIM [204]). In fact, in addition to local hydraulic variables, other environmental conditions around the organisms (e.g., cover availability, water temperature, riverbank characteristics, and biotic interactions) are important in habitat assessment since they significantly affect habitat use [203]. Moreover, methods like MesoHABSIM, which do not require the use of hydraulic models, can be applied also to steep streams or watercourses characterized by a complex morphology [12].

The official guidelines of the MesoHABSIM methodology, integrated with the Geomorphic Units survey and classification System (GUS) [205] and adapted to the Italian context [206, 24], are described in Vezza et al. [12]. According to these guidelines, MesoHABSIM has been recognized as a suitable method to assess spatio-temporal alterations of habitat structure in Italian rivers and streams [12]. The methodology is based on the following main steps.

1. Description of the river habitat: it is carried out in a representative portion of the river stretch, characterized by the same spatial distribution and relative proportion of typical morphological units as the entire stretch [205]. The reach is divided into different hydromorphological units (HMUs), which define the mesohabitat types [202]. A set of environmental descriptors (e.g., depth, velocity, average slope, substrate) is also collected for the characterization of the HMUs. The survey has to be repeated under different flow conditions typical of the hydrological regime of the analyzed watercourse. At least three surveys are necessary to describe the habitat changes according to the flow rate variations, but a higher number of surveys is usually recommended [12].

2. Application of biological models of habitat suitability: multivariate statistical models, like *Random Forests* (RF) [207], generated under reference conditions, provide habitat suitability criteria related to the environmental descriptors for different target species and life stages. In mountain watercourses, the biological component is represented by the reference fish community, whose composition can be extrapolated from existing institutional databases [25]. In the MesoHABSIM methodology, RF is used to identify the parameters that most influence the presence and abundance of each analyzed species and life stage, in order to classify each HMU as "suitable mesohabitat" (probability of presence > 0.5) or "optimal mesohabitat" (probability of abundance > 0.5) [12].

3. Analysis of the river habitat spatio-temporal variations: hydromorphological surveys and habitat suitability models are the basis for the development of **habitat-flow rating curves**, which relate the watercourse flow rate with the area of available habitat for each target species and life stage [25] (see Figure 3.2). The total available habitat in the analyzed watercourse section (H_d) is calculated through the following equation:

$$H_d = H_I \cdot 0.25 + H_O \cdot 0.75 \tag{3.2}$$

where H_I and H_O represent, respectively, the habitat classified as suitable and optimal [32]. Furthermore, the **habitat time series**, representing the variation of available habitat over time, are defined. In particular, the available habitat at time t ($H_d(t)$) is calculated through the following equation:

$$H_d(t) = H(Q(t)) \tag{3.3}$$

where H is the habitat-flow rating curve for a particular species and life stage, and $Q(t)$ is the flow measured in the watercourse at time t [12].

Two habitat indexes are calculated from the habitat time series and applied to assess the habitat integrity for fish when anthropogenic pressures are present in the watercourse [12]. The **Index of Spatial Habitat availability (ISH)** assesses the loss of the average amount of habitat surface due to a particular pressure. It is calculated, for each fish species and life stage, by comparing the average available area over the considered period (in m^2 or % of the total wetted area) in reference hydromorphological conditions ($A_{Hd,r}$), i.e., with no withdrawals (or upstream of the withdrawal dam), and in altered conditions (A_{Hd}), i.e., downstream of the withdrawal dam (Figure 3.3). The ISH value for the entire fish community is then defined as the minimum value among all the target species (and life stages) in the considered watercourse section (Eq. 3.4):

$$ISH = \min\left(\begin{cases} 1 - \frac{|A_{Hd,r} - A_{Hd}|}{A_{Hd,r}}, & \text{if } \frac{|A_{Hd,r} - A_{Hd}|}{A_{Hd,r}} \leq 1 \\ 0, & \text{if } \frac{|A_{Hd,r} - A_{Hd}|}{A_{Hd,r}} > 1 \end{cases}\right)_{species} \tag{3.4}$$

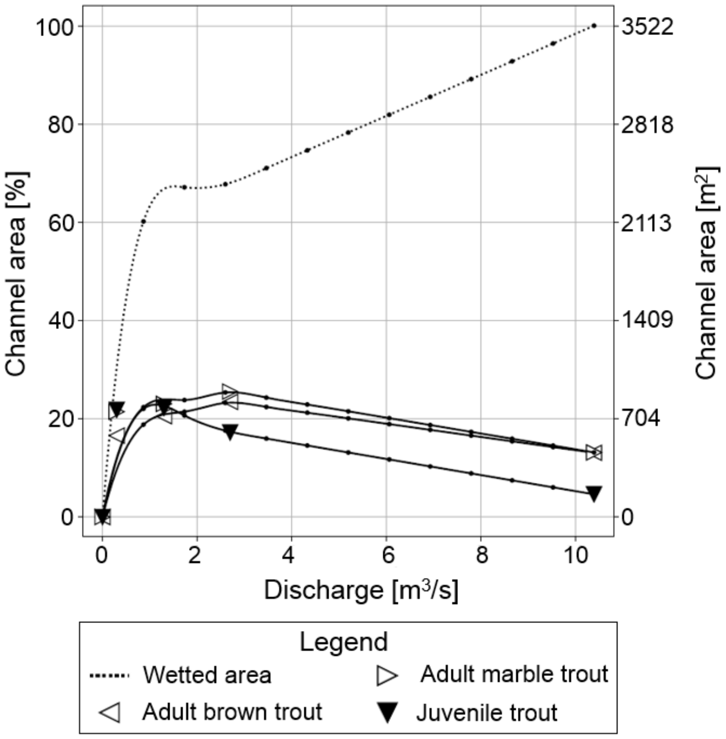
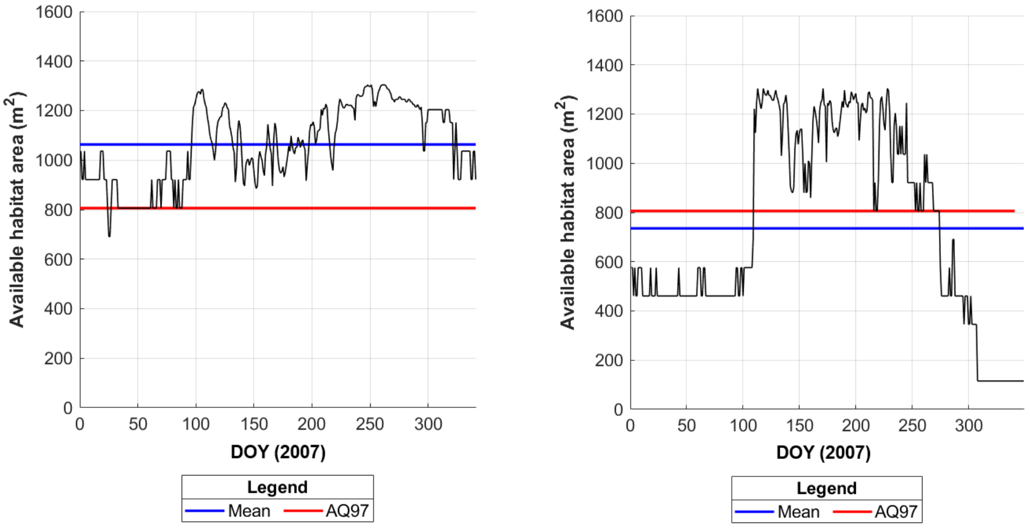


Fig. 3.2 Example of habitat-flow rating curves obtained through the MesoHABSIM methodology for the Savara stream (Aosta Valley, Italy). Excluding the dotted curve (which represents the total wetted area), each curve refers to a different species and life stage (i.e., adult brown trout, adult marble trout, and juvenile trout). The symbols on the curves (changing according to the species) correspond to the discharge values recorded during the surveys (i.e., in this case, 0.3, 1.3, 2.7, 10.4 m^3/s). The percentage values shown on the left y-axis represent the available habitat compared to the total wetted area corresponding to the maximum flow rate measured during the surveys (i.e., 10.4 m^3/s)

The **Index of Temporal Habitat availability (ITH)** assesses the variation of the continuous duration of stress events for the fauna between reference and altered conditions. The duration of stress events is calculated as the number of days in which the available habitat is below a given threshold. The ITH defines the reference habitat threshold as the amount of habitat corresponding, under unaltered conditions, to Q_{97}, i.e., the flow value exceeded 97% of the time (Figure 3.3). This threshold is named A_{Q97} [203, 12].

To calculate the ITH, habitat time series are statistically analyzed using the Uniform Continuous-Under-Threshold (UCUT) curves [202]. The average distance between two UCUT curves, representing the cumulative duration of habitat under-threshold events in reference conditions ($d_{c,r,AQ_{97}}$) and in altered conditions ($d_{c,AQ_{97}}$),



(a) Reference conditions

(b) Altered conditions

Fig. 3.3 Comparison between habitat time series for reference and altered conditions, for the adult brown trout, in the Savara stream (Aosta Valley, Italy). The considered period is January–December 2007. The available habitat area (m^2) is shown on the y-axis. The blue line represents the average value of habitat availability in the considered period, used for the ISH calculation, while the red line indicates the minimum habitat threshold during low flows (A_{Q97}) in reference conditions, used for the ITH calculation (from [1])

is used to evaluate the alteration in the duration of stress events for each considered species through the indicator of Stress Days Alteration (SDA) [203]:

$$SDA = \frac{1}{d_{max,r}} \cdot \sum_{k=1}^{d_{max,r}} \left(\frac{\left| d_{c,AQ_{97}} - d_{c,r,AQ_{97}} \right|}{d_{c,r,AQ_{97}}} \right) \tag{3.5}$$

where $d_{max,r}$ is the maximum under-threshold duration in reference conditions (in days).

The ITH for each species (and life stage) is obtained by means of a negative exponential function (Eq. 3.6), which transforms the SDA indicator into the ITH index (varying between 0 and 1). The ITH value for the entire community is given by the minimum value among all the target species [203, 12].

$$ITH = \min\left(e^{-0.38 \cdot SDA}\right)_{species} \tag{3.6}$$

Table 3.1 Classes of habitat integrity according to the Index of river Habitat integrity (IH) (from [12])

IH	Class
$0.8 \leq \text{IH} \leq 1$	High
$0.6 \leq \text{IH} < 0.8$	Good
$0.4 \leq \text{IH} < 0.6$	Moderate
$0.2 \leq \text{IH} < 0.4$	Poor
$0 \leq \text{IH} < 0.2$	Bad

The scores of the ISH and ITH indexes are used to obtain the Index of river Habitat integrity (IH), which is calculated through the following equation:

$$IH = \min(ISH,\ ITH) \tag{3.7}$$

The IH score ranges between 0 and 1, where 0 represents a very high degree of alteration of the watercourse habitat quality, whereas 1 corresponds to a condition with no hydromorphological alterations (i.e., where the habitat quality is the same as the reference condition). In accordance with the approach used in the European WFD, the habitat integrity is defined in five classes of quality, as shown in Table 3.1. The threshold values defining the division between the different classes have been determined based on the results of simulations in several case studies for which habitat time series of at least 15 years were available. The natural variability (i.e., under reference conditions) of the ISH and ITH indexes was observed for this purpose [12].

3.2.4 Inclusion of the IH index in the final MADM decision tree

Over the years, the initial indicators considered in the MADM model in Aosta Valley have been repeatedly refined in order to increase their reactiveness and the representativeness of the corresponding stakeholders' needs. In particular, the limitations of the indicators previously associated with the criteria Environment and Fishing (see section 3.2.2) highlighted the necessity to replace these indicators with other metrics, directly related to the variation of the watercourse discharge. Due to the positive results of the MesoHABSIM application during its adaptation to the Italian context, especially in mountain watercourses (e.g., [25, 24]), and the experience gained from its use in different sites along the Aosta Valley streams, the Index of river Habitat integrity (IH) was identified as the most suitable metric for this purpose. This decision was further supported by the publication of the national official guidelines on the MesoHABSIM methodology [12].

The IH index allows assessing the effects of water withdrawal on fish population and river environment. From the initial applications of MesoHABSIM in Aosta Valley, this index proved to be suitable to represent the stakes related to both the criteria Environment and Fishing. Thus, it was introduced in the MADM decision tree, merging the two previous criteria into a single criterion, named "Environment & fishing".

The IH indicator was aligned to the other indicators considered in the MADM model by completing a common description form, which contains all the information characterizing the indicator (e.g., name, description, method of elaboration, normalization function, normative references, etc.). A linear normalization function $y = x$ was also defined for the new indicator (see Figure 3.6b). Moreover, a threshold is considered for IH, since its score should remain in the "high" or "good" classes to comply with the normative requirements. Hence, for the final decision, the members of the TAB usually immediately exclude the alternatives with $IH < 0.6$, i.e., not achieving the environmental protection objective identified in the regional planning.

The new MADM decision tree used in Aosta Valley for the assessment of water withdrawal sustainability is represented in Figure 3.4. In addition to the introduction of the IH indicator (highlighted in red in the figure), other indicators were also modified and improved compared to the initial decision tree. All the final indicators comply with the following requirements [16]:

- alignment with the normative framework;
- effective reactiveness, i.e., causal relationship between the indicator and different alternatives;
- representativeness of the related stakeholders' needs and interests;
- compliance with the specific context and scale;
- solidity and transparency of the elaboration technique and availability of the dataset.

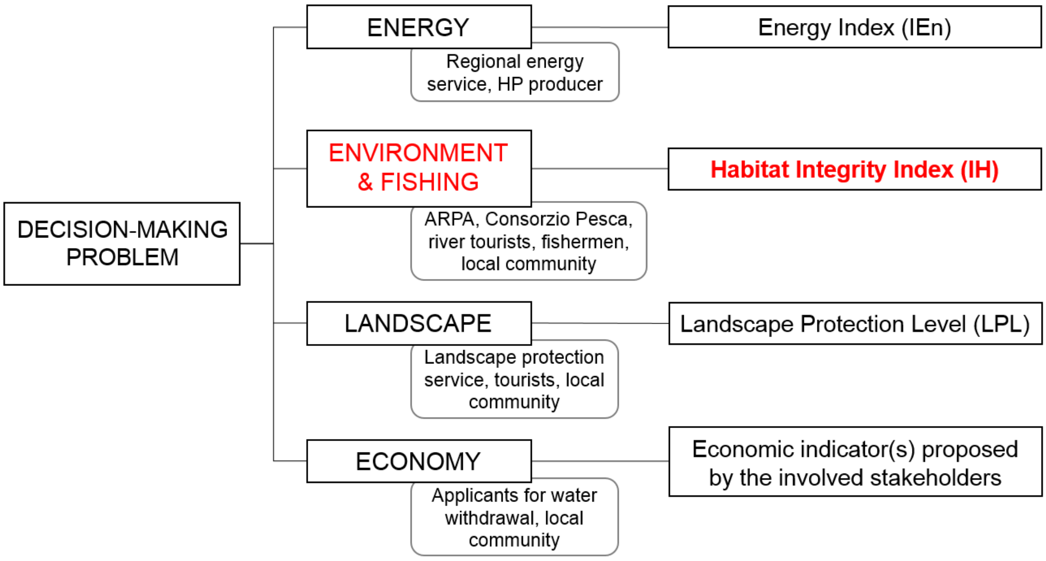


Fig. 3.4 Final decision tree adopted in Aosta Valley for the assessment of water withdrawal sustainability. Compared to the previous decision tree (shown in Figure 3.1), the IH indicator has been introduced, associated with the Environment & fishing criterion (highlighted in red). The other indicators have also been refined over the years (adapted from [1])

Furthermore, all the indicators are directly related to the watercourse discharge, which is the key element of the whole decision-making process. In particular, for the calculation of the IH index, daily discharge data must be measured both upstream and downstream of the withdrawal point for a period of at least five years. This necessity to collect reliable flow data series will require, if it is not already present, the installation of a hydrological monitoring system at the beginning of the decision-making process, as explained in section 3.2.1.

It has to be highlighted that, compared to the initial decision tree, which was used in the first test case studies always concerning withdrawals for HP production, the final decision tree illustrated in Figure 3.4 is currently applied to several real case studies, involving also other types of water withdrawals (e.g., for irrigation and snowmaking, as explained in Chapter 6). Therefore, while the criteria Environment & fishing and Landscape are quantified by the same indicators (i.e., IH and Landscape Protection Level, respectively) in all the decision-making processes, one or more economic indicators are usually defined for each specific case study by the related stakeholders involved in the TAB (i.e., the applicants asking for the release or renewal of a water withdrawal license). These indicators take into account the particular features and datasets of the considered case study, thus quantifying in a more reliable way the economic incomes. Furthermore, the Energy criterion is not included in the decision tree when the MADM process does not involve any HP plants (only in few cases). Otherwise, the same energy indicator (i.e., Energy Index) is generally used, considering the specific characteristics of the involved HP plant(s).

A brief description of the set of indicators adopted in the first complete real case study carried out in Aosta Valley is provided in section 3.3.1.

3.3 First application of the updated MADM procedure on a real case study

Some test case studies were carried out in Aosta Valley since 2009, initially considering the decision tree shown in Figure 3.1, to test and improve the experimental approach based on MADM introduced by the regional River Strategic Plan for the assessment of water withdrawal suitability. More recently, the updated procedure has been applied to real case studies, mainly concerning hydropower withdrawals (see also Chapter 6). The first complete decision-making process regarding a real case study, based on the final decision tree shown in Figure 3.4 and including the application of the MesoHABSIM methodology, is presented below.

3.3.1 Case study on the Graines torrent

The case study concerned a small run-of-the-river hydropower plant located in the municipality of Brusson. The affected watercourse is the Graines torrent, a small Alpine watercourse with a watershed surface of about 20 km^2 and a mean annual discharge of less than 1 m^3/s (Figure 3.5).

The HP plant, whose water intake is located at 1479 m a.s.l., has a total head of 125 m and an average annual nominal power of 566 kW. It withdraws a mean annual discharge of 462 l/s. The water license was released in 2010, but, when the HP plant was built, no discharge data were available. Therefore, the MIF was quantified using the hydrological formulation given in the PTA [52], characterized by a high level of inaccuracy, thus causing the interruption of the withdrawal for about 6 months per year. For this reason, in 2012, based on the request of the HP company (Idroelettrica Brusson S.r.l.), the Regional Water Authority decided to

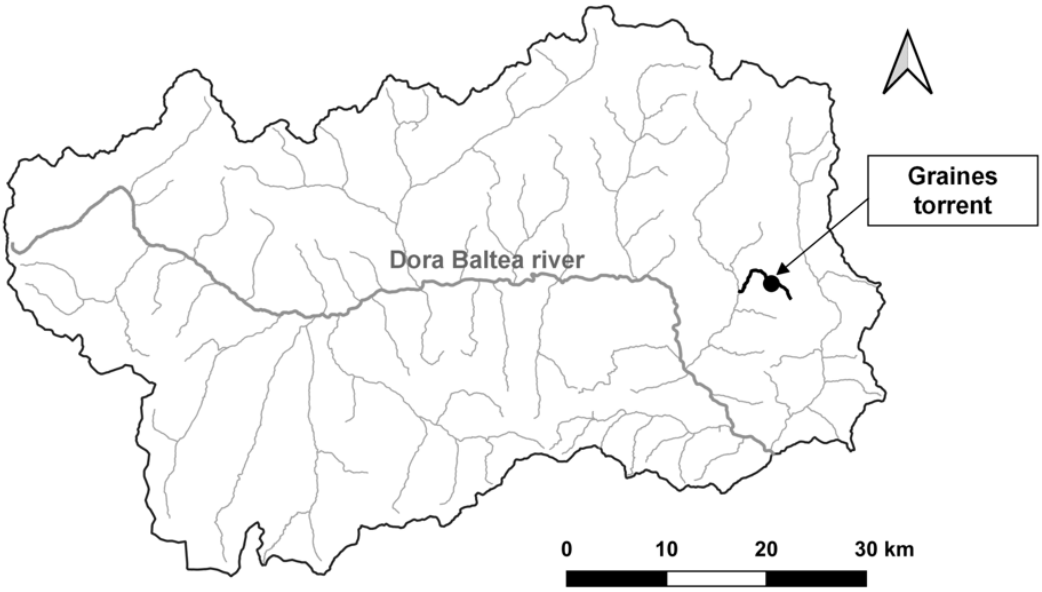


Fig. 3.5 Location of the hydropower plant (highlighted by the dot symbol) on the Graines torrent in Aosta Valley (adapted from [5])

apply the experimental approach based on MADM for the renewal of the HP license. The aim was to identify a new scenario of ecological flows to be released by the HP dam, balancing production needs and the safeguard of environmental conditions in the watercourse.

According to the procedure described in section 3.2.1, key institutional stakeholders were officially involved in the decision-making process, in addition to the members of the HP company, forming a TAB, coordinated by the Regional Water Authority. A total of 31 TAB meetings were organized over the period 2012–2017, during which the different phases of the decision-making process were carried out and yearly validated. Provisional flow releases from the HP dam, formally endorsed by the TAB, were also yearly defined, based on the progressive results of the process. Moreover, a hydrological monitoring program (ongoing since 2012) was implemented by the HP company. Hence, a continuous monitoring system was installed at the dam, with an informative screen showing the real-time values of natural discharge (i.e., watercourse discharge upstream of the dam), flow releases, and energy production.

After the first year of hydrological monitoring, some initial flow release alternatives were defined, in addition to the “reference alternative” (named ALT 0). These scenarios (from ALT 1 to ALT 4, each oriented to a specific stakeholder's interest) usually required the release of ecological flows varying on monthly basis. In the following years, some mediation alternatives (from ALT 5 to ALT 8), agreed by the different stakeholders, were also defined. They were all based on a minimum monthly flow value to be released downstream of the withdrawal dam, incremented by an additional release, varying on an hourly basis, calculated as a percentage (from 12.5% to 30%) of the natural discharge measured upstream. Such alternatives were thus called "real-time alternatives". Overall, a final set of nine scenarios was evaluated by means of MADM (the specific flow release values are shown in Table 3.2):

- ALT 0: it is the "reference alternative", characterized by fixed monthly values quantified through the hydrological formulation defined in the regional River Strategic Plan;
- ALT 1: it is based on a fixed flow release throughout the year. It was proposed by the HP company;
- ALT 2: it is characterized by fixed monthly values defined according to the results of the MesoHABSIM application on the Graines torrent. It was proposed by the Regional Fisheries Consortium and the Regional Agency for the Protection of the Environment;
- ALT 3: it is characterized by real-time flow releases, with higher values in July, August, and September. It was proposed by the Regional Landscape Protection Service, based on landscape protection goals;
- ALT 4: it is a modified version of ALT 3, proposed by the Regional Landscape Protection Service;
- ALT 5, ALT 6, ALT 7, and ALT 8: they are real-time alternatives, agreed by the different members of the TAB, defined in the second part of the decision-making process as mediation alternatives.

The MADM decision tree is represented in Figure 3.4, while the indicators considered in the case study are briefly described below. They were defined and/or reviewed during the decision-making process as a result of the work and collaboration of all the members of the TAB.

Table 3.2 Monthly values of the ecological flow releases (l/s) according to the nine alternatives considered in the Graines case study. The percentage values represent a percentage of the watercourse discharge measured upstream of the withdrawal point, while the other numerical values are the fixed flow rates in l/s defined by the involved stakeholders. The month of June was divided into two halves for ALT 4, due to the high variability of the watercourse discharge (from [5])

	ALT 0	ALT 1	ALT 2	ALT 3	ALT 4	ALT 5	ALT 6	ALT 7	ALT 8
January	90	100	70	70+15%	70+12.5%	70+12.5%	70+15%	70+20%	70+30%
February	90	100	70	70+15%	70+12.5%	70+12.5%	70+15%	70+20%	70+30%
March	90	100	70	70+15%	70+12.5%	70+12.5%	70+15%	70+20%	70+30%
April	135	100	100	70+30%	70+17%	70+12.5%	70+15%	70+20%	70+30%
May	250	100	250	70+25%	70+18%	70+12.5%	70+15%	70+20%	70+30%
June 1	450	100	300	70+35%	70+18%	70+12.5%	70+15%	70+20%	70+30%
June 2					70+25%				
July	360	100	300	250+20%	300	70+12.5%	70+15%	70+20%	70+30%
August	260	100	250	250+30%	250	70+12.5%	70+15%	70+20%	70+30%
September	180	100	100	100+20%	100	70+12.5%	70+15%	70+20%	70+30%
October	135	100	100	70+30%	70+15%	70+12.5%	70+15%	70+20%	70+30%
November	135	100	100	70+15%	70+12.5%	70+12.5%	70+15%	70+20%	70+30%
December	90	100	70	70+15%	70+12.5%	70+12.5%	70+15%	70+20%	70+30%

The Energy Index (IEn) quantifies the losses of HP production due to the flow releases. Its score varies between 0 and 1. It is calculated through the following equation:

$$IEn = E_i / E_0 \tag{3.8}$$

where E_i is the energy produced by applying the i-th alternative (kWh) and E_0 is the energy production calculated according to the average annual nominal power of the HP plant (kWh).

The Index of river Habitat integrity (IH), which assesses the effects of HP withdrawal on fish population and river environment, is presented in section 3.2.3.

The Landscape Protection Level (LPL) assesses how the river landscape perception changes according to flow releases. Its score ranges between 0 and 165. It is calculated by Eq. 3.9:

$$LPL = CF + RF + VEF \tag{3.9}$$

where CF is the Constraint Factor, RF is the Release Factor, and VEF is the Visual Elements Factor. More information about this indicator, which was concerned by extensive modifications in recent years, is provided in Chapter 4, where its application to some real case studies is also presented.

The Economy criterion was further divided into two sub-criteria, representing the economic income of the HP company and the income of the local community (related to services and fees provided by the HP company according to national and regional rules), respectively. The sub-criteria are quantified by different indicators, all varying between 0 and 1.

The Economic Index (IEc) quantifies the economic losses due to water flow releases. It is calculated through the following equation:

$$IEc = \frac{E_i \cdot €_{en} - C_i}{E_0 \cdot €_{en} - C_0} \tag{3.10}$$

where E_i is the energy produced by applying the i-th alternative (kWh), E_0 is the energy production according to the average annual nominal power of the HP plant (kWh), $€_{en}$ is the energy sale price (€/kWh), while C_i and C_0 represent the HP plant management and maintenance costs related to the i-th alternative and to E_0, respectively (€).

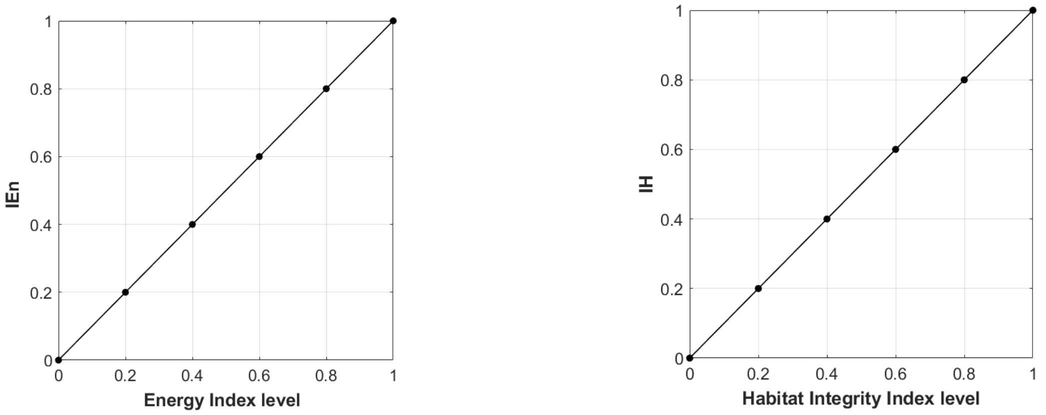
The indicator Services for the community (RCS) estimates the quality and number of services offered by the HP company to the community living in the area affected by the withdrawal (e.g., maintenance of hydraulic works and routes in the area). The indicator is based on an ordinal scale of five classes, corresponding to the following scores: 0.2, 0.4, 0.6, 0.8, and 1. The scores are assigned considering that a higher income for the HP company is usually associated with a larger number of services offered to the local community.

Finally, Financial income for the community (RC) 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 HP production and trade. Therefore, the score of the indicator is calculated based on the Economic Index, according to Eq. 3.11:

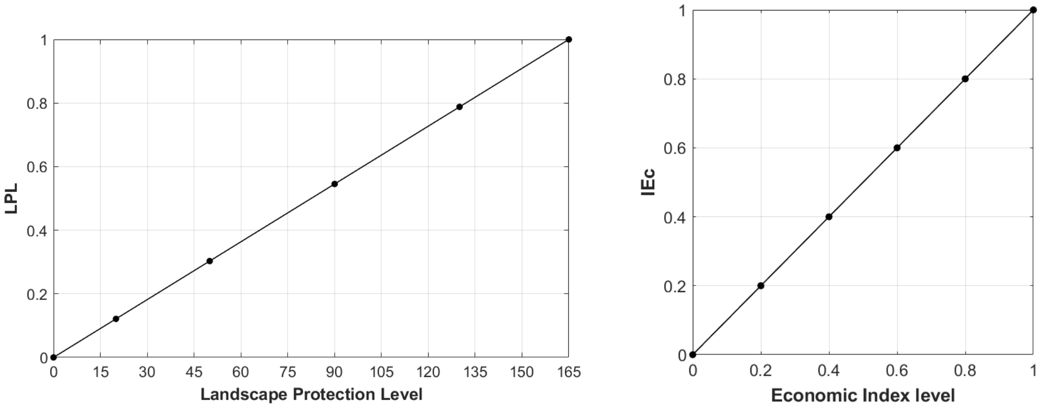
$$RC = IEc^2 \tag{3.11}$$

The normalization functions associated with the considered indicators are illustrated in Figure 3.6. The functions of the indicators RCS and RC are not represented because RCS is based on an ordinal scale already varying between 0 and 1, while RC is directly derived from the IEc values. The normalized decision matrix, containing the normalized scores of the alternatives with respect to each indicator, is shown in Table 3.3.

For a preliminary assessment, the initial results of SHARE MCA were obtained by assigning equal weights to the four criteria (i.e., 0.25 each). As concerns the indicators, weights were allocated first to the two economic sub-criteria, i.e., 0.10 to HP producer income and 0.90 to Community income. The reason was that watercourses are public resources which must be protected for the whole community. Afterward, the weights of the two indicators associated with the sub-criterion Community income were determined, i.e., 0.05 for RCS and 0.95 for RC. The significantly higher preference assigned to the RC indicator underlined the importance of economic incomes for local municipalities. Finally, a relative weight equal to 1 was allocated to the other indicators since the corresponding criteria have only one indicator each.



(a) Energy Index (IEn) (b) Habitat Integrity Index (IH)



(c) Landscape Protection Level (LPL) (d) Economic Index (IEc)

Fig. 3.6 Normalization functions defined for four indicators considered in the final decision tree in Aosta Valley (adapted from [1])

Table 3.3 Normalized decision matrix generated by the *SESAMO SHARE* software for the case study on the Graines torrent (adapted from [5])

	IEn	IH	LPL	IEc	RCS	RC
ALT 0	0.63	0.74	0.596	0.31	0.40	0.10
ALT 1	0.79	0.49	0.202	0.60	0.60	0.36
ALT 2	0.70	0.65	0.522	0.43	0.60	0.19
ALT 3	0.70	0.65	0.597	0.44	0.60	0.19
ALT 4	0.73	0.61	0.493	0.49	0.60	0.24
ALT 5	0.83	0.45	0.238	0.67	0.80	0.46
ALT 6	0.82	0.50	0.243	0.66	0.80	0.44
ALT 7	0.80	0.50	0.293	0.62	0.80	0.39
ALT 8	0.75	0.59	0.403	0.52	0.60	0.27

Table 3.4 Cumulative weights of the bottom-level indicators of the decision tree considered in the Graines case study calculated from the initial (second column) and the final (third column) weight assignment

Indicator	Cumulative weights	
	Initial assignment	Final assignment
IEn	0.25	0.25
IH	0.25	0.30
LPL	0.025	0.015
IEc	0.25	0.25
RCS	0.011	0.007
RC	0.214	0.128

The cumulative weights of the bottom-level indicators resulting from the initial assignment of weights are shown in the second column of Table 3.4.

Furthermore, the ranking of alternatives generated by the *SESAMO SHARE* software based on this initial set of weights is illustrated in Figure 3.7. It can be noticed that the alternative with the highest overall performance score is ALT 3, i.e., the first alternative proposed by the Regional Landscape Protection Service. The alternative with the lowest performance score, on the contrary, is ALT 1, i.e., the fixed release scenario proposed by the HP company.

Sensitivity analysis and final decision

Based on this preliminary ranking of the alternatives, sensitivity analyses were carried out in the second part of the decision-making process to investigate the robustness of the MADM results to changes in the weights assigned to criteria and indicators. In particular, by means of a tool provided by the *SESAMO SHARE* software, MADM calculations were repeated several times, alternatively increasing and decreasing, in each simulation, the initial weight of a criterion or an indicator (consequently, even the other weights proportionally changed, because the weights within each family of criteria and indicators were normalized). The effects of these variations were analyzed, identifying the variations necessary to produce a considerable alteration of the ranking of the alternatives (the modification of the alternative with the highest performance score was mainly considered).

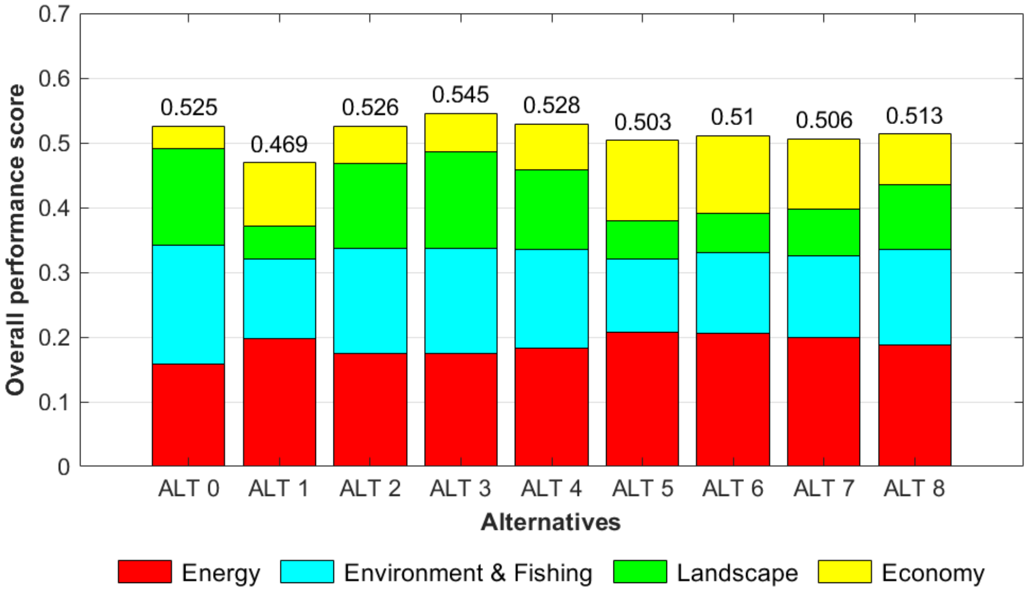


Fig. 3.7 Ranking of alternatives obtained for the case study on the Graines torrent with the initial set of weights. The number at the top of each bar represents the overall performance score of the corresponding alternative (adapted from [5])

The results of sensitivity analyses showed that slight variations of the initial weights did not produce significant changes in the results. In particular, it was noticed that the weights of criteria should be varied by at least 32% (for the Landscape criterion) to modify the alternative with the highest performance score, as shown in Table 3.5. These results confirmed that the MADM results were sufficiently stable and robust.

After this phase, a final set of weights was assigned to the four criteria, i.e., 0.25 to Energy, 0.30 to both Environment & fishing and Landscape, and 0.15 to Economy. These weights were agreed by all the members of the TAB, based on reasons that could be explained to external observers and policy-makers. The higher weight assigned to Environment & fishing was justified by the fact that this criterion represents two stakeholders' interests, i.e., the environmental heritage and the fishing activities affected by the HP plant, and the related sets of laws. Similarly, the higher weight of Landscape was linked to the protection needs of both landscape heritage and tourist activities in the affected area. Finally, to highlight the importance of HP generation as a renewable energy source contributing to the regional, national, and European strategy for the reduction of greenhouse gas emissions, a higher weight was allocated to Energy compared to Economy. On the contrary, the relative weights

Table 3.5 Main results of sensitivity analysis obtained by varying the criteria weights for the Graines case study. The modified weight and the size of the variation of weight necessary to change the alternative with the highest performance score are given in the third and fourth columns, respectively (adapted from [1])

Criterion	Initial weight	Modified weight varying the first-ranked alternative	Size of the initial weight variation
Energy	0.25	0.419 0.552	+68% +121%
Environment & fishing	0.25	0.053 0.387	−79% +55%
Landscape	0.25	0.168	−33%
Economy	0.25	0.060 0.344 0.454	−76% +38% +82%

of the indicators were not modified. The cumulative weights of the bottom-level indicators resulting from this final allocation of weights are given in the third column of Table 3.4.

By considering these weights, the ranking of alternatives represented in Figure 3.8 was obtained. It can be noticed that the first and the last alternatives (i.e., ALT 3 and ALT 1, respectively) are the same as in the initial ranking shown in Figure 3.7. The final performance scores of the alternatives were also similar to the initial results, with a mean variation of about 2.9%.

Based on these results and after several discussions among the members of the TAB, a final decision on the flow release alternative to be adopted was made. As noticed in Figure 3.7, the four best-ranked alternatives (i.e., ALT 0, ALT 2, ALT 3, and ALT 4) have comparable performance scores. Among these alternatives, ALT 4 (although not characterized by the highest performance score) was selected as the best mediation solution, balancing river ecosystem and landscape requirements with HP production needs. This alternative is characterized by higher fixed flow releases in summer months, when the presence of tourists in the area is more relevant. In the other months, on the contrary, a basic release of 70 l/s, incremented by an additional release quantified in real time (from 12.5% to 25% of the natural discharge), is required.

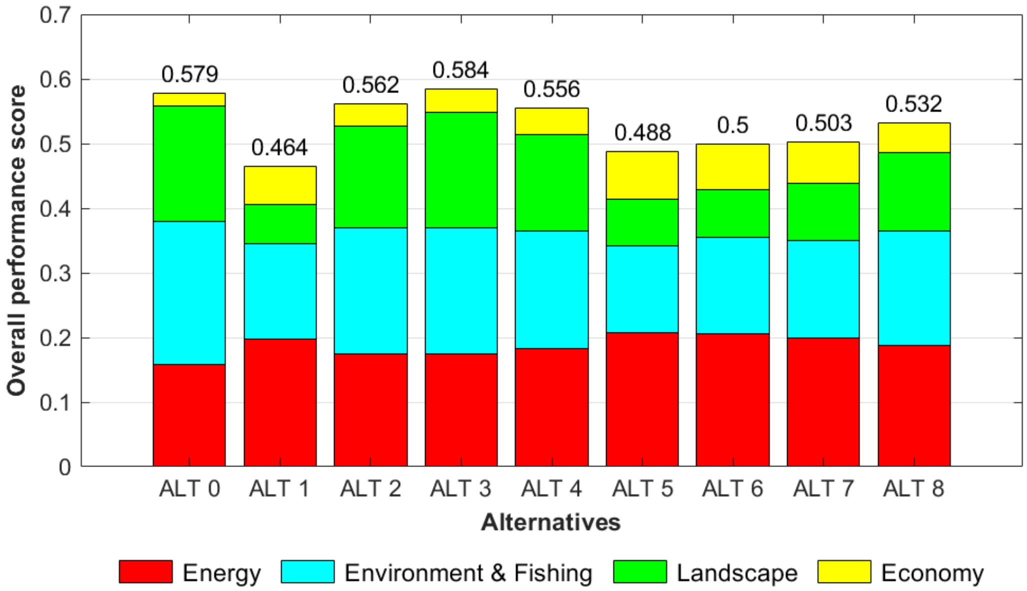


Fig. 3.8 Ranking of alternatives obtained for the Graines case study with the final set of weights. The number at the top of each bar represents the overall performance score of the corresponding alternative (adapted from [5])

In February 2018, the Regional Government ratified the results of the decision-making process, officially approving the flow release alternative selected by the members of the TAB. This alternative is currently implemented downstream of the considered HP plant. Furthermore, in 2018, the nine alternatives were *ex-post* validated, using a larger dataset coming from the ongoing hydrological monitoring program, to test the reliability of the MADM results. According to this analysis, the actual performance scores proved to be very similar to the simulated ones and the ranking of the alternatives did not vary.

3.3.2 Strengths and weaknesses of the methodological approach

Since its first application to the case study on the Graines torrent, the experimental approach developed in Aosta Valley has proven to be a suitable tool to support decision-making processes for water withdrawal assessment. A central characteristic of the proposed methodology is the active involvement of the main concerned stakeholders throughout the decision-making process. Continuous collaboration among the different actors is required, overcoming conflicts through dialogue and discussions, in order to identify a management alternative that best supports the various stakes.

Another important aspect of the methodology is the relevance attributed to the watercourse discharge, which is the main parameter of the process. Indeed, all the indicators included in the final decision tree are directly related to the watercourse discharge, withdrawn and released at the dam. Therefore, the installation of a reliable hydrological monitoring system at the withdrawal dam is required from the beginning of the decision-making process. This system also supports direct controls carried out by the Regional Water Authority to monitor compliance with the water license requirements. Moreover, recent HP plants, like the one located on the Graines torrent, are frequently equipped to implement real-time withdrawal: based on the flow data series measured upstream of the dam, a programmable logic controller determines the opening or closing of the withdrawal devices. Such systems allow the implementation of real-time alternatives, more adapted to water availability than the alternatives based on fixed flow releases. Indeed, real-time alternatives define ecological flows characterized by more natural variability, essential to support the ecological processes of riverine ecosystems [27].

A significant result achieved during the decision-making process concerning the case study on the Graines torrent is the definition of a set of reactive indicators, based on the normative framework (see the final decision tree illustrated in Figure 3.4). In particular, the use of the IH indicator, derived from the MesoHABSIM methodology, to quantify the effects of water withdrawal on river environment and fishing activities has allowed overcoming the limitations of the previous WFD biological indicators. Indeed, these indicators responded to multiple pressures in the river (e.g., presence of wastewater discharge, level of dissolved organic load, type of substrate, etc.), but they were scarcely related to flow release variations, as demonstrated by different local studies carried out in Aosta Valley. Several scientific articles also highlighted that most of the WFD methods are not sensitive to hydrological alterations (e.g., [28]). However, for each water withdrawal license, environmental quality indexes required by the WFD (based on macrozoobenthos, physical, chemical, and microbiological parameters) are systematically monitored along the affected watercourse to also ensure the compliance of flow releases with European regulations. The Graines torrent, for example, results in a “good” ecological status from the analyses implemented in the bypassed stretch.

Moreover, all the indicators considered in the MADM decision tree are suitable for the assessment of ecological flows in a mountain context like the Alpine area, where water withdrawal is a significant pressure. In particular, compared to other habitat models, MesoHABSIM can be applied even to watercourses for which the characteristics of the riverbed do not allow the use of hydraulic simulation models, like steep Alpine streams [12].

All the considered indicators also have explicit normative references, thus ensuring an actual endorsement into administrative practices. As concerns the IH indicator, there is full compliance with two national decrees, i.e., DD 29/2017 [30] and DD 30/2017 [31]. These decrees define new methodological guidelines on water withdrawal planning, monitoring, and assessment in Italy, ensuring the achievement of environmental quality objectives defined by the WFD for surface water bodies.

Furthermore, the operators responsible for the application of the MesoHABSIM methodology are required to attend a training course. The method is based on a rigorous standard ensured by ISPRA, it is reliable and traceable, and it uses open-source software. Moreover, the judgment expressed through the IH index is divided into five classes, in compliance with European legislation. For the final decision, alternatives characterized by an IH value lower than 0.6 are usually excluded since they do not achieve the environmental protection objective identified in the regional planning (i.e., the “good” status class).

However, despite the advantages of the described approach in supporting decision-making processes concerning water withdrawal assessment in Aosta Valley, some weaknesses have been noticed. For example, looking at the decision tree shown in Figure 3.4, a partial redundancy between the criteria Energy and Economy can be observed. In fact, the economic incomes are obviously linked to the energy produced by the considered HP plant. Nevertheless, both the criteria correspond to crucial stakes and thus they cannot be excluded from the MADM decision tree. Indeed, energy return also represents the regional goal of contributing, through renewable energy production, to the national and European objectives for the reduction of greenhouse gas emissions. Economic incomes, on the contrary, represent the interests of both the HP producer(s) and the local community, whose income is related to fees and services provided by the HP company. To reduce this drawback, in the final phase of the decision-making process concerning the Graines torrent, a lower weight was assigned to these two criteria compared to Landscape and Environment & fishing.

However, in future case studies, other economic indicators, less dependent on HP production, should be identified. An additional energy indicator quantifying the HP plant contribution to reducing greenhouse gas emissions should also be included in the decision tree. Some activities are currently ongoing in the Region to achieve these improvements.

Another limitation of the described approach concerns the higher difficulty in explaining the whole procedure, including data collection and processing (e.g., MesoHABSIM application, calculation of other indicators' score, etc.), to administrators and stakeholders without a technical background, compared to other methods for environmental assessment. Actually, the MADM method and the indicators considered in Aosta Valley are based on an informative standard easy to be understood by both engineers and regional technicians. Nevertheless, the assessment procedure may appear much more complex than it usually is for decision-makers. In addition, it is necessary to clearly explain to all the involved actors the strategic importance of hydrological monitoring, which contributes to increasing the transparency and the quality of the decision-making process. Due to this complexity, the possibility to include more stakeholders (e.g., members of the local communities and river landscape users) in the TAB is currently limited.

Finally, as previously underlined, the collection of a reliable and updated flow data series is essential. Therefore, a decision-making process usually covers a period of at least five years, necessary to collect reliable discharge data to be used in the MADM implementation (but the hydrological monitoring also continues after the license release, for a total of at least 15 years [199, 29]). This time extension may appear as a drawback, above all for the stakeholder applying for the release of a water withdrawal license, since the final decision is achieved after a long period. However, during the decision-making process, provisional schemes of instream flow releases, agreed by the members of the TAB, are adopted. Furthermore, based on the satisfying results obtained in the first case studies, also the applicants are acknowledging the advantages of the described procedure, which takes into account the interests of the different concerned stakeholders.

3.4 Concluding remarks

The methodological approach adopted in Aosta Valley represents an innovative procedure supporting decision-making processes for the assessment of water withdrawal sustainability. In particular, MADM is used to identify the most appropriate scheme of ecological flows to be implemented downstream of a withdrawal dam to ensure sustainable river management. The approach is employed in a mountain river network that is currently affected by evident water withdrawal pressures. Indeed, several studies concerning the Alpine area highlighted the need for integrated water resources management, involving relevant stakeholders, to solve water-related problems [17].

The main different interests affected by water withdrawal in Aosta Valley are considered in the MADM decision tree by means of four criteria (i.e., Energy, Environment & fishing, Landscape, and Economy), quantified by measurable indicators related to the watercourse discharge. The MesoHABSIM methodology has been integrated into the described procedure through the Habitat Integrity Index (IH), which is the indicator quantifying the impacts of water withdrawal on fish population and river environment. Compared to the previous biological indicators derived from the European WFD, the IH index proved to be fully reactive to flow releases.

The first complete decision-making process, concerning a real HP plant on the Graines torrent, proved the suitability of the procedure, based on the final decision tree represented in Figure 3.4, for withdrawal assessment. Despite some limitations, in fact, the methodological approach allowed identifying a scenario of ecological flows protecting river ecosystems and landscape, but also satisfying the HP production needs. The selected alternative (varying in real time based on the natural discharge of the watercourse) has been officially endorsed by the Regional Government and it is currently implemented downstream of the considered HP plant.

All the different stakeholders involved in this first decision-making process were satisfied with the achieved results. Moreover, an improvement in the quality of the decision-making process was noticed. For these reasons, the described approach is currently being applied to other real case studies in Aosta Valley, concerning different types of water withdrawals. More information about the decision-making processes concluded and ongoing over the regional territory is provided in Chapter 6.

Chapter 4

Definition of a new indicator quantifying water withdrawal impacts on the downstream river landscape

4.1 Introduction

Part of the work described in this Chapter has been previously published in the paper [6].

Hydropower plants and other water withdrawals have significant effects on mountainous areas, altering natural habitats and characteristic landscapes [22, 23]. Since the remaining pristine river stretches have become increasingly rare in the Alps [18], in recent decades there is a growing awareness of the extreme importance of strategies focusing not only on the conservation of river ecosystems but also on the protection of natural landscapes to avoid irreversible impacts [39].

However, the assessment of river landscape (hereafter, *riverscape*) attributes is particularly challenging, above all considering aesthetic quality, due to the difficulties in unambiguously attributing sensory responses to particular elements of riverscapes [208]. Hitherto, riverscape assessments have usually focused on riparian vegetation and river geomorphology (e.g., [209, 210]), river flow preferences (e.g., [211, 208]), and river restoration measures (e.g., [212]). Nevertheless, only few studies in the scientific literature have focused on the effects of water withdrawal on the stakeholders' perception of riverscape aesthetic quality proposing specific metrics or indicators concerning the downstream watercourse stretch. Some of these studies analyze changes in riparian vegetation and geomorphological elements (e.g., [210]), which however occur over long timescales. The other researchers mainly considered hydraulic parameters, such as water level and water flow dynamics (e.g., [213, 214]), or visual characteristics, like the color of water and exposed gravel (e.g., [208]). Other features frequently considered in the literature are more qualitative, assessing the preferences and perceptions of watercourse users and stakeholders, often using photographs as surrogates for landscape [215]. For example, preferences for natural conditions (e.g., [216]), perceived effects on recreational opportunities (e.g., [217]), or aesthetic impressions of the local scenery (e.g., [218]) have often been investigated.

In Aosta Valley, as illustrated in Chapter 3, "Landscape" is among the official criteria included in the MADM framework to assess the sustainability of water withdrawals. In fact, tourism is an important resource in the region, with over 3.6 million overnight stays in 2019 [219]. The important natural and architectural heritage of the region, deserving particular safeguard, mainly attracts tourists in July and August (with almost 37% of total overnight stays in 2019), or in the winter season (between December and March, largely related to winter sports) [220, 219]. Moreover, the inclusion of the Landscape criterion in the MADM assessment is in line with the European Landscape Convention, which requires establishing and implementing policies aimed at landscape protection, management, and planning [221].

Due to the lack of a specific metric in the literature to be directly used in the MADM decision tree (illustrated in Figure 3.4), a new indicator has been elaborated in Aosta Valley to quantify the Landscape criterion. The indicator, named Landscape Protection Level (LPL), assesses the effects of water withdrawals on the riverscape in the bypassed watercourse stretch. It is an index that takes into account the local landscape protection constraints, the amount of flow released downstream of the withdrawal site, and the impact on the visual perception.

The aim of this Chapter is to illustrate the LPL indicator developed in Aosta Valley and its use in the MADM framework for the assessment of water withdrawal sustainability. The main properties of the indicator are analyzed based on the results obtained in four real case studies, concerning different watercourses and hydropower plants.

The Chapter is organized as follows: the LPL indicator is described in section 4.2, presenting the three parameters evaluated to obtain the final LPL score and the way in which the indicator is used to assess different flow release alternatives in the MADM procedure carried out in Aosta Valley. In section 4.3, different examples of the LPL results obtained in four case studies are illustrated. Based on these results, in section 4.4, the main indicator properties are analyzed using a set of evaluation criteria (e.g., reactiveness, representativeness of the corresponding stakeholders' needs, etc.); other characteristics of the indicator are also discussed. Finally, some concluding remarks about the effectiveness of the proposed indicator are presented in section 4.5, suggesting possible future improvements.

4.2 Landscape Protection Level (LPL) indicator

The LPL indicator adopted in Aosta Valley for the assessment of water withdrawal impacts on the downstream riverscape was derived from a criterion of nature conservation used in Tyrol (Austria) for sustainable HP development [222]. After an initial adaptation to the Aosta Valley context, different revisions were carried out to ensure proper representativeness of the related stakeholders' satisfaction level. The more recent modifications of the indicator were mainly aimed at including visual effects of flow release amounts on the considered riverscape.

The calculation of the LPL indicator initially requires the division of the bypassed watercourse stretch downstream of the dam into different portions, usually named "subsections", characterized by homogeneous visibility (as explained in section 4.2.1). This procedure is completed by the experts of the Regional Landscape Protection Service (RLPS), based on regional cartography, orthophotos, and direct surveys. The LPL score for each selected subsection is then obtained by summing up three different parameters, i.e., Constraint Factor (CF), Release Factor (RF), and Visual Elements Factor (VEF):

$$LPL = CF + RF + VEF \tag{4.1}$$

High LPL scores (i.e., between 90 and 165, as shown in Table 4.3) indicate an acceptable or high level of landscape protection ensured by the flow release scenario in the considered watercourse subsection. Lower LPL values, on the contrary, represent a limited landscape protection level, generally due to insufficient amounts of flow releases. Low LPL scores might also be obtained when a watercourse subsection is characterized by significant landscape properties and, therefore, even a minimal water withdrawal would likely impact the riverscape.

4.2.1 Calculation of the Constraint Factor (CF)

Once the bypassed watercourse stretch has been split into different subsections, the RLPS experts assign a class of visibility to each subsection according to the distance from which it is visible and to its accessibility. Three classes of visibility are considered: A) high visibility (subsection highly visible from a significant distance and/or easily accessible through roads or paths), B) medium visibility (subsection well visible from a short distance), and C) low visibility (subsection slightly visible and accessible or not visible at all, e.g., a watercourse subsection flowing into a gorge).

According to the class of visibility, the maximum score of CF is equal to 15, 30, or 45 (for high, medium, or low visibility, respectively). This score is assigned when, in the considered subsection, there are no significant landscape or cultural heritage elements safeguarded by specific national or regional laws. The presence of such elements, listed in Table 4.1, is verified by the RLPS experts based on cartographic representations and on their direct knowledge of the territory. For each element identified in the considered subsection, a specific score is subtracted from the maximum score.

As shown in Table 4.1, most elements refer to specific constraints defined by the national and regional landscape protection laws (i.e., Legislative Decree n. 42/2004 [223] and Territorial Landscape Plan of Aosta Valley – PTP [224]), aimed at safeguarding different areas of specific interest. Moreover, the recreational value of the considered subsection is also taken into account. It is evaluated through expert judgment according to the presence and value of cultural and historical assets considered in the PTP [224]. A score from 2 to 6 is thus subtracted from the maximum CF score (higher values correspond to an upper recreational level) only when cultural and historical assets are present in the analyzed subsection. Furthermore, a score is usually assigned to Visibility (first row of Table 4.1). Only when the subsection is not accessible and substantially not visible (e.g., in the case of a very deep gorge) the score in the first row of column C is not subtracted from the maximum final score.

It has to be highlighted that the scores shown in Table 4.1 were defined based on the hierarchy of importance of the constraints regulated by the considered laws in the regional context. For example, visible waterfalls have a higher score compared to glacial terraces because they are considered more important assets in the regional riverscape. Therefore, the scores of the considered elements were proportionally defined for each visibility class according to this hierarchy.

Based on this framework, the resulting CF value for a subsection characterized by high visibility (class A) and by the presence of several significant landscape and cultural heritage elements will be very low. This will contribute to decreasing the final LPL result for a watercourse subsection characterized by significant landscape properties, since water withdrawal would probably have a strong negative impact on its riverscape.

4.2.2 Calculation of the Release Factor (RF)

The Release Factor quantifies the "naturalness" level of flow releases downstream of the dam compared to the flow rate measured upstream. The discharge flowing in the bypassed stretch is given by the sum of three different water amounts:

- the ecological flows, i.e., the discharge released from the withdrawal dam, based on the scheme of flow releases defined in the water license;
- the discharge released in addition to the ecological flows when the watercourse flow rate exceeds the maximum discharge that can be withdrawn;
- the contribution of the watershed to the bypassed subsection, for example, through small tributaries downstream of the dam.

The RF value is calculated according to the following equation:

$$RF = \alpha \cdot \frac{Q_{e-flow}}{Q_{ref}} \tag{4.2}$$

Table 4.1 Scores corresponding to the significant landscape and cultural heritage elements, safeguarded by law, considered for the calculation of the Constraint Factor according to the visibility of the watercourse subsection (adapted from [6])

Significant riverscape elements		Subsection score		
		A) High visibility	B) Medium visibility	C) Low visibility
Visibility		1	2	3
Origin of landscape elements – Specific landscape constraints	Buildings and areas of considerable public interest [223]	1	3	4
	Rivers, streams, watercourses [223]	1	3	4
	River system	1	2	3
Origin of landscape elements – Particular landscape constraints	Lakes [224]	1	2	3
	Areas of specific landscape interest [224]	1	2	4
	System of natural areas	1	2	3
Uniqueness of the landscape – Background landscape constraints	Lakes; Forests and areas subject to reforestation restrictions [223]	1	2	4
	Mountain areas over 1600 m a.s.l.; National or regional parks and other protected areas; Areas of archaeological interest [223]	1	2	3
	Areas of specific archeological interest [224]	1	2	3
Representativeness – Significant components of the landscape	Waterfalls, alluvial fans	1	3	5
	Ridges, peaks, important rocks	1	2	3
	Gorges, glacial terraces	1	2	3
Recreational value – Fruition of cultural and historical assets	Low	2	3	4
	Medium	3	4	5
	High	4	5	6
Maximum final score (no constraints and high recreational value		15	30	45

where Q_{e-flow} is the discharge released downstream of the dam (m^3/s), Q_{ref} is the reference watercourse discharge available upstream (m^3/s), and α is a dimensionless coefficient varying according to the visibility of the considered subsection.

The value of α is equal to 60 for class A (high visibility), 45 for class B (medium visibility), and 30 for class C (low visibility). These values were defined in order to increase the influence of RF on the LPL indicator results when the visibility of the subsection is higher. In fact, it is considered more important to ensure higher naturalness of flow rates in more visible river reaches. Moreover, the selected α values properly quantify the influence of flow releases on the final LPL results, thus improving the reactiveness of the indicator and its variability in a range comparable with the other indicators used in the MADM assessment. These values also ensure that the total range of the LPL indicator is the same for the three classes of visibility, thus allowing its normalization, as explained in section 4.2.4.

4.2.3 Calculation of the Visual Elements Factor (VEF)

For the calculation of the VEF, the RLPS experts initially identify an appropriate viewpoint for the installation of a fixed camera (or webcam) that will take a set of photos of the bypassed stretch under different discharge conditions. The viewpoint must ensure good visibility of a representative section of the entire bypassed stretch, allowing the assessment of all the visual metrics listed in Table 4.2. The camera is installed by the dam owner and synchronized with the continuous hydrological monitoring system. Indeed, for each photo, the corresponding discharge value in l/s must be recorded. Furthermore, the same focal length and enlargement must be used for all the pictures. The orientation of the camera and the best moment during the day to take photos also require proper planning, ensuring an accurate evaluation of the visual metrics by the experts.

Once a consistent set of images has been collected, the RLPS experts start the assessment of the riverscape perception. The analysis is carried out by comparing each selected photo corresponding to the discharges released downstream of the dam (representing the altered conditions) with a photo corresponding to the watercourse discharge measured upstream (representing the reference conditions). The two images, displayed on two different computer screens, are examined by the experts, who assign a score to each visual metric according to their level of alteration, due

Table 4.2 Scores corresponding to the visual metrics of riverscape perception, considered for the calculation of the Visual Elements Factor, according to their level of alteration compared to reference conditions (from [6])

Visual metrics of riverscape perception	Scores (expert judgment)		
	Natural	Acceptable	Altered
Natural water turbulence	90	45	9
Average water depth	90	45	9
Ratio of dry to wet riverbed	90	45	9
Presence of small waterfalls	90	45	9
Filling level of pools	90	45	9

to the withdrawal, compared to the reference conditions. To reduce the risk of a subjective expert judgment, at least three landscape experts are involved in the assessment.

The reference conditions always refer to the watercourse characteristics and the measured flow rate upstream of the considered dam, also in case of a river affected by multiple dams. In fact, the LPL indicator assesses only the impacts of a single withdrawal and, therefore, it considers the conditions “unaltered” by the investigated dam as the reference conditions.

The analyzed metrics of riverscape perception and the corresponding scores according to the level of visual perception alteration (i.e., natural, acceptable, or altered) are shown in Table 4.2. All the metrics focus on the watercourse channel and represent features that have a direct impact on river users’ perception. In fact, an alteration of these metrics caused by the water withdrawal can be immediately perceived through a visual assessment. For this reason, for example, geomorphological characteristics and riparian vegetation have not been considered, since their variations occur over long timescales.

The scores of the visual metrics were defined in order to highly differentiate altered and natural conditions. Moreover, in this way, the VEF parameter has the largest influence on the final LPL result. It has to be highlighted that the minimum score assigned to each metric is 9. In fact, the “altered” judgment indicates a significant deviation from the reference conditions, but with flow releases considered not completely unacceptable. The VEF parameter is set equal to 0 only in the rare cases in which the flow release is extremely low compared to reference conditions.

The final VEF value is obtained, for the entire bypassed stretch, as the average of the scores assigned to each visual metric based on the expert judgment. Hence, it ranges between 9 (when all the metrics are considered “altered”) and 90 (when all the metrics are judged as “natural”). If some metrics are not relevant for the analyzed watercourse stretch (e.g., there are no pools), they will be excluded from the calculation.

4.2.4 Final calculation of the LPL indicator

The LPL value for each subsection into which the considered bypassed stretch has been split is calculated as the sum of the scores of CF, RF, and VEF (see Eq. 4.1). The final value of the indicator, for the entire bypassed stretch ($LPL_{stretch}$, dimensionless), is calculated as a weighted average of the LPL values obtained for each subsection, according to their lengths (Eq. 4.3):

$$LPL_{stretch} = \frac{\sum_{i=1}^{N} (LPL_{subsection\ i} \cdot l_{subsection\ i})}{l_{tot}} \tag{4.3}$$

where N is the number of subsections, $LPL_{subsection\ i}$ is the LPL value calculated for the subsection i (dimensionless), $l_{subsection\ i}$ represents its length (m), and l_{tot} is the length of the entire bypassed stretch (m).

The LPL indicator can be used to assess a specific flow release value (altered condition) compared to the available watercourse discharge upstream of the withdrawal dam (reference condition). However, it can also be adopted to assess different flow release scenarios, varying over the year, compared to variable reference conditions (corresponding to the flow regime unaltered by the considered dam).

In Aosta Valley, the indicator is used in the MADM procedure carried out for the assessment of water withdrawal sustainability, described in Chapter 3. In this case, different flow release alternatives are considered and their impacts on the riverscape perception are compared based on the LPL value calculated for each of them. The alternatives are usually characterized by varying discharge values, either on a monthly basis (i.e., with a fixed flow release value set for each month) or in real time (i.e., with a minimum monthly flow value incremented by an additional release calculated as a percentage of the discharge measured upstream of the dam). Therefore, the LPL calculation is disaggregated on a monthly basis (sometimes even

Table 4.3 Classes of landscape protection according to the Landscape Protection Level (LPL) indicator (adapted from [6])

LPL	Normalized LPL values	Class
$130 < LPL \leq 165$	$0.79 < LPL \leq 1$	High
$90 < LPL \leq 130$	$0.55 < LPL \leq 0.79$	Good
$50 < LPL \leq 90$	$0.31 < LPL \leq 0.55$	Moderate
$20 < LPL \leq 50$	$0.12 < LPL \leq 0.31$	Poor
$0 \leq LPL \leq 20$	$0 \leq LPL \leq 0.12$	Bad

fortnightly, when the watercourse flow regime is particularly variable during the month). For this reason, monthly RF and VEF values are calculated considering, respectively, the average monthly values of reference discharge and flow releases and the images of the bypassed stretch corresponding to these flow rates. The CF values obtained for each subsection, on the contrary, do not vary. The LPL score for the overall alternative, thus, is achieved through a weighted average of the LPL values calculated for the different months. Generally, RLPS experts assign higher weights to the months characterized by a greater landscape interest, thus increasing the protection level when the recreational and aesthetic value of the riverscape is higher (i.e., usually, in summer).

In accordance with the approach used for the other indicators included in the MADM decision tree, the overall score of the LPL indicator is divided into five classes, as shown in Table 4.3. The threshold values defining the division between the classes were established based on the results of tests carried out in different regional river contexts, for the main 32 bypassed stretches in the region and, subsequently, for other 29 smaller watercourse sections. The correspondence of the indicator results with the experts' qualitative judgment was checked in each test. Moreover, a linear normalization function (represented in Figure 3.6c in Chapter 3) was defined for the indicator.

4.3 Application of the LPL indicator to four real case studies

The LPL indicator is being used in several decision-making processes carried out in different regional contexts for the assessment of water withdrawal sustainability. In this section, various examples of the indicator results, obtained in four real case studies of existing HP plants, are illustrated.

4.3.1 Case studies

The four considered case studies concern three different torrents in Aosta Valley (Figure 4.1), all characterized by a snow-pluvial hydrological regime. In each case study, the LPL indicator has been used, within the MADM framework, to quantify the impact of an existing run-of-the-river HP plant on the downstream riverscape. In case study 4, a pre-existing withdrawal for agricultural use (withdrawing a fixed monthly value of discharge from May to the beginning of October), is also present in the bypassed stretch. The LPL indicator is thus employed to assess the combined effect of both the water withdrawals. The main characteristics of the four case studies are listed in Table 4.4.

In all the considered case studies, a continuous hydrological monitoring system was installed at the dam to collect flow data series. The stage was continuously measured through water level sensors (submerged pressure transducer or acoustic systems) and converted into discharge data through the stage-discharge relation determined for the monitored watercourse cross-section. Flow rate data were collected on an hourly basis, but they were subsequently aggregated to obtain daily discharge series to be used for the calculation of the LPL indicator.

Furthermore, a webcam or scout camera was installed near the dam to collect images of the bypassed stretch under different discharge conditions. Photos were taken daily, during the central hours of the day, when sunlight is appropriate to ensure good visibility of the watercourse stretch and a correct evaluation of all the visual metrics considered in the VEF parameter. Before starting the routine monitoring, a set of sample images was sent to the RLPS experts for their approval.

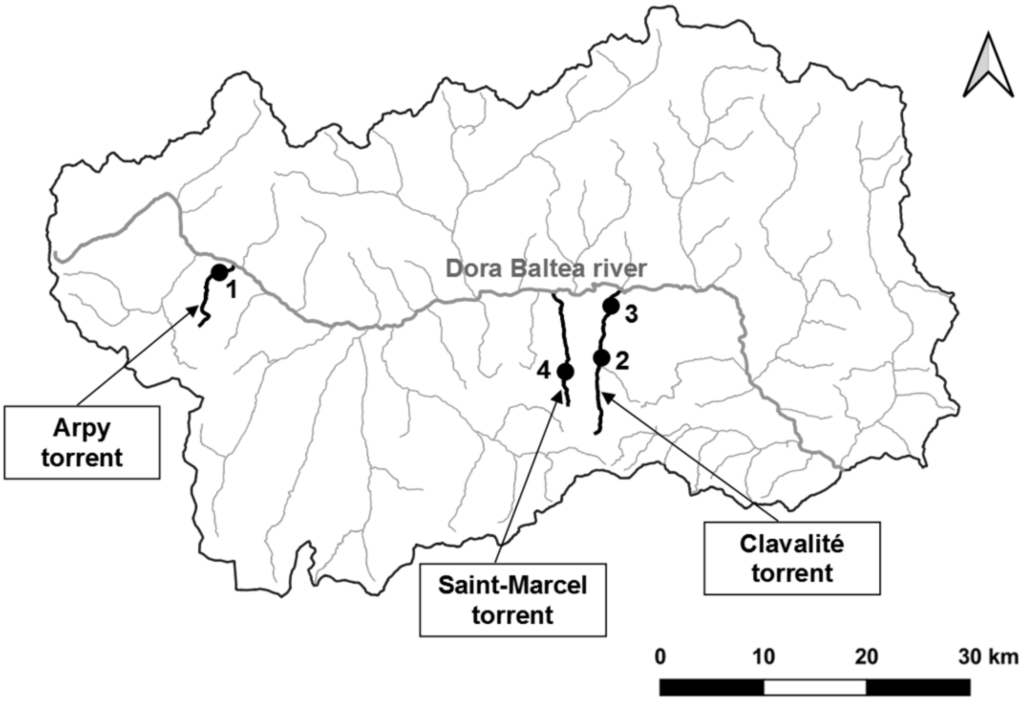


Fig. 4.1 Location of the watercourses affected by the four case studies in Aosta Valley: Arpy torrent (case study 1), Clavalité torrent (case study 2, upper watershed, and case study 3, lower watershed), and Saint-Marcel torrent (case study 4). The location of each HP plant is indicated by a black dot symbol, with the number of the corresponding case study (from [6])

For each case study, different flow release alternatives (ALT) were defined to be assessed in a MADM procedure (see the last row of Table 4.4). All the considered alternatives were characterized by fixed monthly (or fortnightly) values of flow release, defined as a percentage of the average monthly (or fortnightly) discharge of the watercourse measured upstream of the withdrawal dam (an example of a set of alternatives for case study 1 is provided in Table 4.11).

4.3.2 Examples of the LPL results obtained in the case studies

For the calculation of the LPL indicator, each bypassed stretch was divided by the RLPS experts into different subsections (three subsections for case study 2, five for the other case studies). For each of them, the related Constraint Factor (CF), Release Factor (RF), and Visual Elements Factor (VEF) were calculated. Table 4.5 illustrates an example of the calculation of the CF value, for case study 2. On the contrary, Table 4.6 shows, for case study 2, different examples of the evaluation of the VEF value,

Table 4.4 Main characteristics of the watercourses and hydropower plants concerned by the four considered case studies (adapted from [6])

Characteristics	Case study 1	Case study 2	Case study 3	Case study 4
Name of the watercourse	Arpy torrent	Clavalité torrent – upper watershed	Clavalité torrent – lower watershed	Saint-Marcel torrent
Strahler's stream order [225]	1	2	2	1
Average annual discharge (m^3/s)	0.26	1.64	3.63	0.70
Length of the bypassed stretch (m)	922	1736	3931	2578
Altitude of the water intake point (m a.s.l.)	1378	1491	1207	1830
Altitude of the release point (m a.s.l.)	983	1144	597	1409
Average annual nominal power of the HP plant (kW)	697.5	2955.4	6651.3	960.8
Total head (m)	395	347	610	421
Mean annual withdrawn discharge (m^3/s)	0.18	0.87	1.28	0.23
Number of flow release alternatives (ALT) assessed in the MADM process	7 (from ALT A to ALT G)	7 (from ALT A to ALT G)	6 (from ALT A to ALT F)	7 (from ALT A to ALT G)

which changes according to the flow releases (Q_{e-flow}) and the average watercourse discharge (Q_{ref}). Four examples of images used by the landscape experts for the assessment of the VEF parameter are also provided in Figure 4.2.

Furthermore, Tables 4.7, 4.8, and 4.9 represent some examples of the LPL calculations for case studies 2, 3, and 4, respectively. The results of case study 2 highlight how the LPL values vary for different flow releases, when the available discharge is the same (in this case, $Q_{ref} = 1718\ \mathrm{l/s}$, in July). On the contrary, for both case studies 3 and 4, three different flow release values (Q_{e-flow}) have been selected, related to periods of low, moderate, and higher flows in the watercourse.

As mentioned above, the results of case study 4, shown in Table 4.9, refer to a more complex situation, involving both a hydropower plant and a pre-existing withdrawal for agricultural use. The first two subsections of the bypassed stretch affected by both the water withdrawals are illustrated in Figure 4.3. The agricultural diversion can withdraw up to 310 l/s from May to September and up to 100 l/s in October, but only when there is enough water because the value of Q_{e-flow} required in the downstream watercourse stretch must always be ensured. Therefore, in these periods, the additional fixed amount of water for the agricultural withdrawal is released by the HP producer in the first subsection *ab* (at point *a'* in Figure 4.3, in addition to the value of Q_{e-flow} released in *a*) and it is withdrawn by the agricultural diversion in the lower part of the second subsection *bc* (at point *b'*). For this reason, the water amount flowing in the first two subsections of this stretch (between *a'* and *b'*) is higher. Downstream of the agricultural withdrawal, on the contrary, the discharge flowing in the watercourse is again the required Q_{e-flow}. The additional flow release is considered in the calculation of the LPL value, as shown in Table 4.9 for the last two examples, where the corresponding values have been highlighted in blue.

Most of the examples shown in Tables 4.7, 4.8, and 4.9 refer to a calculation of the LPL indicator on a monthly basis. In these cases, Q_{ref} is the average flow rate of the considered month. On the contrary, in some examples, the indicator is calculated on a fortnightly basis (e.g., May 1–15 in both Table 4.8 and Table 4.9, which refers to the first 15 days of May). In these cases, Q_{ref} and Q_{e-flow} correspond to the average values calculated over the considered 15 days and the selected photos of the bypassed stretch correspond to these flow rates.

Table 4.5 Calculation of the Constraint Factor for case study 2 on the Clavalité torrent (upper watershed). The same significant riverscape elements shown in Table 4.1 are listed in the first column (even if some of their names are abbreviated). No score has been assigned to the elements that are not present in the considered subsection

	Subsection 1	Subsection 2	Subsection 3
Visibility	A – high	C – low	B – medium
Max final score	15	45	30
Visibility	1	3	2
Buildings			
Watercourses			
River system	1	3	2
Lakes			
Areas of landscape interest			
Natural areas		3	
Lakes and forests	1	4	2
Mountain areas, protected areas, etc.			2
Areas of archaeological interest			
Waterfalls		4	
Peaks, rocks, etc.		3	2
Gorges, glacial terraces	1	3	2
High recreational value	4		
Sum of constraints	8	23	12
Constraint Factor	**7**	**22**	**18**

(a) $Q_{\text{e-flow}} = 130\,\mathrm{l/s}$ (b) $Q_{\text{e-flow}} = 805\,\mathrm{l/s}$

(c) $Q_{\text{e-flow}} = 1520\,\mathrm{l/s}$ (d) $Q_{\text{e-flow}} = 1980\,\mathrm{l/s}$

Fig. 4.2 Examples of images used by the landscape experts for the assessment of the Visual Elements Factor in case study 2. The corresponding flow release ($Q_{\text{e-flow}}$) is indicated in the caption of each image (photo credit: Alga S.r.l.)

Table 4.6 Examples of the calculation of the Visual Elements Factor (VEF) for case study 2, corresponding to different flow releases ($Q_{\text{e-flow}}$) and average watercourse discharges (Q_{ref}). From the fourth to the eighth columns, the scores allocated to the visual metrics of riverscape perception listed in Table 4.2, according to their level of alteration, are provided (the names of the metrics are abbreviated; turb. = turbulence)

ALT – Month	Q_{ref} (l/s)	$Q_{\text{e-flow}}$ (l/s)	Turb.	Depth	Dry/wet riverbed	Small waterfalls	Pools	VEF
C – Jan	203	100	9	9	45	9	9	16.2
C – Mar	139	100	45	45	90	45	45	54.0
F – Mar	139	130	90	90	90	90	90	90.0
A – Jul	1718	1520	90	45	45	90	45	63.0
B – Jul	1718	805	45	9	9	45	45	30.6
E – Jul	1718	150	9	9	9	9	9	9.0

Looking at the tables, it can be noticed that the CF values assigned to the subsections do not vary for the same case study. In fact, this parameter quantifies the landscape value of the bypassed stretch, in terms of the presence of significant elements safeguarded by law, and it is not influenced by the amount of water released by the HP plant. Nevertheless, the CF values change according to the case study since the subsections in the four considered bypassed stretches are characterized by different classes of visibility and constraints. However, calculating an overall CF value for each stretch (as a weighted average of the CF values of the different subsections, based on their lengths), it can be noticed that the values obtained for the four case studies are similar, i.e., 20.4, 20.1, 17.6, and 16.9 for case studies from 1 to 4, respectively.

The RF and VEF values, on the contrary, vary for the same bypassed stretch according to the ratio Q_{e-flow}/Q_{ref}. Figure 4.4 shows the trend of all the final LPL scores available for the four case studies (i.e., all the LPL monthly, or fortnightly, values calculated for the different alternatives considered in each case study) with the increase of the ratio Q_{e-flow}/Q_{ref}. It can be observed that the results generally follow a similar increasing trend. However, not all the values present this tendency. This is due to the fact that the VEF parameter does not necessarily increase with the ratio Q_{e-flow}/Q_{ref}. Indeed, the effect of the percentage increase in flow rate on the observer's visual perception can be different, in particular during periods of low water levels or with higher flows.

Table 4.7 Examples of the results of the landscape indicator (LPL) for case study 2, corresponding to different flow releases ($Q_{\text{e-flow}}$) and average watercourse discharges (Q_{ref}). The Constraint Factor (CF), Release Factor (RF), and Visual Elements Factor (VEF) are given for each example. The colors in the last column highlight the different classes of landscape protection (as in Table 4.3) (adapted from [6])

ALT E – July:	Q_{ref} = 1718 l/s;		$Q_{\text{e-flow}}$ = 150 l/s;			$Q_{\text{e-flow}}/Q_{\text{ref}}$ = 0.09			
Subsections		Visibility	Length (m)	CF	RF	VEF	$LPL_{\text{subsection}}$	LPL_{stretch} (normalized)	Class
1	ab	A – high	87	7	5.2	9.0	21.2	32.2 (0.20)	Poor
2	bc	C – low	1152	22	2.6		33.6		
3	cd	B – medium	497	18	3.9		30.9		
ALT B – July:	Q_{ref} = 1718 l/s;		$Q_{\text{e-flow}}$ = 805 l/s;			$Q_{\text{e-flow}}/Q_{\text{ref}}$ = 0.47			
Subsections		Visibility	Length (m)	CF	RF	VEF	$LPL_{\text{subsection}}$	LPL_{stretch} (normalized)	Class
1	ab	A – high	87	7	28.1	30.6	65.7	67.5 (0.41)	Moderate
2	bc	C – low	1152	22	14.1		66.7		
3	cd	B – medium	497	18	21.1		69.7		
ALT A – July:	Q_{ref} = 1718 l/s;		$Q_{\text{e-flow}}$ = 1520 l/s;			$Q_{\text{e-flow}}/Q_{\text{ref}}$ = 0.88			
Subsections		Visibility	Length (m)	CF	RF	VEF	$LPL_{\text{subsection}}$	LPL_{stretch} (normalized)	Class
1	ab	A – high	87	7	53.1	63.0	123.1	114.8 (0.70)	Good
2	bc	C – low	1152	22	26.5		111.5		
3	cd	B – medium	497	18	39.8		120.8		

Table 4.8 Examples of the results of the landscape indicator (LPL) for case study 3 on the Clavalité torrent (lower watershed) (adapted from [6])

ALT B – December:		Q_{ref} = 500 l/s;		$Q_{e\text{-}flow}$ = 100 l/s;		$Q_{e\text{-}flow}/Q_{ref}$ = 0.20			
Subsections		Visibility	Length (m)	CF	RF	VEF	$LPL_{subsection}$	$LPL_{stretch}$	Class
1	ab	B – medium	497	17	9.0	9.0	35.0	35.2 (0.21)	Poor
2	bc	A – high	1001	7	12.0		28.0		
3	cd	B – medium	910	18	9.0		36.0		
4	de	C – low	1412	25	6.0		40.0		
5	ef	B – medium	111	17	9.0		35.0		
ALT A – May 1–15:		Q_{ref} = 740 l/s;		$Q_{e\text{-}flow}$ = 740 l/s;		$Q_{e\text{-}flow}/Q_{ref}$ = 1			
Subsections		Visibility	Length (m)	CF	RF	VEF	$LPL_{subsection}$	$LPL_{stretch}$	Class
1	ab	B – medium	497	17	45.0	90.0	152.0	151.0 (0.92)	High
2	bc	A – high	1001	7	60.0		157.0		
3	cd	B – medium	910	18	45.0		153.0		
4	de	C – low	1412	25	30.0		145.0		
5	ef	B – medium	111	17	45.0		152.0		
ALT A – June:		Q_{ref} = 6888 l/s;		$Q_{e\text{-}flow}$ = 1428 l/s;		$Q_{e\text{-}flow}/Q_{ref}$ = 0.21			
Subsections		Visibility	Length (m)	CF	RF	VEF	$LPL_{subsection}$	$LPL_{stretch}$	Class
1	ab	B – medium	497	17	9.3	27.0	53.3	53.6 (0.32)	Moderate
2	bc	A – high	1001	7	12.4		46.4		
3	cd	B – medium	910	18	9.3		54.3		
4	de	C – low	1412	25	6.2		58.2		
5	ef	B – medium	111	17	9.3		53.3		

Table 4.9 Examples of the results of the landscape indicator (LPL) for case study 4 on the Saint-Marcel torrent. In the examples proposed for ALT F and ALT D, the water amount flowing in the subsections whose values have been highlighted in blue (from *a'* to *b'*) is higher. As explained in section 4.3.2, this is due to the presence of a pre-existing agricultural diversion, withdrawing a fixed amount of water from May to the beginning of October (sub = subsection, L = length)

ALT G – April: Q_{ref} = 108 l/s; $Q_{e\text{-}flow}$ = 108 l/s; $Q_{e\text{-}flow}/Q_{ref}$ = 1

Sub		Visibility	L (m)	CF	RF	VEF	LPL_{sub}	$LPL_{stretch}$	Class
1	ab	high	323	8	60.0	90.0	158.0	146.9 (0.89)	High
2	bc	medium	592	15	45.0		150.0		
3	cd	low	898	20	30.0		140.0		
4	de	medium	489	17	45.0		152.0		
5	ef	low	276	21	30.0		141.0		

ALT F – May 1–15: Q_{ref} = 962 l/s; $Q_{e\text{-}flow}$ = 410 l/s; $Q_{e\text{-}flow}/Q_{ref}$ = 0.43
($Q_{e\text{-}flow\ a'b'\ (10\ days)}$ = 720 l/s; $Q_{e\text{-}flow}/Q_{ref\ a'b'}$ = 0.64)

Sub		Visibility	L (m)	CF	RF	VEF	LPL_{sub}	$LPL_{stretch}$	Class
1	aa'	high	58	8	25.6	36.0	69.6	78.7 (0.48)	Moderate
	a'b		265		38.5	57.0	103.5		
2	bb'	medium	444	15	28.8	57.0	100.8		
	b'c		148		19.2	36.0	70.2		
3	cd	low	898	20	12.8		68.8		
4	de	medium	489	17	19.2	36.0	72.2		
5	ef	low	276	21	12.8		69.8		

ALT D – June 1–15: Q_{ref} = 2076 l/s; $Q_{e\text{-}flow}$ = 1500 l/s; $Q_{e\text{-}flow}/Q_{ref}$ = 0.72
($Q_{e\text{-}flow\ a'b'\ (10\ days)}$ = 1810 l/s; $Q_{e\text{-}flow}/Q_{ref\ a'b'}$ = 0.87)

Sub		Visibility	L (m)	CF	RF	VEF	LPL_{sub}	$LPL_{stretch}$	Class
1	aa'	high	58	8	43.4	78.8	130.1	129.7 (0.79)	Good
	a'b		265		52.3	90.0	150.3		
2	bb'	medium	444	15	39.2	90.0	144.2		
	b'c		148		32.5	78.8	126.3		
3	cd	low	898	20	21.7		120.4		
4	de	medium	489	17	32.5	78.8	128.3		
5	ef	low	276	21	21.7		121.4		

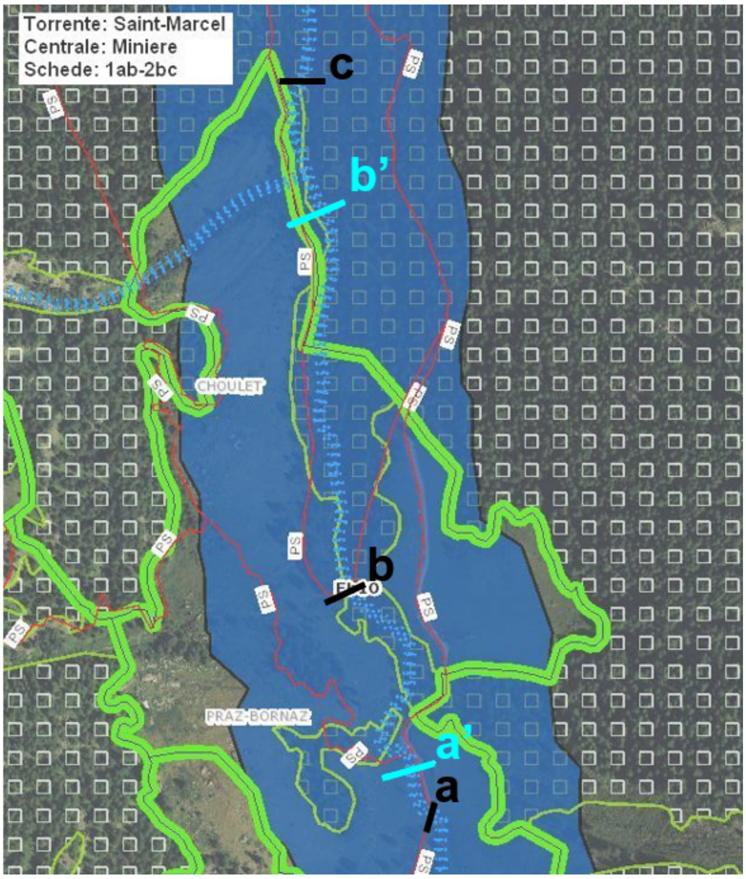


Fig. 4.3 First two subsections (*ab* and *bc*) into which the bypassed stretch on the Saint-Marcel torrent (case study 4) has been divided. Due to the presence of an agricultural withdrawal in *b'*, the hydropower producer releases the discharge required by the license in *a* and, from May to the beginning of October, an additional water amount in *a'*, which is withdrawn by the agricultural diversion in *b'*

An example is represented, for case study 3, by the LPL values corresponding to $Q_{e-flow}/Q_{ref} = 0.33$ and $Q_{e-flow}/Q_{ref} = 0.44$ (both highlighted with a red symbol edge in Figure 4.4), which are particularly high. However, they both refer to June, when the average watercourse discharge is 6888 l/s (higher flow level). A flow release of 2300 l/s (ALT F) or 3000 l/s (ALT E) can cause a relatively low alternation of visual riverscape perception, compared to the reference condition, even if they correspond to a ratio Q_{e-flow}/Q_{ref} of only 0.33 and 0.44, respectively.

The opposite situation is represented, for example, by the LPL values corresponding to $Q_{e-flow}/Q_{ref} = 0.65$, 0.69, 0.72, and 0.75 for case study 1 (highlighted with a red symbol edge in Figure 4.4), which are significantly low compared to the other results. However, all these values refer to a period of low water level, i.e., the second

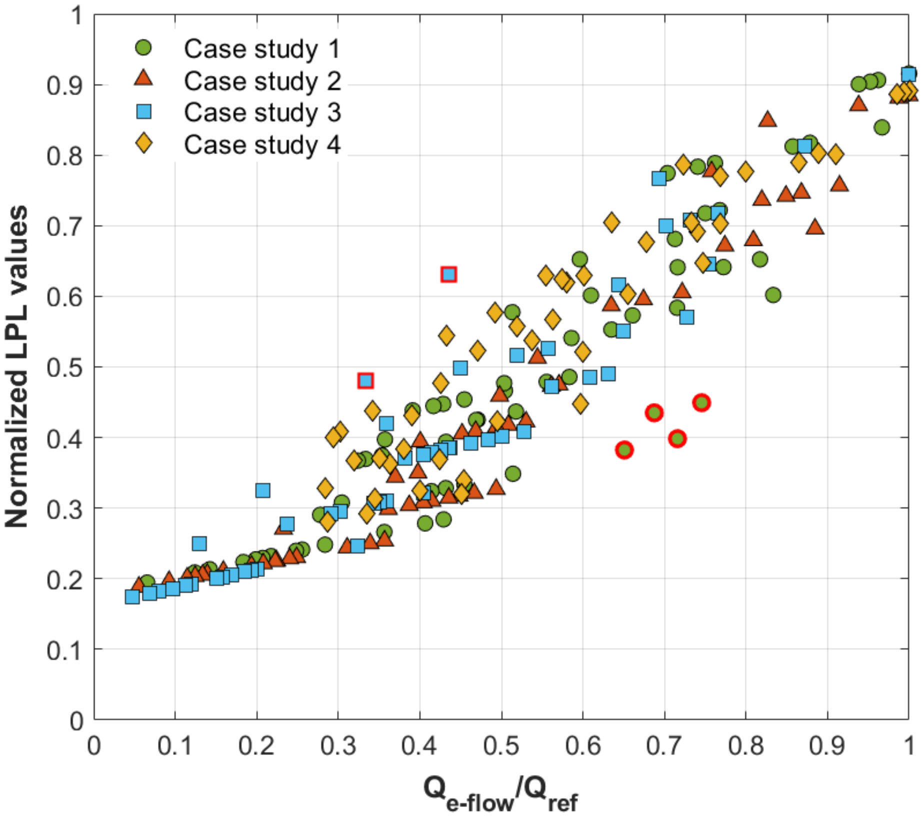


Fig. 4.4 Trend of all the available results of the landscape indicator (LPL) for the four considered case studies according to the ratio of flow release downstream of the hydropower plant (Q_{e-flow}) to the average monthly available discharge of the watercourse (Q_{ref}). The symbols highlighted with a red edge are some results discussed in section 4.3.2

half of August (for the first and the last value), with $Q_{ref} = 169\,\mathrm{l/s}$, and the month of November (for the other two examples), with $Q_{ref} = 176\,\mathrm{l/s}$. The considered flow releases are, respectively: 110 l/s (ALT G, $Q_{e-flow}/Q_{ref} = 0.65$), 121 l/s (ALT A, $Q_{e-flow}/Q_{ref} = 0.69$), 126 l/s (ALT F, $Q_{e-flow}/Q_{ref} = 0.72$), and 126 l/s (ALT E, $Q_{e-flow}/Q_{ref} = 0.75$). Thus, even if the decrease of the discharge downstream of the withdrawal point is not particularly high (i.e., the ratio Q_{e-flow}/Q_{ref} is relatively high), its impact on the observer's visual riverscape perception is considerable because the amount of water flowing in the bypassed stretch will be significantly low.

Furthermore, Figure 4.4 shows that, for the considered case studies, the maximum protection score (i.e., $LPL = 1$) is never reached, even when the HP plant is not withdrawing (i.e., with $Q_{e-flow}/Q_{ref} = 1$). The reason is that the normative landscape constraints considered in the CF parameter are highly widespread in the Aosta Valley territory and they are not specifically related to the presence of a withdrawal. Hence, CF only reaches the maximum value when there are no significant landscape elements in the considered bypassed stretch. Nevertheless, this contributes to reducing the final LPL score for river subsections characterized by significant landscape properties, where the presence of a water withdrawal would have strong negative impacts. Moreover, CF varies for different watercourse stretches. Thus, in future assessments, it could be used to compare different stretches in the same watershed by quantifying their landscape asset, in addition to the flow release impacts.

Example of the indicator use to assess flow release alternatives

As explained in section 4.2.4, the LPL indicator is adopted to assess different flow release scenarios in the MADM procedure carried out in Aosta Valley for the evaluation of water withdrawal sustainability. Table 4.10 illustrates the set of flow release alternatives, proposed by different stakeholders, considered in case study 1. Each column of the table, from ALT A to ALT G, refers to a different alternative. All the alternatives are characterized by a fixed flow release value for each month (Q_{e-flow}), defined as a percentage of the average monthly discharge of the watercourse, given in the second column. Only the months of April and August have been divided into two halves. The values of Q_{e-flow} written in red in Table 4.10 refer to the release of the total natural discharge arriving at the dam. The values written in green, on the contrary, are given by the sum of the ecological flow required by the alternative and the additional discharge overflowing downstream of the dam when Q_{ref} exceeds the maximum flow rate that can be withdrawn.

The LPL values calculated for the seven flow release alternatives are shown in Table 4.11. For each alternative, the monthly (or fortnightly) LPL values are indicated, as well as the final LPL score (in the last row), which is calculated as a weighted average (as explained in section 4.2.4). In the second column of Table 4.11, the weights assigned to each month by the RLPS experts are provided. They were defined according to the data, available from institutional databases, about the presence of tourists in the area during the different periods of the year. The highest weight (i.e., 0.20) was assigned to the summer months of July and August, but high weights were also assigned to June (0.15), September (0.14), and May (0.12). During these periods, in fact, there are many tourists (but also local people) hiking in the

Table 4.10 Monthly (or fortnightly) values of flow release (Q_{e-flow}) defined for each alternative (ALT A – ALT G) considered in case study 1, on the Arpy torrent. In the second column, the average monthly values of the watercourse discharge (Q_{ref}) are also shown. The values in red are the same as the corresponding watercourse discharge (i.e., $Q_{e-flow}/Q_{ref} = 1$), while the values in green correspond to the sum of the ecological flow and the additional discharge overflowing when the watercourse discharge exceeds the maximum flow rate that can be withdrawn

Month	Q_{ref}	$Q_{e\text{-flow}}$ (l/s)						
	(l/s)	ALT A	ALT B	ALT C	ALT D	ALT E	ALT F	ALT G
Jan	99	58	45	35	58	58	76	58
Feb	60	58	45	35	58	58	58	58
Mar	81	58	45	35	58	58	76	58
Apr 1-15	126	121	45	35	121	105	121	80
Apr 16-30	282	121	70	35	121	145	201	80
May	735	160	135	135	160	370	370	135
Jun	1233	633	633	633	633	633	735	633
Jul	533	250	190	35	250	251	276	250
Aug 1-15	246	190	100	35	190	176	201	150
Aug 16-31	169	169	70	35	169	126	169	110
Sep	105	105	45	35	100	90	101	80
Oct	108	108	45	35	80	76	76	80
Nov	176	121	45	35	80	76	126	80
Dec	115	58	45	35	58	76	101	58

area and enjoying its natural and historical beauty. On the contrary, a minimum weight (i.e., 0.01) was assigned to the months from November to February, when few visitors reach the considered watercourse stretch due to the presence of snow.

An analogous table, representing the results of the landscape evaluation, is presented to the decision-makers and stakeholders involved in each MADM process carried out in Aosta Valley for water withdrawal sustainability. In particular, the final LPL scores of the different alternatives are included in the decision matrix, together with the scores of the other indicators considered in the MADM assessment, and they contribute to the final ranking of the alternatives.

Table 4.11 Example of the calculation of the LPL indicator for the flow release alternatives (ALT A – ALT G) illustrated in Table 4.10, for case study 1. The monthly (or fortnightly) LPL values are indicated for each alternative. In the second column, the weights assigned to the different months are also shown. The final LPL results, calculated for each alternative ($LPL_{ALTERNATIVE}$) and used in the MADM assessment, are given in the last row. The colors represent the different classes of landscape protection (i.e., blue = high, green = good, yellow = moderate, orange = poor)

Month	Weight	Normalized LPL values						
		ALT A	ALT B	ALT C	ALT D	ALT E	ALT F	ALT G
Jan	0.01	0.54	0.45	0.37	0.54	0.54	0.72	0.54
Feb	0.01	0.84	0.72	0.49	0.84	0.84	0.84	0.84
Mar	0.05	0.64	0.48	0.39	0.64	0.64	0.90	0.64
Apr 1-15	0.05	0.91	0.40	0.29	0.91	0.60	0.91	0.55
Apr 16-30		0.28	0.24	0.21	0.28	0.35	0.68	0.25
May	0.12	0.23	0.22	0.22	0.23	0.48	0.48	0.22
Jun	0.15	0.58	0.58	0.58	0.58	0.58	0.65	0.58
Jul	0.20	0.42	0.27	0.19	0.42	0.43	0.44	0.42
Aug 1-15	0.20	0.64	0.28	0.21	0.64	0.58	0.65	0.60
Aug 16-31		0.92	0.32	0.23	0.92	0.45	0.93	0.38
Sep	0.14	0.92	0.45	0.37	0.90	0.81	0.91	0.79
Oct	0.05	0.92	0.44	0.37	0.78	0.77	0.77	0.78
Nov	0.01	0.43	0.24	0.23	0.33	0.33	0.40	0.33
Dec	0.01	0.47	0.44	0.31	0.47	0.57	0.82	0.47
$LPL_{ALTERNATIVE}$		0.61	0.37	0.31	0.60	0.56	0.67	0.52

4.4 Analysis of the main characteristics of the described indicator

A critical analysis of the main properties of the LPL indicator, based on the results obtained for the four considered case studies, was carried out to identify its main strengths and some possible weaknesses. Four evaluation criteria were considered for this purpose, i.e., reactiveness, representativeness of the corresponding stakeholders' needs, comparability with the other MADM indicators, and objectivity of the results. Moreover, other characteristics usually considered to assess the suitability of an indicator [16] are discussed in section 4.4.2. They concern, for example, the transparency of the elaboration procedure, the availability of the necessary dataset, and the transferability to different river contexts (i.e., the possibility to be adapted to different locations and scales).

4.4.1 Use of evaluation criteria to analyze the main indicator properties

The first considered evaluation criterion analyzed the effective **reactiveness** of the indicator, i.e., the causal relationship between the indicator and the different alternatives. This characteristic is essential because the use of non-reactive indicators limits the significance of the MADM assessment [16].

For the LPL indicator, the results should vary accordingly with the variation in the riverscape conditions of the investigated watercourse stretch. In this case, the variation is mainly related to the different flow releases required by the considered alternatives. Indeed, the variation of flow releases, in particular of the ratio Q_{e-flow}/Q_{ref}, affects both the RF and VEF values. An example is represented by the three results shown in Table 4.7 for case study 2, which all refer to July, when the average reference discharge of the watercourse is 1718 l/s. According to the flow release required by the three different alternatives in this month (i.e., 150, 805, and 1520 l/s for ALT E, ALT B, and ALT A, respectively), the ratio Q_{e-flow}/Q_{ref} considerably changes, directly influencing the RF values (for example, RF varies from 5.2 in ALT E to 53.1 in ALT A for subsection 1). Moreover, the flow release variation also affects the assessment of the level of alteration of the visual metrics considered for the calculation of the VEF parameter, leading to different VEF values (i.e., in this case, 9, 30.6, and 63, respectively). Consequently, also the final LPL score changes according to the required flow release. In the examples proposed for case study 2, LPL is 0.20 in ALT E, 0.41 in ALT B, and 0.70 in ALT A, which even correspond to different classes of landscape protection (i.e., poor, moderate, and good, respectively).

Another example demonstrating the reactiveness of the LPL indicator is represented in Table 4.12. It shows some LPL results for case study 1 corresponding to different months but all requiring the same flow release (i.e., 58 l/s). Therefore, the ratio Q_{e-flow}/Q_{ref} decreases with the increase of the average available discharge of the different months (i.e., 60 l/s in February, 81 l/s in March, and 115 l/s in December). This influences the values of RF and VEF and the final LPL score, which changes from 0.84 (in February) to 0.64 (in March) and 0.47 (in December), corresponding again to different classes of landscape protection (i.e., high, good, and moderate, respectively).

Table 4.12 Different results of the landscape indicator (LPL, normalized) for case study 1, on the Arpy torrent, with the same flow release ($Q_{e\text{-flow}} = 58$ l/s). The results correspond to different months: therefore, the average watercourse discharge (Q_{ref}) is different. This variation influences both the Release Factor (RF) and Visual Elements Factor (VEF), while the Constraint Factor (CF) does not vary (adapted from [6])

$Q_{e\text{-flow}} = 58$ l/s					**ALT A – February** $Q_{ref} = 60$ l/s $Q_{e\text{-flow}}/Q_{ref} = 0.97$			**ALT A – March** $Q_{ref} = 81$ l/s $Q_{e\text{-flow}}/Q_{ref} = 0.72$			**ALT A – December** $Q_{ref} = 115$ l/s $Q_{e\text{-flow}}/Q_{ref} = 0.50$		
Subsections		Visibility	Length (m)	CF	RF	VEF	LPL (Class)	RF	VEF	LPL (Class)	RF	VEF	LPL (Class)
1	ab	B – medium	157	18	43.5	78.8	0.84 (High)	32.2	56.3	0.64 (Good)	22.7	36.0	0.47 (Moderate)
2	bc	C – low	170	28	29.0			21.5			15.1		
3	cd	A – high	111	9	58.0			43.0			30.3		
4	de	C – low	209	28	29.0			21.5			15.1		
5	ef	B – medium	275	16	43.5			32.2			22.7		

A second important feature of the indicator is its **representativeness** of the related stakeholders' needs and interests. The compliance of the LPL results with the expert judgment of the Regional Landscape Protection Service representatives is ensured, in particular, by VEF. This parameter, in fact, requires the assessment of different metrics of riverscape perception, using a set of images of the bypassed stretch, quantifying their level of alteration compared to the reference conditions. Therefore, the VEF value allows a measure of the visual effects of the flow releases, directly based on the knowledge and requirements of the RLPS experts.

Furthermore, with a maximum value of 90 points, VEF accounts for 55% of the total range of the LPL indicator (i.e., 165). It has, therefore, the largest influence on the indicator results. This is confirmed by the trend represented in Figure 4.5, which shows that, for all the case studies, the VEF values generally increase from 9 to 90 with the increase of the final LPL results. Hence, it is evident that also the overall indicator fully represents the satisfaction level of the landscape experts, who in turn represent the stakes of the direct riverscape users.

Moreover, the CF parameter is related to the safeguard of significant landscape elements identified by national and regional laws, which by themselves represent a considerable value for the local community. Besides, the parameter also includes the point of view of the potential riverscape users by evaluating the visibility of the analyzed watercourse stretch. The possibility of directly involving riverscape users in the LPL assessment is discussed in the concluding remarks (section 4.5).

Another evaluation criterion analyzed the **comparability** of the LPL indicator with the other indicators considered in the MADM framework adopted in Aosta Valley for the assessment of water withdrawal sustainability. The SHARE MCA method is a linear additive technique that requires the same preference direction of the scales of all the considered indicators and the normalization of their final scores. These two conditions are satisfied by the LPL indicator. As highlighted, for example, in Tables 4.7, 4.8, and 4.9, in the second to last column, the final LPL scores have corresponding normalized values, varying between 0 and 1 (in brackets in the tables). Moreover, since the considered decision problem is of maximization (i.e., the best alternative is the scenario with the highest score), also the scale of the LPL indicator has a preference direction of maximization. In fact, a higher LPL score corresponds to a better satisfaction level of the related stakeholders, as illustrated in Table 4.3 through the different classes of landscape protection. The examples provided in

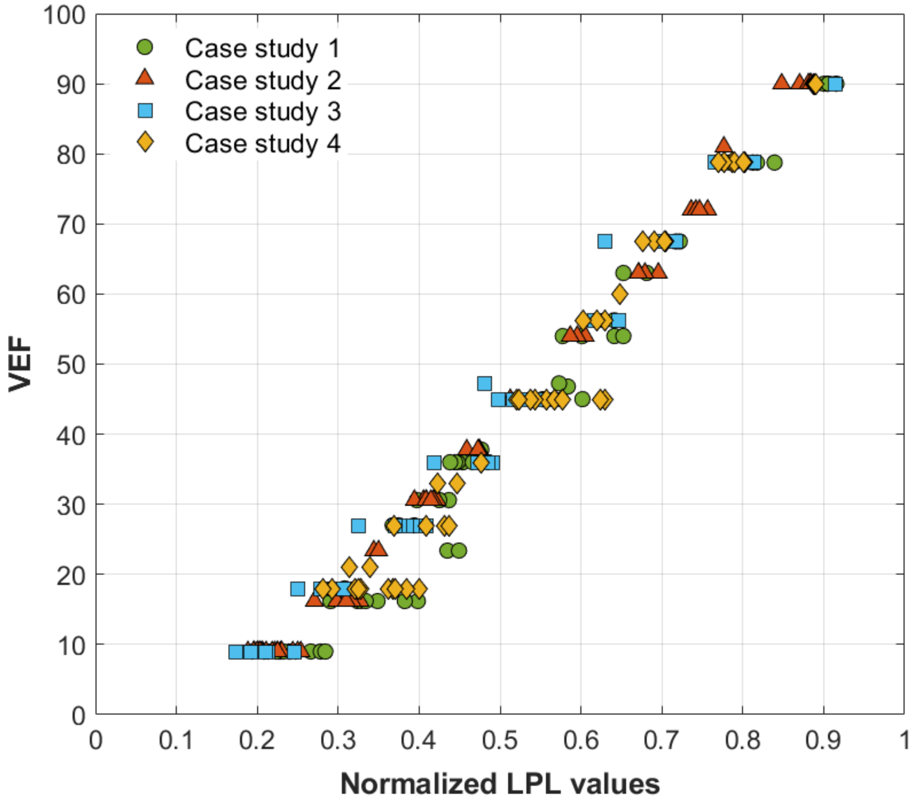


Fig. 4.5 Trend of the scores of the Visual Elements Factor (VEF) with the increase of the final landscape indicator values (LPL), for the four considered case studies. All the values available for the four case studies (i.e., all the VEF and LPL monthly, or fortnightly, values calculated for the different considered alternatives) are taken into account

section 4.3.2 reveal that better riverscape conditions in the bypassed stretch (due to higher values of Q_{e-flow} related to the available discharge) correspond to higher LPL scores and, frequently, to a better class of landscape protection (e.g., from poor to good for case study 2 in Table 4.7). In addition, Table 4.11 illustrates how the final LPL score is calculated for different flow release alternatives (described in Table 4.10) considered in a MADM procedure. This example demonstrates that the LPL indicator allows a quantification of the water withdrawal effects on the river landscape, as well as the other indicators included in the MADM decision tree quantify the impacts on the other affected sectors (i.e., environment, energy production, and economic aspects).

A further relevant feature of the indicator is the **objectivity** of its results, which should not be influenced by a subjective evaluation of the experts involved in the analysis of the available data. For the LPL indicator, this property can be assessed considering each parameter leading to the calculation of the final LPL score. The CF values calculated for the subsections do not vary in the different evaluations related to the same bypassed stretch. Moreover, they are verified on a cartographic basis, thus ensuring the objectivity of the parameter, in addition to a direct normative reference. The RF values, quantifying the “naturalness” level of flow releases downstream of the dam, are not affected by personal evaluations since they are directly related to the ratio Q_{e-flow}/Q_{ref}. The necessary flow data series are continuously collected by a hydrological monitoring system installed at the withdrawal dam. On the contrary, the evaluation carried out by the landscape experts to quantify the VEF parameter, analyzing different images of the bypassed stretch, has a margin of subjectivity, in particular, when it is carried out by only one expert. However, to minimize subjectivity as much as possible, at least three RLPS experts are involved in the analysis of the collected set of images for each case study. Moreover, these experts have a great direct knowledge of the territory and a large experience in quantifying the level of alteration of the considered metrics of riverscape perception.

4.4.2 Further characteristics of the LPL indicator

The procedure for the calculation of the landscape indicator described in this Chapter is traceable and transparent. It is carried out by a group of experts of the Regional Landscape Protection Service, whose specific knowledge is necessary (especially for the assessment of the CF and VEF values), but the entire procedure can also be understood by decision-makers and stakeholders without a technical background. Moreover, the data used for the LPL calculation are transparently shared with all the other actors involved in the MADM process.

Another important characteristic of the indicator is represented by the RF parameter, which correlates the landscape protection level with the flow releases required by the considered alternative. Actually, the difference between levels of riverscape alteration corresponding to releases that differ by a few tens of $\mathrm{l/s}$ is not often easily perceivable, in particular by a generic landscape user. However, this correlation is essential since all the indicators included in the MADM decision tree are related to the watercourse discharge. Therefore, the RF parameter allows the compensation of the different levels of efficiency usually characterizing the use of water resources by different river beneficiaries (i.e., for example, a decrease in flow release of 10 l/s can actually increase HP production, but it would probably not be detected by a general visual assessment).

Furthermore, the LPL indicator can also be used for *ex-ante* evaluations, i.e., to assess the suitability of a new water withdrawal license. In this case, the alternatives are different possible schemes of flow releases to be implemented downstream of the potential withdrawal point. The LPL indicator is thus employed to predict the impact of a new withdrawal dam on the downstream riverscape before its construction. The same phases described in section 4.2 are followed to calculate the final LPL score. To assess the VEF parameter, the photos representing the altered conditions are selected among the images of the considered watercourse stretch corresponding to the same discharge value as the proposed flow releases. In fact, during the application for a new water withdrawal license, the proponent is required to install a basic hydrological monitoring station in the watercourse, also collecting a set of photos related to the measured flow values. Nevertheless, longer periods are usually necessary to gather a sufficient database for *ex-ante* evaluations since the different conditions of the flow regime should be analyzed. On the contrary, for existing withdrawals, a significant part of the desired flow conditions could also be determined by manipulating the releases from the existing dam.

The landscape indicator presented in this Chapter has been developed to be specifically used in the Aosta Valley context (e.g., by considering regional and national landscape protection constraints for the calculation of CF). However, its transferability to different river contexts could be implemented in the future, after some revisions. In particular, for the adaptation to another location, the CF parameter should be updated according to the local regulations in force. Moreover, the visual metrics of riverscape perception currently considered for the assessment of VEF are typical of mountain watercourses, usually characterized by a mean annual discharge of a few m^3/s, a steep slope, and the presence of pools and small waterfalls. Therefore, for an adaptation of the LPL indicator to a larger scale (e.g., to large rivers in the floodplain), these elements should be revised as well. Visual metrics corresponding to all the main hydromorphological units characterizing the different types of watercourses present in the area should thus be identified for this purpose.

Despite the numerous benefits deriving from the use of the LPL indicator discussed above, some limitations are still present. For example, the assessment of the VEF parameter requires the collection of representative images of the bypassed stretch covering the entire variability of the hydrological regime, aligned with flow data. This process can take a long time (almost one year, according to recent experience), especially for *ex-ante* evaluations. Furthermore, the time necessary to gather a reliable visual database is added to the time required for data processing and validation, thus increasing the overall time extension taken to achieve the final LPL scores.

Moreover, to quantify the effect of each alternative considered in the MADM assessment on the riverscape, different LPL values have to be calculated, for each monthly (or fortnightly) flow release. For this reason, the work carried out by the landscape experts could be particularly demanding. In particular, the analysis of the collected set of images, assessing the visual metrics of riverscape perception, to calculate the VEF values is a complex procedure, which may also be affected by a certain level of uncertainty. Hence, at least three RLPS experts are regularly involved in this task, to ensure the maximum expertise and the highest possible objectivity. For each case study considered in this paper, the calculation of all the LPL scores required on average about 2.5 weeks. However, this duration was mainly dependent on the number of considered alternatives and on the number of subsections into which the bypassed stretch was split.

4.5 Concluding remarks

The Landscape Protection Level indicator developed in Aosta Valley allows the assessment of water withdrawal effects on the riverscape of a bypassed watercourse stretch. As demonstrated by the examples presented in section 4.3, the indicator can be used to assess both the suitability of a specific flow release value and different flow release scenarios, varying along the year, evaluated through a MADM procedure. The examples of the LPL application demonstrate its fitness for real case studies, even in more complex situations involving different withdrawals, as in case study 4, on the Saint-Marcel torrent (see Table 4.9).

Compared to previous studies, the LPL indicator allows the quantification of both the landscape asset of the watercourse stretch (through the CF parameter, ensuring also a direct normative reference) and the impact of flow releases on the visual riverscape perception (by means of VEF). Moreover, the RF parameter enables a correlation of the landscape protection level with a precise value of the discharge flowing downstream of the withdrawal dam.

Nevertheless, since some limitations of the indicator have been noticed, additional efforts should be made to further improve its applicability. For example, to ensure a more scientific basis for the VEF parameter, the visual metrics of riverscape perception should be aligned with the classification of hydromorphological units proposed by Rinaldi et al. [205], also considered in the MesoHABSIM methodology (see Chapter 3, section 3.2.3). In this way, the possible variations of the watercourse morphology downstream of the withdrawal dam, which can influence the visual perception of the river users, would be included in the landscape assessment. Moreover, this revision could be the starting point to allow the transferability of the LPL indicator to other river contexts.

Furthermore, some activities could be directed to involve the riverscape users in the procedure of water withdrawal suitability assessment, in particular for a final evaluation of the selected flow release alternative. In fact, the real beneficiaries of the river landscape, i.e., the local community and tourists, are currently not “directly” involved in the evaluation of the LPL indicator. For example, the use of surveys or interviews, adopted in numerous studies about the assessment of landscape attributes (e.g., [214, 217]), has not been considered until now. The reason is that a generic landscape user would hardly be able to perform an accurate evaluation of the riverscape perception changes related to even slight variations of the watercourse discharge. Specific expertise for evaluating a complex mix of different elements composing the cultural heritage is required. Moreover, the RLPS experts also have a deep direct knowledge of the regional territory and they usually organize field surveys in the site in which the withdrawal dam is (or will be) located to ensure a more accurate assessment of the different parameters. Therefore, the needs and interests of the direct landscape stakeholders are well represented by the LPL indicator, calculated by the landscape experts.

However, for some case studies, the riverscape users could be involved, in particular after the implementation of the release scenario selected at the end of the MADM process, collecting their impressions of the aesthetic quality and naturalness of the affected watercourse section. This analysis could be implemented by means of surveys or interviews with a representative sample of the main river users (e.g., tourists, fishermen, canoeists, etc.) in order to obtain their *ex-post* assessment of the actual withdrawal effect on the riverscape perception.

Chapter 5

Comparison of different MADM methods applied to the same case study of hydropower management

5.1 Introduction

Part of the work described in this Chapter has been previously published in the paper [7].

The use of multi-criteria decision-making to address real decision problems can lead to relevant actions (e.g., construction of a dam, allocation of water resources to different areas, etc.), as demonstrated by the results of the review analyzed in Chapter 2. Therefore, evaluating how different MADM methods may affect the preference ordering of the considered alternatives (and, thus, the final decision) is extremely important. This assessment could also provide specific guidance on choosing the most appropriate approach to support decision-makers dealing with surface water resources management.

As illustrated in Chapter 2, 25.3% of the scientific articles selected for the review applied different MADM methods to the same case study and compared the obtained results. However, in most of these studies, the comparative analysis was performed only in qualitative terms, briefly discussing the main differences among the rankings generated by the considered methods. Only few authors carried out a more in-depth assessment of the obtained results. For example, in some studies, correlation tests, like Spearman and Kendall tests, were used to statistically analyze the correlation among the obtained rankings (e.g., [188, 137]). Aggregation methods, like Borda and Copeland techniques, were also used by some authors to combine the rankings produced by the different MADM methods, determining in this way the final ordering of the considered alternatives (e.g., [194, 226]). In other studies, these techniques were used to identify the most suitable MADM method for the considered case study by comparing each ranking with the ranking calculated through the aggregation technique (e.g., [227, 228]).

The MADM procedure presented in this thesis is applied to real case studies in Aosta Valley for the assessment of water withdrawal sustainability, as explained in Chapter 3. In each case study, different flow release alternatives are proposed by the involved stakeholders to identify the most appropriate scenario of ecological flows to be released downstream of the withdrawal point. The alternative selected at the end of the decision-making process is implemented in the affected watercourse stretch, after the official endorsement of the Regional Government. Therefore, the MADM procedure has actual effects on the management of surface water uses.

For this reason, to assess the effectiveness of the MADM method adopted in Aosta Valley, i.e., SHARE MCA, other MADM techniques have been tested on the same case study of hydropower management, considering the revised decision tree described in the previous Chapters. Six methods were selected among the most used in the literature [71, 229], i.e., SAW, WPM, AHP, TOPSIS, VIKOR, and ELECTRE III.

The aim of this Chapter is to test the applicability of the considered MADM methods to the decision problems typically faced in Aosta Valley, i.e., the selection of an optimal flow release scenario to be implemented downstream of a withdrawal dam. Comparative analyses of the MADM techniques are carried out based on the obtained rankings of the alternatives and by evaluating the main features of each methodological approach. These analyses are used to assess whether the results of SHARE MCA are in line with the results generated by other popular MADM methods and whether its methodological approach is the most appropriate for the considered decision-making processes.

The Chapter is organized as follows: the application of the considered MADM methods to a real case study is described in section 5.2, illustrating the data and the tools used to implement the different techniques. In section 5.3, the rankings generated by the considered MADM methods and the results of the comparative and sensitivity analyses are presented. Moreover, in section 5.4, the different methodological approaches are evaluated according to their suitability for the considered decision-making problem, assessing some significant features (e.g., necessary datasets, ease of use, reliability, etc.). Finally, some concluding remarks about the obtained results are presented in section 5.5, highlighting the reasons why SHARE MCA is considered highly suitable for the procedure adopted in Aosta Valley for water withdrawal management.

5.2 Application of different MADM methods to the same real case study

The results of the review presented in Chapter 2 showed that several MADM methods, based on different theoretical approaches, have been considered in the literature to deal with a variety of decision-making problems concerning surface water resources management (see section 2.3.2). As highlighted in Chapter 2, no method can be considered better than the others in any decision-making situation [44]. Therefore, the selected technique should be the most appropriate for the decision context and the stakeholders' technical background. For this reason, investigating and comparing different MADM methods can contribute to improving the quality of decision-making.

5.2.1 Selected MADM methods

In this Chapter, the following seven MADM methods are applied to the same decision problem to compare their ranking performance:

- SHARE MCA [200], i.e., the method used in the decision-making processes carried out in Aosta Valley, based on a hierarchical framework, the use of normalization functions, and additive aggregation to calculate the overall performance score of each alternative (see Chapter 3, section 3.2.1);

- SAW (Simple Additive Weighting) [72], which ranks the alternatives based on their weighted sum performance;
- WPM (Weighted Product Method) [230], which calculates the overall value of each alternative by multiplying different ratios, one for each criterion, raised to the corresponding criterion weight;
- AHP (Analytical Hierarchy Process) [73], in which the alternatives are pairwise compared on each criterion and an additive aggregation is used to obtain their overall performance value;
- TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) [11], which ranks the alternatives according to their distance from the ideal and the negative-ideal solutions;
- VIKOR (multicriteria optimization and compromise ranking) [231], which identifies the compromise solution(s) among the considered alternatives based on their closeness to the ideal solution;
- ELECTRE III (elimination and choice translating reality) [232], which is based on the outranking binary relation between the alternatives and the use of pseudo-criteria.

The last six methods, to be compared with SHARE MCA, have been selected because they are among the most widely used in the literature, as demonstrated also by the results of the review presented in Chapter 2. Moreover, each method is based on a different theoretical approach to represent the decision-maker's preference structure. All the three broad categories identified by Belton and Stewart [3] (see section 2.2.2) are represented: SAW, WPM, and AHP are methods based on *value measurement*, TOPSIS and VIKOR can be included in the category of *goal, aspiration, or reference level models*, while ELECTRE III is an *outranking* method. Furthermore, different techniques are used for the normalization of the decision matrix, which is usually necessary to handle different types of attributes (but in ELECTRE III, for example, normalization is not required). Besides, VIKOR and ELECTRE III produce a different output compared to the other selected methods and they do not always achieve a global ranking of the alternatives [229].

Additional information about the selected methods (excluding SHARE MCA) can be found in Appendix B, where the most popular MADM methods are described.

5.2.2 Implementation of the MADM methods in the case study

The case study on which the different MADM methods were tested concerns the same small run-of-the-river HP plant, located on the Graines torrent, described in Chapter 3. The aim was to identify the optimal flow release scenario to be implemented downstream of the withdrawal dam. As explained in section 3.3.1, a set of nine flow release alternatives (from ALT 0 to ALT 8) was evaluated, including the "reference alternative" (ALT 0), i.e., the initial scenario of ecological flows. Some alternatives are based on fixed monthly values of flow releases. Other scenarios, on the contrary, are "real-time alternatives", based on a minimum monthly flow release value, incremented by an additional release, varying on an hourly basis, calculated as a percentage of the natural watercourse discharge. The set of evaluated alternatives has already been presented in Chapter 3 (Table 3.2).

Moreover, the revised decision tree illustrated in Figure 3.4 was considered for all the MADM methods. The indicators adopted in the case study have been described in section 3.3.1 (additional information about the revised landscape indicator has been provided in Chapter 4). They all have the same preference direction, i.e., of maximization. Furthermore, the same set of weights defined at the end of the decision-making process on the Graines torrent was adopted. Later, for sensitivity analysis, another scheme of weights, assigning equal importance to all the main criteria, was also considered. Table 5.1 shows the decision matrix of the considered case study, with the scores of the nine flow release alternatives according to the different indicators. The cumulative weights and the direction of preference of the indicators are also highlighted. These data were used for the implementation of all the selected MADM methods, in order to obtain comparable results.

Most of the considered MADM methods, i.e., SAW, WPM, TOPSIS, and VIKOR, are based on simple algorithms. Therefore, their computational procedure was implemented in Microsoft Excel®. For the other methods, specific software was employed. The *SESAMO SHARE* software [200] was used for SHARE MCA: it directly calculates the overall performance score of each alternative based on the normalization functions and the relative weights introduced by the user. Instead, the SuperDecisions® software, version 3.2.0 [233], was used to implement the mathematical calculations of AHP, including the pairwise comparison process, consistency analysis, and normalization of results. Finally, the mathematical procedure of ELECTRE III was performed through the J-ELECTRE software, version 2.0 [234].

Table 5.1 Decision matrix of the case study on the Graines torrent, including the cumulative weights of the indicators (IEn = Energy Index, IH = Index of river Habitat integrity, LPL = Landscape Protection Level, IEc = Economic Index, RCS = Services for the community, RC = Financial income for the community), their preference direction (max. = maximization), and the thresholds required by ELECTRE III (q = indifference, p = preference, v = veto) (adapted from [7])

		IEn	IH	LPL	IEc	RCS	RC
Weights		0.25	0.3	0.3	0.015	0.007	0.128
Preference direction		max.	max.	max.	max.	max.	max.
ELECTRE thresholds	q	0.036	0.06	19.8	0.035	0	0.001
	p	0.186	0.20	40.0	0.220	0	0.048
	v	0.60	0.30	80.0	0.60	0.6	0.36
ALT 0		0.63	0.74	98.3	0.31	0.40	0.10
ALT 1		0.79	0.49	33.3	0.60	0.60	0.36
ALT 2		0.70	0.65	86.1	0.43	0.60	0.19
ALT 3		0.70	0.65	98.5	0.44	0.60	0.19
ALT 4		0.73	0.61	81.3	0.49	0.60	0.24
ALT 5		0.83	0.45	39.3	0.67	0.80	0.46
ALT 6		0.82	0.50	40.1	0.66	0.80	0.44
ALT 7		0.80	0.50	48.3	0.62	0.80	0.39
ALT 8		0.75	0.59	66.4	0.52	0.60	0.27

The software calculates the concordance, discordance, and credibility matrices, the ascending and descending rankings, and the final pre-order of the alternatives.

Furthermore, some of the considered MADM methods require the definition of additional parameters. The way in which they were determined is described below.

For SHARE MCA, the normalization function of each indicator was defined by the corresponding stakeholders, along with the elaboration of the indicator itself. The normalization functions associated with the indicators Energy Index (IEn), Habitat Integrity Index (IH), Landscape Protection Level (LPL), and Economic Index (IEc) have been represented in Chapter 3 (Figure 3.6). They are all linear functions. The normalization functions of the indicators Services for the community (RCS) and Financial income for the community (RC) are not illustrated since RCS is based on an ordinal scale, while RC is derived from the IEc values.

Table 5.2 Simulated pairwise comparisons of the criteria (for the final set of weights defined in the case study). The last column shows the criteria weights calculated by the SuperDecisions® software. The inconsistency is 0.023 (thus acceptable because < 0.10)

	Energy	Environment & fishing	Landscape	Economy	Weights
Energy	1	1/2	1/2	2	0.20
Environment & fishing	2	1	1	2	0.33
Landscape	2	1	1	2	0.33
Economy	1/2	1/2	1/2	1	0.14

Table 5.3 Simulated pairwise comparisons between the two economic sub-criteria. The last column shows the sub-criteria weights calculated by the SuperDecisions® software. The inconsistency is 0 since only two elements are compared

	HP producer income	Community income	Weights
HP producer income	1	1/8	0.11
Community income	8	1	0.89

In the AHP method, pairwise comparisons of criteria, economic sub-criteria, and indicators were simulated based on the set of weights defined by the stakeholders involved in the real case study. The results are presented in Tables 5.2, 5.3, and 5.4, showing, in the last column, the weights of the compared elements calculated by the SuperDecisions® software. On the contrary, comparisons of the alternatives with respect to each indicator were obtained through direct input, i.e., by introducing the scores shown in Table 5.1 in the specific “direct input area” of the software. Therefore, real pairwise comparisons, directly involving the decision-maker or the stakeholders, were not carried out. The main reason for this choice was the intent to use input data (scores and weights) analogous to the values also considered for the other MADM methods, thus obtaining a final ranking comparable with the other results.

For VIKOR, the coefficient υ was set equal to 0.5. In this way, the two strategies of “the majority of criteria” and “the individual regret” were compromised.

Finally, in ELECTRE III, the indifference, preference, and veto thresholds (q_j, p_j, and v_j) for each indicator were defined with the support of some experts and

Table 5.4 Simulated pairwise comparisons between the indicators associated with the sub-criterion Community income. The last column shows the indicators' weights calculated by the SuperDecisions® software. The inconsistency is 0

	Services (RCS)	Financial income (RC)	Weights
Services (RCS)	1	1/9	0.10
Financial income (RC)	9	1	0.90

stakeholders involved in the case study. Their values are shown in Table 5.1. The indifference threshold was defined by evaluating the level of uncertainty associated with the procedure of quantification of the indicator. In fact, it was assumed that, when the scores of two alternatives differ for a value lower than this level of uncertainty, the discrimination between the two alternatives is difficult. On the contrary, the preference and veto thresholds were defined, for each indicator, based on the level of satisfaction of the corresponding stakeholders.

More specifically, the indifference threshold of IEn was established using a hydrological series of the Graines torrent, considering the average amount of energy produced by the HP plant in 15 days. Indeed, 15 days per year of downtime for an HP plant are generally considered usual by HP producers (due to non-predictable failures, required maintenance operations, etc.) and the consequent losses of energy production can be considered acceptable. Therefore, the corresponding value of IEn, assessed as 3.6%, was assigned to q. Instead, the preference threshold was defined by considering the difference, in terms of average annual energy production, between two flow release scenarios, one of which received a net preference compared to the other one. The corresponding value of IEn, assessed as 18.65%, was assigned to p. Finally, the veto threshold was set equal to 0.60, based on the classification used for the Energy Index, which is analogous to the classification of the IH indicator (see Table 3.1 in Chapter 3). In fact, 0.6 corresponds to the difference between two alternatives that are in two classes considered strongly different (e.g., high and poor or good and bad). The alternative with the lower value of IEn would be considered unacceptable in terms of energy production.

The values of the thresholds for IEc ($q = 3.5\%$, $p = 22\%$, $v = 0.60$) and RC ($q = 0.1\%$, $p = 4.8\%$, $v = 0.36$) were obtained based on analogous considerations.

Instead, to define the indifference threshold for IH, the level of uncertainty associated with the calculation of the indicator, based on the MesoHABSIM method, was assessed. An expert was thus involved in this assessment, according to his large experience in applying the method, and the value of q was estimated as 0.06. The p value, on the contrary, was set equal to 0.20 based on the classification of the IH scores into five classes of quality (as illustrated in Table 3.1). In fact, a difference of 0.20 between two alternatives means that they are in two different, contiguous, classes of quality and a net preference must be assigned to the alternative in the higher class. Moreover, the veto threshold, $v = 0.30$, was established based on several simulations. The value corresponds to a difference between two alternatives considered significant enough to judge the alternative with the lower score as unacceptable for the ecological status of the watercourse. This veto might appear too low compared to the total range of the IH score (variable from 0 to 1). However, generally, the range of the IH scores calculated for the same watercourse stretch in different conditions is relatively small and a difference of 0.3 can discriminate between two very different situations.

The thresholds defined for the LPL indicator were based on similar considerations. The value of q was defined by estimating the level of uncertainty associated with the procedure for the calculation of the LPL score, especially for the quantification of the VEF parameter by the landscape experts. It was considered that an error may occur mainly in the assessment of photos related to the summer months with lower discharges, i.e., July and August. Therefore, taking into account the weights assigned to these months in the specific case study, this level of uncertainty (and, thus, the value of q) was estimated as equal to 19.8. The values $p = 40$ and $v = 80$, on the contrary, were defined according to the classification of the LPL scores (see Table 4.3 in Chapter 4), based on the same observations made for the IH indicator.

Finally, RCS is a true criterion since it is based on an ordinal scale. Therefore, $q = p = 0$. Furthermore, the selected value of the veto threshold, i.e., $v = 0.6$, corresponds to a difference between two alternatives significant enough to consider the alternative with the lowest score as unacceptable for the local community.

5.3 Comparison of the results obtained through the different MADM methods

Different comparative analyses were carried out to measure the degree of agreement of the MADM methods applied to the case study on the Graines torrent. Kendall's tau and Spearman's rho correlation tests were performed to analyze the correlation among the obtained rankings. The similarity between each ranking and the aggregated order generated through the Borda and Copeland methods was also examined to compare the performance of the considered MADM techniques. (A description of the considered correlation tests and aggregation methods is provided in Appendix C.) Furthermore, based on previous studies comparing different MADM methods (e.g., [71, 235]), an additional test was performed by evaluating the number of ranks matched, expressed as the percentage of the total number of alternatives.

The same comparative analyses were carried out to assess the results obtained by adopting two different sets of weights. Therefore, the sensitivity of each MADM method when affected by weight uncertainty was also investigated.

5.3.1 Comparative analyses of the different rankings

The results of the seven considered MADM methods applied to the case study on the Grained torrent are presented in Table 5.5. For SHARE MCA, SAW, WPM, and AHP, the final performance value (P_i) and the rank (r_i) of each alternative are indicated in the table. For TOPSIS, the distance of each alternative from the ideal solution (D_i^*) and from the negative-ideal solution (D_i^-), as well as its relative closeness to the ideal solution (RC_i), are also shown. The ranking positions r_i of these five methods are highlighted in bold type. For VIKOR, the values S_i, R_i, and Q_i of the three rankings produced by the method are indicated. In the row corresponding to r_i, the ranks obtained according to the condition of the "acceptable advantage" (see Appendix B) are shown. Moreover, the alternatives identified as compromise solutions are highlighted in bold type. Finally, for ELECTRE III, the position of each alternative in the rankings generated by the ascending distillation (R_{Ai}) and the descending distillation (R_{Di}) are indicated, while the final pre-order of the alternatives is represented in Figure 5.1.

Table 5.5 Results of the case study on the Graines torrent according to the different MADM methods, using the final set of weights (P_i = final performance value of alternative i; r_i = position in the ranking; D_i^* = distance from the ideal solution, D_i^- = distance from the negative-ideal solution, RC_i = relative closeness, calculated in TOPSIS; S_i, R_i, Q_i = values calculated in VIKOR; r_{Ai} = position in the ascending ranking, and r_{Di} = position in the descending ranking, for ELECTRE III) (adapted from [7])

		ALT 0	ALT 1	ALT 2	ALT 3	ALT 4	ALT 5	ALT 6	ALT 7	ALT 8
SHARE MCA	P_i	0.579	0.464	0.562	0.584	0.556	0.488	0.500	0.503	0.532
	r_i	**2**	**9**	**3**	**1**	**4**	**8**	**7**	**6**	**5**
SAW	P_i	0.599	0.349	0.578	0.635	0.572	0.428	0.463	0.456	0.520
	r_i	**2**	**9**	**3**	**1**	**4**	**8**	**6**	**7**	**5**
WPM	P_i	2.344	1.890	2.434	2.535	2.448	2.031	2.089	2.161	2.334
	r_i	**4**	**9**	**3**	**1**	**2**	**8**	**7**	**6**	**5**
AHP	P_i	0.040	0.029	0.039	0.041	0.038	0.031	0.032	0.033	0.035
	r_i	**2**	**9**	**3**	**1**	**4**	**8**	**7**	**6**	**5**
TOPSIS	D_i^*	0.054	0.103	0.046	0.042	0.046	0.098	0.093	0.083	0.059
	D_i^-	0.105	0.040	0.084	0.100	0.077	0.054	0.052	0.049	0.059
	RC_i	0.663	0.279	0.647	0.703	0.626	0.356	0.360	0.372	0.501
	r_i	**2**	**9**	**3**	**1**	**4**	**8**	**7**	**6**	**5**
VIKOR	S_i	0.401	0.651	0.422	0.365	0.428	0.572	0.537	0.544	0.480
	R_i	0.250	0.300	0.163	0.163	0.134	0.300	0.269	0.248	0.155
	Q_i	0.412	1.000	0.185	0.085	0.111	0.863	0.708	0.657	0.264
	r_i	3	6	**1**	**1**	**1**	5	4	4	2
ELECTRE III	r_{Ai}	1	4	5	1	1	3	2	2	1
	r_{Di}	5	6	2	2	3	6	4	6	1

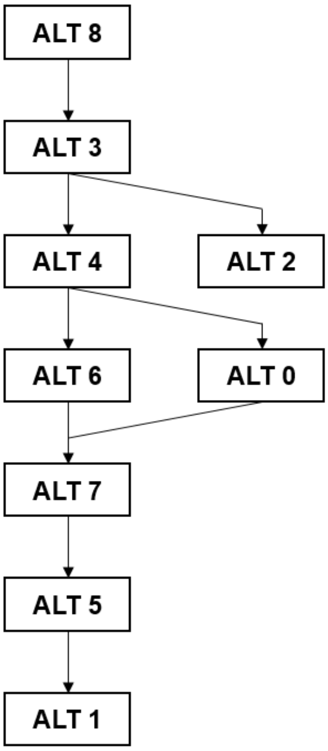


Fig. 5.1 Final pre-order of the alternatives generated by the SuperDecisions® software for the ELECTRE III method considering the final set of weights defined in the case study (adapted from [7])

Similar rankings were generated by the first five methods, whereas VIKOR and ELECTRE III produced different types of results, not only in terms of ranking order but also of format. In particular, the results of VIKOR are three rankings (by Q, S, and R) and a proposed set of compromise solutions. In fact, the best-ranked alternative by Q (i.e., the alternative with the minimum value of Q) was ALT 3. However, the condition of the "acceptable advantage" (i.e., $Q(ALT4) - Q(ALT3) > DQ$, where ALT 4 was the second-ranked alternative by Q and $DQ = 1/(m-1) = 0.125$) was not satisfied. Therefore, a set of three compromise solutions (for which the relation $Q(ALTi) - Q(ALT3) < 0.125$ is still valid) was identified, i.e., ALT 3, ALT 4, and ALT 2. The other ranks r_i were also defined based on the condition of the "acceptable advantage".

On the contrary, looking at the results of ELECTRE III shown in Figure 5.1, it is evident that the final pre-order of the alternatives is affected by some relations of incomparability (i.e., considering two alternatives A_1 and A_2, A_1 is incomparable to

Table 5.6 Results of the Kendall's tau and Spearman's rho correlation tests between the compared methods (excluding VIKOR and ELECTRE III), considering the final set of weights defined in the case study (from [7])

Kendall's tau coefficient					
	SHARE MCA	SAW	WPM	AHP	TOPSIS
SHARE MCA	1.000	0.944	0.833	1.000	1.000
SAW		1.000	0.778	0.944	0.944
WPM			1.000	0.833	0.833
AHP				1.000	1.000
TOPSIS					1.000
Spearman's rho coefficient					
	SHARE MCA	SAW	WPM	AHP	TOPSIS
SHARE MCA	1.000	0.983	0.933	1.000	1.000
SAW		1.000	0.917	0.983	0.983
WPM			1.000	0.933	0.933
AHP				1.000	1.000
TOPSIS					1.000

A_2 if A_1 does not outrank A_2 and A_2 does not outrank A_1, as explained in Chapter 2, section 2.2.3). In fact, ALT 0 is incomparable to ALT 6, while ALT 2 is incomparable to all the other alternatives of the ranking, except ALT 8 and ALT 3.

For these reasons, VIKOR and ELECTRE III were excluded from the statistical comparisons. The other five methods, instead, produced comparable results. Therefore, Kendall's tau (τ) and Spearman's rho (ρ) correlation tests were implemented in Matlab®, R2019b, to analyze the correlation among the obtained rankings. The results of both the statistical tests, provided in Table 5.6, show a high correlation between the considered MADM methods, with $\tau \geq 0.778$ and $\rho \geq 0.917$.

Furthermore, the Borda and Copeland methods were also used to compare the results of the first five MADM techniques. Table 5.7 shows the calculation of the aggregated order through the Borda method, whereas the correlations between each MADM method and the Borda order are illustrated in Figure 5.2. A high similarity of all the rankings is evident. In particular, the Borda ranking is exactly the same as the order produced by SHARE MCA, AHP, and TOPSIS. The results of SAW and WPM, on the contrary, only slightly differ from the Borda ranking ($R^2 = 0.967$ and

Table 5.7 Scores calculated through the Borda method for each MADM technique, Borda sum, and resulting aggregated ranking, using the final set of weights defined in the case study

	SHARE MCA	SAW	WPM	AHP	TOPSIS	Borda sum	Borda ranking
ALT 0	7	7	5	7	7	33	2
ALT 1	0	0	0	0	0	0	9
ALT 2	6	6	6	6	6	30	3
ALT 3	8	8	8	8	8	40	1
ALT 4	5	5	7	5	5	27	4
ALT 5	1	1	1	1	1	5	8
ALT 6	2	3	2	2	2	11	7
ALT 7	3	2	3	3	3	14	6
ALT 8	4	4	4	4	4	20	5

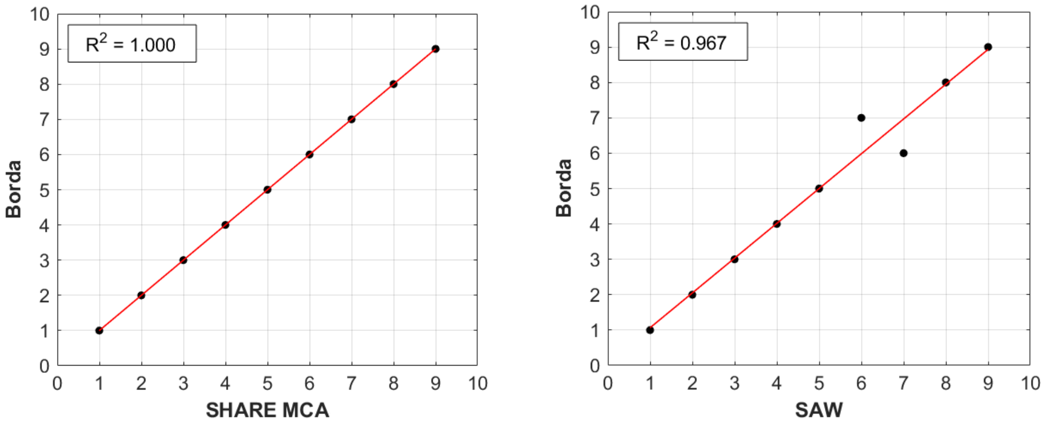
$R^2 = 0.871$, respectively). The aggregated ranking achieved through the Copeland method is the same as the Borda ranking, as represented in Table 5.8.

As concerns the number of ranks matched, Table 5.5 shows that SHARE MCA, TOPSIS, and AHP produced the same ranking (100% of ranks matched). Compared to these methods, the ranking generated by SAW only differs for ALT 6 and ALT 7, whose positions are switched (77.8% of ranks matched). Similarly, the WPM final ranking is only slightly different from the other methods, with the ranks of ALT 4 and ALT 0 switched (77.8% of ranks matched compared to SHARE MCA, TOPSIS, and AHP, and 55.6% compared to SAW).

This test could not be directly applied to the results produced by VIKOR and ELECTRE III, due to their different format. Nevertheless, a qualitative comparison of the obtained rankings was carried out for these methods as well. Considering the ranking by Q calculated for VIKOR, for example, it is evident that the first three alternatives, i.e., ALT 3, ALT 4, and ALT 2 (which represent the set of compromise solutions), are the same as WPM. However, these alternatives are followed by ALT 8, which is only in the fifth position according to the other methods. Moreover, ALT 0 only ranks fifth, while it is in the second rank according to SHARE MCA, SAW, TOPSIS, and AHP. The final part of the ranking, on the contrary, is in line with the results generated by the other methods. Instead, the final ranking produced by ELECTRE III (Figure 5.1) is significantly different. In particular, ALT 8 is the best-ranked alternative, followed by ALT 3, ALT 4, and ALT 2. Moreover, ALT 2 is

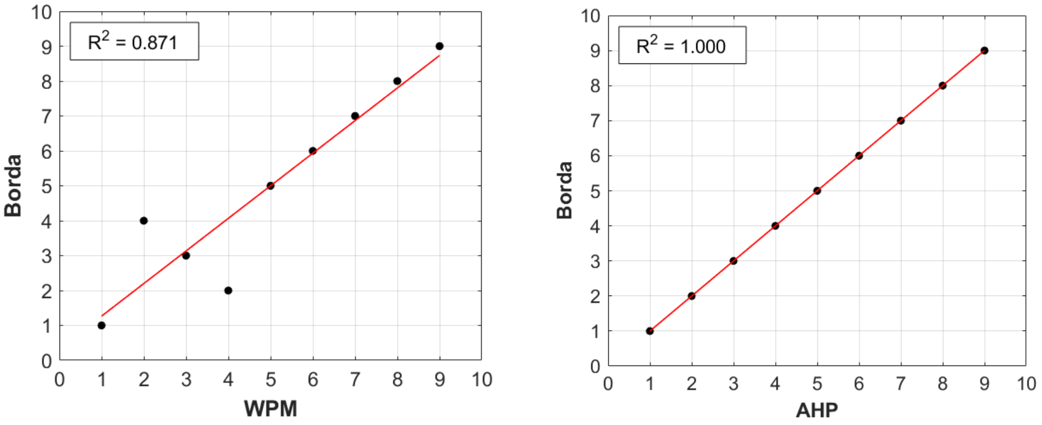
Table 5.8 Pairwise matrix calculated through the Copeland method, number of pairwise victories (V), number of pairwise defeats (L), difference between these two numbers ($V - L$), and resulting aggregated ranking, using the final set of weights defined in the case study

	ALT 0	ALT 1	ALT 2	ALT 3	ALT 4	ALT 5	ALT 6	ALT 7	ALT 8	V	L	$V - L$	Copeland ranking
ALT 0	–	1	1	0	1	1	1	1	1	7	1	6	2
ALT 1	0	–	0	0	0	0	0	0	0	0	8	−8	9
ALT 2	0	1	–	0	1	1	1	1	1	6	2	4	3
ALT 3	1	1	1	–	1	1	1	1	1	8	0	8	1
ALT 4	0	1	0	0	–	1	1	1	1	5	3	2	4
ALT 5	0	1	0	0	0	–	0	0	0	1	7	−6	8
ALT 6	0	1	0	0	0	1	–	0	0	2	6	−4	7
ALT 7	0	1	0	0	0	1	1	–	0	3	5	−2	6
ALT 8	0	1	0	0	0	1	1	1	–	4	4	0	5



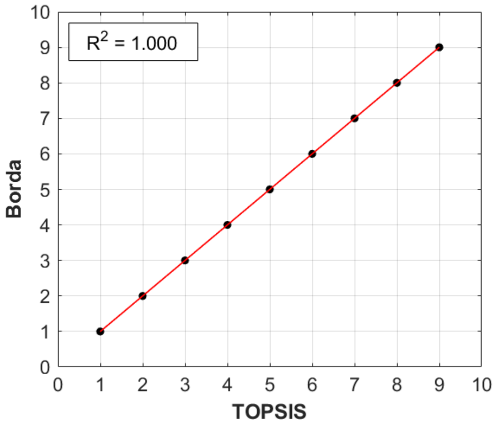
(a) Correlation between SHARE MCA and Borda

(b) Correlation between SAW and Borda



(c) Correlation between WPM and Borda

(d) Correlation between AHP and Borda



(e) Correlation between TOPSIS and Borda

Fig. 5.2 Correlation between each MADM method and the Borda ranking, with the final set of weights defined in the case study. The values from 1 to 9 correspond to the ranks

Table 5.9 Second scheme of weights assigned to the indicators for the sensitivity analysis (from [7])

	IEn	IH	LPL	IEc	RCS	RC
Weights	0.25	0.25	0.25	0.025	0.011	0.214

incomparable to all the alternatives from ALT 4 to the end of the ranking, while ALT 0 is incomparable to ALT 6, in the fourth rank. However, even in this case, ALT 5 (a real-time alternative characterized by relatively low ecological flows) and ALT 1 (a fixed flow release scenario of 100 l/s) are the last alternatives, as for all the other considered MADM methods.

5.3.2 Results of the sensitivity analysis

A sensitivity analysis was performed to investigate the robustness of the considered MADM methods when affected by weight uncertainty. Therefore, a second scheme of weights was adopted and the obtained rankings were compared with the previous results, for each method. The other parameters of the MADM techniques (e.g., the normalization functions for SHARE MCA, the thresholds of ELECTRE III, etc.), on the contrary, were not varied.

The second scheme of weights was based on the assignment of equal importance to the four criteria, i.e., a weight of 0.25 was allocated to Energy, Environment & fishing, Landscape, and Economy. The relative weights assigned to the economic sub-criteria, (i.e., 0.10 for HP producer income and 0.90 for Community income) and to the indicators (i.e., 0.05 to RCS, 0.95 to RC, and 1 to the other indicators), on the contrary, were not varied compared to the values defined during the real decision-making process (explained in Chapter 3, section 3.3.1). The consequent cumulative weights of the indicators, for the second scheme, are shown in Table 5.9.

The new results of the seven considered MADM methods obtained for the case study by applying the second scheme of weights are presented in Table 5.10. Besides, the new final pre-order of the alternatives generated by ELECTRE III is illustrated in Figure 5.3. In this case, a relation of indifference between two alternatives (ALT 5 and ALT 6) is evident.

Table 5.10 Results of the case study according to the different MADM methods, using the second scheme of weights defined for the sensitivity analysis (P_i = final performance value of alternative i; r_i = position in the ranking; D_i^* = distance from the ideal solution, D_i^- = distance from the negative-ideal solution, RC_i = relative closeness, calculated in TOPSIS; S_i, R_i, Q_i = values calculated in VIKOR; r_{Ai} = position in the ascending ranking, and r_{Di} = position in the descending ranking, for ELECTRE III) (adapted from [7])

		ALT 0	ALT 1	ALT 2	ALT 3	ALT 4	ALT 5	ALT 6	ALT 7	ALT 8
SHARE MCA	P_i	0.525	0.469	0.526	0.545	0.528	0.503	0.510	0.506	0.513
	r_i	**4**	**9**	**3**	**1**	**2**	**8**	**6**	**7**	**5**
SAW	P_i	0.499	0.415	0.530	0.578	0.548	0.523	0.544	0.518	0.519
	r_i	**8**	**9**	**4**	**1**	**2**	**5**	**3**	**7**	**6**
WPM	P_i	1.528	1.495	1.707	1.767	1.765	1.637	1.667	1.690	1.721
	r_i	**8**	**9**	**4**	**1**	**2**	**7**	**6**	**5**	**3**
AHP	P_i	0.0343	0.0308	0.0347	0.0364	0.0351	0.0341	0.0344	0.0340	0.0339
	r_i	**5**	**9**	**3**	**1**	**2**	**6**	**4**	**7**	**8**
TOPSIS	D_i^*	0.084	0.088	0.066	0.064	0.058	0.082	0.078	0.071	0.062
	D_i^-	0.088	0.062	0.072	0.085	0.0707	0.085	0.080	0.071	0.060
	RC_i	0.5093	0.4114	0.5239	0.5714	0.5469	0.5094	0.5094	0.5012	0.4924
	r_i	**6**	**9**	**3**	**1**	**2**	**4**	**5**	**7**	**8**
VIKOR	S_i	0.501	0.585	0.470	0.422	0.452	0.477	0.456	0.482	0.481
	R_i	0.250	0.250	0.163	0.163	0.131	0.250	0.224	0.207	0.129
	Q_i	0.741	1.000	0.285	0.138	0.097	0.668	0.497	0.504	0.181
	r_i	4	5	2	**1**	**1**	4	3	3	**1**
ELECTRE III	r_{Ai}	6	5	5	2	1	1	1	3	4
	r_{Di}	6	6	5	3	1	2	2	3	4

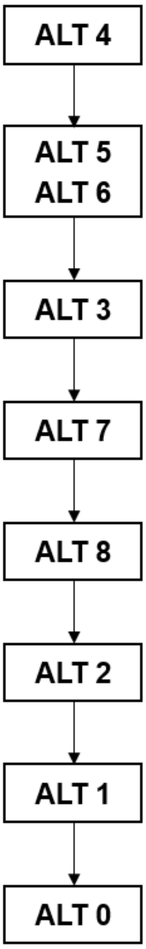


Fig. 5.3 Final pre-order of the alternatives generated by the SuperDecisions® software for ELECTRE III considering the second scheme of weights (adapted from [7])

The rankings generated by the considered MADM methods with the second scheme of weights are quite different. This is also demonstrated by the new results of the Kendall's tau and Spearman's rho correlation tests applied to the first five methods, presented in Table 5.11. These results are visibly lower than the values calculated above (Table 5.6). The most correlated MADM methods are AHP and TOPSIS ($\tau = 0.889$ and $\rho = 0.950$), whereas WPM has the lowest correlation with the other methods, especially with AHP and TOPSIS ($\tau = 0.5$ and $\rho = 0.633$). It has to be highlighted that the critical value of τ in this study (i.e., with 9 ranks) is 0.5 for $\alpha = 0.05$. In other words, the value of τ should be higher than 0.5 to be significant with 95% certainty. Hence, the correlation values of WPM with AHP and

Table 5.11 Results of the Kendall's tau and Spearman's rho correlation tests between the compared methods (excluding VIKOR and ELECTRE III), considering the second scheme of weights defined for the sensitivity analysis (* = not significant correlation value, equal to the critical value)

Kendall's tau coefficient					
	SHARE MCA	SAW	WPM	AHP	TOPSIS
SHARE MCA	1.000	0.556	0.667	0.722	0.611
SAW		1.000	0.667	0.722	0.722
WPM			1.000	0.500*	0.500*
AHP				1.000	0.889
TOPSIS					1.000
Spearman's rho coefficient					
	SHARE MCA	SAW	WPM	AHP	TOPSIS
SHARE MCA	1.000	0.700	0.783	0.850	0.750
SAW		1.000	0.783	0.867	0.883
WPM			1.000	0.633	0.633
AHP				1.000	0.950
TOPSIS					1.000

TOPSIS are not significant according to the Kendall's tau test, but they are significant according to the Spearman's rho test (since the critical value of ρ is 0.6).

The differences among the new rankings of the alternatives generated by the first five MADM methods are also evident by comparing them with the aggregated rankings calculated through the Borda and Copeland techniques, as illustrated in Table 5.12. In fact, unlike the results obtained with the previous set of weights (presented in section 5.3.1), in this case, SAW is the method characterized by the highest correlation with the Borda ranking ($R^2 = 0.926$), followed by AHP and TOPSIS ($R^2 = 0.817$). On the contrary, the results of SHARE MCA and WPM differ more significantly from the Borda ranking ($R^2 = 0.686$ and $R^2 = 0.645$, respectively). Similar remarks can be made by comparing the results of the five MADM methods with the Copeland aggregated ranking: AHP and TOPSIS have the highest correlation with Copeland ($R^2 = 0.934$), followed by SAW ($R^2 = 0.871$), whereas SHARE MCA and WPM are characterized by more differences ($R^2 = 0.667$ and $R^2 = 0.467$, respectively).

Table 5.12 Comparison of the rankings generated by the different MADM methods with the aggregated rankings calculated through the Borda and Copeland methods, considering the second scheme of weights defined for the sensitivity analysis

	SHARE MCA	SAW	WPM	AHP	TOPSIS	Borda	Copeland
ALT 0	4	8	8	5	6	7	6
ALT 1	9	9	9	9	9	9	9
ALT 2	3	4	4	3	3	3	3
ALT 3	1	1	1	1	1	1	1
ALT 4	2	2	2	2	2	2	2
ALT 5	8	5	7	6	4	5.5	5
ALT 6	6	3	6	4	5	4	4
ALT 7	7	7	5	7	7	8	8
ALT 8	5	6	3	8	8	5.5	7

However, the best and the second-ranked alternatives, i.e., ALT 3 and ALT 4, respectively, do not vary. Besides, they are also included in the set of compromise solutions identified by VIKOR (in addition to ALT 8). Both these scenarios are real-time alternatives characterized by higher flow releases in the summer months. Moreover, ALT 1 is the worst alternative according to all the considered MADM methods, apart from ELECTRE III, which classified ALT 1 second to last, followed by ALT 0. In fact, the results of ELECTRE III are significantly different from the results generated by the other methods even considering the second scheme of weights. For example, the best alternative, in this case, is ALT 4, followed by ALT 5 and ALT 6 (indifferent), which, on the contrary, are usually in the middle or lowest part of the ranking according to the other methods.

Furthermore, comparing the rankings obtained with the two different schemes of weights, SHARE MCA and WPM seem to be the most robust methods, since they are not extensively affected by the variation of weights considered in the case study ($\tau = 0.78$ and $\rho = 0.92$ for SHARE MCA; $\tau = 0.72$ and $\rho = 0.80$ for WPM). For VIKOR as well, considering the rankings by Q, no significant changes occur after the variation of the set of weights ($\tau = 0.67$, $\rho = 0.85$). On the contrary, SAW and TOPSIS appear highly affected by the selected weights ($\tau < 0.4$ and $\rho < 0.6$), whereas lower deviations characterize the AHP rankings ($\tau = 0.50$ and $\rho = 0.70$). Finally, looking at Figure 5.1 and Figure 5.3, the final pre-order of the alternatives produced by ELECTRE III appears particularly sensitive to the changes of weights.

Indeed, the previous results were affected by some relations of incomparability, while the new ranking is linear. Moreover, all the ranks change (sometimes substantially), using the second scheme of weights, including the first alternative (ALT 4 instead of ALT 8) and the last one (ALT 0 instead of ALT 1).

5.4 Evaluation of the different methodological approaches

The methodological approaches of the seven considered MADM methods were compared based on the results obtained through their application to the same case study. Feedback collected from some involved stakeholders and a representative of the Regional Water Authority was also taken into account.

Based on previous studies comparing different MADM methods (e.g., [99, 236, 237]), a set of features, concerning the transparency and effectiveness of each method, the input data, and the obtained results, was evaluated. The outcomes of this comparative assessment are summarized in Table 5.13 and discussed below.

Need for additional parameters

The first analyzed feature assesses the level of interaction with the user, i.e., the amount of information (both technical and non-technical) required from the decision-maker or involved stakeholders to achieve the final ranking of the alternatives. The need for many additional parameters usually increases the time necessary for the implementation of the method. Moreover, it often increases subjectivity and potential errors, since the definition of the additional parameters is related to choices made by the user [237].

SAW, WPM, and TOPSIS do not require additional parameters, excluding the scores and the weights of the indicators, whereas VIKOR only needs the definition of the coefficient υ. Instead, the other three methods require a higher level of interaction with the users. Different normalization functions, one for each indicator, have to be defined for SHARE MCA. ELECTRE III, on the contrary, requires the definition of three thresholds for each indicator, whose meaning should be clearly understood for a proper assessment. Nevertheless, the highest level of interaction with the user is

Table 5.13 Summary of the evaluation of the different MADM methodological approaches, based on the following features: need for additional parameters (excluding the indicators' scores and the weights directly assigned by stakeholders or decision-makers); ease of understanding and transparency; characteristics of the input data; level of transformation of the original data; visualization of the results; consistency of the results; overall feasibility and replicability (Quant. = quantitative, Qual. = qualitative, r. = ranking, pref. = preference) (adapted from [7])

	Additional parameters	Transparency	Input data	Transformation	Visualization	Consistency	Feasibility and replicability
SHARE MCA	Yes	Medium	Quant.	Moderate	Complete r. + scores	High	High
SAW	No	High	Quant.	Moderate	Complete r. + scores	Low	Medium
WPM	No	Medium	Quant.	None (if same pref. direction)	Complete r. + scores	High	High
AHP	Yes	Medium	Quant./ Qual.	Moderate	Complete r. + scores	Medium	Medium
TOPSIS	No	Medium	Quant.	Moderate	Complete r. + scores	Low	Medium
VIKOR	Yes	Medium	Quant.	Moderate	Complete r./ Partial r.	High	High
ELECTRE III	Yes	Low	Quant./ Qual. + uncertainty	None	Complete r./ Partial r. No score	Low	Low

required by AHP. Indeed, in this method, several pairwise comparisons have to be performed for each level of the hierarchical structure, as explained in Appendix B.

Ease of understanding and transparency

The second feature evaluates whether the MADM method is easily understandable by all the stakeholders. The assessment was carried out by estimating the time needed for a generic user (including administrators and stakeholders without a technical background) to understand all the mathematical procedures. If any user can easily understand the different steps of its implementation, the method will be perceived as more transparent and the results will probably be widely accepted [99]. On the contrary, a complex methodological approach could appear as a “black box”, even if there is a user-friendly software interface, thus decreasing the level of trust of the users [61].

Among the seven MADM methods applied to the case study on the Graines torrent, SAW is the simplest one, well-known even to practitioners [71]. WPM is also based on a simple theoretical approach, but its mathematical concept is more “practitioner-unattractive” [71]. Similarly, in Aosta Valley, SHARE MCA was not immediately accepted by non-technical stakeholders, even if it is based on the same principle of SAW. The reason was probably related to the initial difficulty in understanding the hierarchical structure of the problem, as well as the role of the normalization functions. Similar observations can be made for AHP. Indeed, the breakdown of the problem into a hierarchical structure supports the decision-makers in the assignment of judgments, by means of pairwise comparisons [13]. Nevertheless, a software interface is generally used to calculate the overall performance value for each alternative and this may decrease the level of confidence of non-technical users. On the contrary, the algorithms of TOPSIS and VIKOR are rather easy and can be implemented in a simple spreadsheet. However, more time may be necessary to explain their theoretical approach (i.e., minimization of the distance from an ideal solution) to the user.

Finally, ELECTRE III is characterized by the most complex methodological approach. Indeed, it requires understanding different concepts (e.g., outranking, strict and weak preference, etc.) and the algorithm is based on several steps (e.g., calculation of the concordance and discordance matrices for each indicator), which may not be easily understood by non-technical users. The procedure is usually implemented with the support of a software interface, but the decision-makers may lack confidence in the tool [236] if they do not completely understand how the input data are processed. Moreover, the definition of realistic threshold values can also be challenging.

Characteristics of the input data

This feature assesses the possibility to use both quantitative and qualitative scores for the indicators. Most of the MADM methods applied to the case study on the Graines torrent require the input of quantitative scores. Only AHP and ELECTRE III can also handle qualitative scores. Indeed, in AHP the alternatives are pairwise compared with respect to each criterion or indicator based on the 9-points rating scale developed by Saaty (see Table A.1 in Appendix A). Through this scale, the user can judge how many times an alternative is more important than another one, even for a qualitative criterion or indicator. A numerical pairwise comparison matrix is thus obtained, allowing the calculation of the overall performance value for each alternative.

ELECTRE III, on the contrary, was explicitly designed to deal with inaccuracy, uncertainty, and ill-determination of data [58]. By introducing pseudo-criteria, characterized by discrimination thresholds, in fact, the imperfect nature of the evaluations can be taken into account [58]. Hence, this method can also handle ordinal or descriptive information and normalization of the decision matrix is not necessary [71].

Level of transformation of the original data

This feature considers the level of transformation that the initial data undergo through the different steps of the MADM method. When several transformation phases are required, there is a higher risk to lose some initial information, thus affecting the final performance values of the alternatives.

Among the considered MADM methods, ELECTRE III and WPM were considered the best according to this feature. Indeed, ELECTRE III does not require normalization of data since it can handle different types of attributes [71]. Therefore, all the data are used in their original form. Similar observations can be made for

WPM, which directly compares the alternatives based on some ratios (one for each indicator). When all the indicators are characterized by the same preference direction (i.e., maximization or minimization), normalization of the initial decision matrix is not necessary [238].

On the contrary, in the first phase of SHARE MCA, SAW, TOPSIS, and VIKOR, the decision matrix has to be normalized in order to transform the different types of indicators into comparable, non-dimensional, values. However, this transformation alters the initial data, with a possible loss of information. Besides, the choice of the normalization method among the different existing techniques may affect the MADM results [90]. Similarly, in AHP, pairwise comparisons among the alternatives, with respect to each indicator, transform the original data [237]. Furthermore, even if a direct input approach is used (i.e., introducing the scores of the initial decision matrix in the software), as in the considered case study (see section 5.2.2), the scores are normalized since they are divided by their sum [71].

Visualization of the results

The visualization, or typology, of the results produced by a MADM method evaluates, in particular, the possibility to obtain a complete or partial ranking of the alternatives and to calculate an overall performance value for each alternative. As indicated in Table 5.5 and Table 5.10, SHARE MCA, SAW, WPM, AHP, and TOPSIS generate a complete ranking of the alternatives, for each of which a performance score $P(A_i)$ is calculated.

On the contrary, VIKOR produces three rankings, i.e., by Q, S, and R (with the corresponding performance values). Based on these results, one or more compromise solutions are proposed [239]. Moreover, in some cases, a complete ranking of the alternatives cannot be achieved [229]. Instead, the results of ELECTRE III (shown in Figures 5.1 and 5.3) are completely different since the alternatives are not associated with a performance value but only with an ordinal rank. This may reduce the level of confidence of the user. Furthermore, the obtained ranking can be affected by some relations of incomparability among the alternatives (as in Figures 5.1), thus increasing the difficulties in understanding the results. Besides, in some cases, a complete ranking of the alternatives cannot be achieved [236].

Consistency of the results

This feature assesses the robustness of the rankings obtained through the implementation of the MADM method. It was evaluated based on the outcomes of the sensitivity analysis, presented in section 5.3.2. If the ranking of the alternatives is completely modified after a slight variation of the weights, the consistency of the method will be low.

In the case study on the Graines torrent, SHARE MCA, WPM, and VIKOR were not significantly affected by the variation of weights. Therefore, they can be considered robust. On the contrary, a lower consistency was assessed for AHP and, above all, for SAW, TOPSIS, and ELECTRE III. The rankings generated by these methods, in fact, were affected by important changes after a relatively low modification of weights. In particular, in ELECTRE III, the ranks of all the alternatives varied, including the first and the last ones.

Furthermore, it has to be highlighted that the sensitivity analysis described in section 5.3.2 only concerned the weights. However, other parameters, like the normalization functions in SHARE MCA, the coefficient υ in VIKOR, or the thresholds in ELECTRE III, can also affect the consistency of the results.

Overall feasibility and replicability

This last feature assesses the overall applicability and effectiveness of each MADM method, not only for the considered case study, which was relatively simple, involving only one small HP plant, but also for more complex decision-making processes. For example, there should also be the possibility to adopt the procedure for managing a system of water withdrawals. Therefore, not only the consistency and reliability of the produced results are important, but also the transparency of the procedure and the possibility to directly involve different stakeholders in the decision-making process without decreasing their level of confidence. Moreover, these characteristics influence the possibility to integrate the methodological approach into regulatory and management tools. The evaluations presented in the previous paragraphs were also taken into account for the assessment of this feature.

The real decision-making process carried out on the Graines torrent demonstrated the feasibility of SHARE MCA and the possibility to be officially integrated into regulatory tools. In fact, even if the method was not immediately understood by non-technical stakeholders, its hierarchical structure allows the breakdown of complex problems, thus simplifying its evaluation. Moreover, the calculation of the final performance values of the alternatives is based on the same additive principle of SAW, which is easily understood by stakeholders and decision-makers. Besides, the sensitivity analysis presented in section 5.3.2 proved the robustness of the method.

WPM and VIKOR also showed interesting characteristics, like the high consistency of the results and the relatively easy procedure, which can be implemented in a simple spreadsheet. However, their mathematical concepts may require more time to be accepted by non-technical users. Another strength of VIKOR is the check (in the ranking by Q) of an "acceptable advantage" between the best alternative and the following ones in order to identify the compromise solution(s).

Lower feasibility was assessed for AHP, due to the high level of interaction with the user, necessary to perform the pairwise comparisons. A strength of AHP is the breakdown of the problem into a hierarchical structure. Nevertheless, the calculation of the overall performance value of the alternatives is usually performed through a software interface, which may reduce the level of confidence of stakeholders and decision-makers.

On the contrary, TOPSIS and, above all, SAW can be easily explained even to non-technical users and their mathematical procedure can be performed in a simple spreadsheet. Therefore, the level of trust of stakeholders and decision-makers would probably be high. However, the sensitivity analysis carried out in the case study (section 5.3.2) showed a low consistency of the results. Indeed, the obtained rankings significantly changed after a relatively low variation of weights.

Finally, ELECTRE III was assessed as the least feasible method, above all for complex decision-making problems. Indeed, despite its strengths (like the rigorous mathematical procedure and the possibility to handle uncertain and imprecise data), the algorithm is relatively difficult to be understood by non-technical users. Moreover, the method, which is usually implemented through a software interface, does not calculate an overall performance value for each alternative, but only the ranks. Besides, the results can be affected by some relations of incomparability between the alternatives and, in some cases, a complete ranking cannot even be achieved. All these aspects usually reduce the level of confidence of the involved stakeholders and decision-makers. Furthermore, according to the outcomes of the sensitivity analysis described in section 5.3.2, the consistency of the method appeared particularly low.

5.5 Concluding remarks

Assessing how the choice of different MADM methods may affect the final decision is particularly important when MADM is used in real decision-making processes, leading to relevant actions. For this reason, in this Chapter, the results and the methodological approaches of different MADM techniques have been compared, to evaluate whether SHARE MCA is the appropriate method to be used in Aosta Valley for decision-making processes concerning water withdrawal management.

By applying the different MADM methods to the same real case study described in Chapter 3, the rankings of the alternatives obtained with the final set of weights defined by the involved stakeholders were generally highly correlated. Only VIKOR and ELECTRE III produced different types of results, not only in terms of ranking order but also of format. These observations are in line with the conclusions of Zamani-Sabzi et al. [229], who investigated and statistically compared the performances of ten MADM methods (i.e., SAW, WPM, TOPSIS, four types of AHP, VIKOR, ELECTRE, and compromise programming). Moreover, the outcomes of the sensitivity analysis, performed by adopting a slightly different scheme of weights, showed a high consistency of some methods, i.e., SHARE MCA, WPM, and VIKOR, which can thus be considered robust.

The results presented in section 5.3 also revealed that the alternatives ranked in the first positions always corresponded to flow release scenarios variable over the year. For example, the best-ranked alternative according to all the methods (except ELECTRE III) was ALT 3, a real-time alternative characterized by higher flow releases in the summer months (see Table 3.2 in Chapter 3). On the contrary, ALT 1, a fixed flow release scenario of 100 l/s proposed by the HP company, was always the last-ranked alternative (apart from the results of ELECTRE III obtained with the second scheme of weights, in which it was second to last).

Therefore, these results further demonstrated that ecological flow scenarios characterized by a fixed release throughout the year are not sustainable. Indeed, their negative impacts on watercourse ecology and landscape are significant and they are even not counterbalanced by the high related economic income. On the contrary, real-time alternatives ensure a more natural variability of the flow, which is necessary to maintain the ecological functioning of ecosystems [27]. Besides, these alternatives usually allow a better compromise among the different stakeholders' interests. However, it has to be highlighted that, in the considered case study, real-time withdrawal could be implemented because the small HP plant had been recently built. Hence, it was equipped with a modern system allowing the opening and closing of the withdrawal devices based on the flow data series measured upstream of the dam. Such a system is often present in recent HP plants in Aosta Valley. On the contrary, older HP plants usually cannot be adapted to implement real-time withdrawal.

By evaluating the overall methodological approach of the considered MADM methods (section 5.4), the main strengths and weaknesses were highlighted. In particular, some techniques appeared as more feasible and replicable, also for more complex problems. For example, several decision-making processes currently carried out in Aosta Valley involve multiple water withdrawals, with the upstream flow release scenario affecting the downstream scenarios (more information will be provided in Chapter 6). In these cases, using a MADM method characterized not only by reliable results but also by a transparent procedure is necessary to increase the level of trust of all the involved actors. For these reasons, methods like ELECTRE III were considered hardly replicable for complex water management problems since the algorithms may be too difficult to be understood by stakeholders and decision-makers without a technical background. On the contrary, less complex methods are generally characterized by a higher level of transparency [61].

The real decision-making process carried out on the Graines torrent proved the feasibility of SHARE MCA, which led to a management decision endorsed by the Regional Government and actually implemented in the affected watercourse stretch (as illustrated in Chapter 3). Furthermore, the similarity of the rankings of the alternatives obtained through the different MADM methods (presented in section 5.3) has demonstrated that the results of SHARE MCA are in line with the results produced by the most popular MADM techniques, thus increasing the robustness of the decision achieved through SHARE MCA. Besides, the results have proven to be highly consistent. Therefore, the evaluations discussed in this Chapter have confirmed the effectiveness and replicability of the method adopted in Aosta Valley, which is, therefore, being applied to several other real case studies in the region (see Chapter 6).

However, according to the outcomes and the stakeholders' feedback presented in this Chapter, other MADM methods, like WPM and VIKOR, also showed interesting characteristics in terms of overall feasibility. In the future, these methods could be tested in other real case studies, in addition to SHARE MCA, for the definition of ecological flows.

Chapter 6

Use of the updated MADM framework over the Aosta Valley territory

6.1 Introduction

In the previous Chapters, the methodological framework, based on MADM, adopted in Aosta Valley to assess water withdrawal sustainability has been presented, highlighting the improvements carried out over the last years. An important achievement has been the revision of the MADM decision tree, through the definition of a set of reactive indicators, based on the normative framework. In particular, the introduction of the Index of river Habitat integrity (IH), derived from the MesoHABSIM methodology, to quantify the effects of water withdrawal on river ecosystems and fish communities has allowed overcoming the limitations of the previous biological indicators (see Chapter 3). Besides, the new Landscape Protection Level (LPL) indicator, assessing the effects of water withdrawal on the river landscape, has demonstrated to be more representative of the related stakeholders' needs compared to the previous version of the indicator (see Chapter 4). Furthermore, testing different MADM methods on the same case study, the results obtained with SHARE MCA, the technique adopted in Aosta Valley, have proven to be in line with the results of the methods most used in the literature. The evaluations presented in Chapter 5 have demonstrated the feasibility and effectiveness of the SHARE MCA method.

The first decision-making processes in which the updated procedure was applied led to satisfactory outcomes for all the involved stakeholders. Moreover, the decision-makers also noticed an increase in the decision-making quality. For these reasons, the revised methodological approach has been formally adopted in the institutional water withdrawal licensing procedure in Aosta Valley for the definition of ecological flows. It is currently applied to several real case studies over the regional territory, concerning different types of water withdrawals.

The aim of this Chapter is to present an overview of the decision-making processes in Aosta Valley, both concluded and ongoing, using the revised procedure to identify the most appropriate scenario of ecological flows to be implemented downstream of one or more withdrawal dams. Moreover, the opinions of the involved stakeholders on the revised procedure are assessed to test their satisfaction level.

The Chapter is organized as follows: the different case studies, concluded and ongoing in Aosta Valley for water withdrawal assessment, are illustrated in section 6.2, describing the main characteristics of the MADM decision-making processes and of the involved withdrawals. In section 6.3, stakeholders' feedback on the revised methodological framework is evaluated considering, in particular, their satisfaction with the final set of indicators. Finally, some concluding remarks about the effectiveness of the described procedure are presented in section 6.4.

6.2 Decision-making processes for water withdrawal assessment concluded and ongoing in Aosta Valley

Over the last years, the revised methodological framework presented in this dissertation has been applied to several case studies of water withdrawal management, all over the regional territory. At present, 38 decision-making processes are ongoing in Aosta Valley, 9 of which have just begun, whereas 7 case studies have already been concluded.

6.2.1 Main characteristics of the decision-making processes

The MADM procedure is used to define the ecological flows for either the release or the renewal of a water withdrawal license. As explained in Chapter 3, the main stakeholders, i.e., the applicants and the representatives of the main concerned regional technical bodies, are officially involved in the decision-making process. They are required to assess the compatibility of the withdrawal with the other water users' interests.

Hydrological monitoring is considered fundamental for this purpose. Indeed, reliable data about the watercourse discharge, measured both upstream and downstream of the withdrawal dam, are necessary to evaluate the effects of the water diversion, thus ensuring appropriate protection of the aquatic ecosystems and river landscape. Recently, in some case studies in which the installation of a continuous monitoring system at the dam was particularly difficult, hydrological models have been applied to simulate streamflow data.

Each decision-making process usually covers a period of at least five years, necessary to collect reliable flow data series. During this period, the stakeholders are actively involved in a series of meetings for the implementation of the MADM procedure. The decision-making process can be divided into five main phases, i.e.:

A) beginning of the decision-making process and of the monitoring;

B) problem structuring and MADM model building;

C) analysis of the initial set of flow release alternatives;

D) MADM model refining and sensitivity analyses;

E) end of the decision-making process and adoption of the flow release scheme.

The initial phase, **beginning of the decision-making process and of the monitoring**, is characterized by the following steps:

- application for beginning a new decision-making (DM) process to assess water withdrawal sustainability;
- organization of the Technical Assessment Board (TAB), including the concerned stakeholders, and kickoff meeting;
- preliminary survey along the watercourse stretch affected by the withdrawal to identify the appropriate sites for the hydrological monitoring system, the hydromorphological analyses (for the application of the MesoHABSIM methodology

and the definition of the IH indicator), the collection of photos of the river landscape (for the calculation of the LPL indicator), and the chemical-physical and biological analyses required by the Water Framework Directive (to define the quality status of the watercourse);

- beginning of the hydrological, environmental, and landscape monitoring programs.

During the second phase, **problem structuring and MADM model building**, the following steps are carried out:

- definition of the MADM structure;
- definition of criteria;
- definition of indicators;
- definition of an initial set of flow release alternatives;
- evaluation of the normalized scores and filling in of the decision matrix.

The third phase concerns the **analysis of the initial set of flow release alternatives**. The following steps are usually implemented:

- allocation of weights to indicators;
- allocation of weights to criteria;
- calculation of the overall performance score for each alternative and analysis of the initial ranking of the alternatives;
- preliminary selection of an alternative to be implemented in the bypassed watercourse stretch (i.e., the stream section downstream of the withdrawal point);
- possible release of a temporary authorization measure;
- assessment of the effects of the temporary authorization measure.

The fourth phase, **MADM model refining and sensitivity analyses**, is characterized by the following steps:

- possible definition of further flow release alternatives;
- evaluation of the normalized scores corresponding to the new alternatives and filling in of the revised decision matrix;
- possible new allocation of weights to indicators;
- new allocation of weights to criteria and sensitivity analyses;
- calculation of the overall performance score for each alternative and analysis of the final ranking of the alternatives;
- selection of the alternative representing the best mediation scenario among the different water users' interests;
- possible further release of a temporary authorization measure;
- assessment of the effects of the temporary authorization measure.

Finally, during the last phase, **end of the decision-making process and adoption of the flow release scheme**, two steps are carried out:

- final decision on the flow release alternative to be adopted in the bypassed watercourse stretch, officially approved by the Regional Government;
- release of the final authorization measure.

Table 6.1 provides a list of all the decision-making processes started in Aosta Valley since 2012 (data updated to March 2022). The last column shows the percentage of steps that have already been concluded compared to the total number of steps necessary to complete the whole decision-making process (i.e., 25). It can be noticed that several case studies have recently begun: 6.7% of the 45 decision-making processes have started in 2019, 28.9% in 2021, and 20.0% (from case study 37 to case study 45) have just begun. Moreover, as explained above, the procedure is characterized by many steps and usually takes some years to achieve a compromise solution among the different involved stakeholders. For these reasons, most of the case studies are still carrying out the initial phases (37.8% are in phase A, while 26.7% have concluded phase A and are currently in phase B – see Figure 6.1).

On the contrary, 7 decision-making processes are concluded. It can be noticed that some of these case studies covered a relatively short period (case study 23 took about one year, case studies 32 and 35 only some months). The reason is that, at the beginning of the procedure, reliable flow data series (12 or 15 years long) were already available: they had been collected through a hydrological monitoring system or simulated by means of a hydrological model. Therefore, only landscape and environmental monitoring programs had to be implemented during the decision-making process and the MADM application was faster. Furthermore, among the concluded case studies, only one has not achieved the end of the procedure (case study 18), because the involved stakeholders were not able to define flow release alternatives representing a compromise among the different water users' interests. However, even in this case, MADM supported the decision-makers, who recognized that the ecological flows initially quantified using a hydrological formulation, according to the regional River Strategic Plan [52], represented the best solution for the concerned bypassed watercourse stretch.

Table 6.1 Main information about the decision-making processes for the definition of the ecological flows concluded and ongoing in Aosta Valley (data updated to March 2022): C.M.F. = farmers' consortium; * = planned hydropower plant

N.	Applicant(s)	Affected watercourse(s)	Average nominal power of the HP plant(s) (kW)	*Ex-ante*/ *ex-post* process	Start date	End date	% of concluded steps
1	Idroelettrica Brusson S.r.l.	Graines torrent	566.21	*Ex-post*	2012	2018	100%
2	Cooperativa Forza e Luce di Aosta S.C.	Buthier torrent	71.94	*Ex-post*	2015	2021	100%
3	Società Cooperativa elettrica Gignod	Artanavaz and Menouve torrents	2994.37	*Ex-post*	2016	Ongoing	92%
	Cooperativa Forza e Luce di Aosta S.C.	Artanavaz torrent	1523.7				
4	Grand Eyvia Cogne Energie S.r.l.	Grauson torrent	543.46	*Ex-post*	2017	Ongoing	32%
	Jeantet Carlo		44.9				
	Municipality of Cogne		247.25				
	C.M.F. Prés de Saint Ours		/ (irrigation)				
5	Valdigne Energie S.r.l.	Dora di Verney and Orgères torrents	4144.45	*Ex-post*	2017	Ongoing	88%
6	Idroelettrica Quinson S.r.l.	Arpy torrent	697.45	*Ex-post*	2017	Ongoing	68%
7	Idroelettrica Cervino S.r.l.	Marmore torrent	336.47	*Ex-post*	2017	Ongoing	68%

Continued from previous page

N.	Applicant(s)	Affected watercourse(s)	Average nominal power (kW)	*Ex-ante*/ *ex-post*	Start date	End date	% of concluded steps
8	Joux Energie Verrayes S.r.l., C.M.F. Ru de Joux St Barth Alto S.r.l., C.M.F. Ru Blanc et Luseney Eco Dynamics S.r.l., C.M.F. Rivo Val Saint-Barth Basso S.r.l. C.V.A. S.p.A.	Saint-Barthélemy torrent	949.63 397.75 * 249.39 216.28 * 3658.25	*Ex-ante*	2017	Ongoing	16%
9	Verdenergia S.r.l.	Saint- Marcel torrent	200 960.78 186.86	*Ex-post*	2017	2021	100%
10	F.lli Ronc S.r.l.	Savara torrent Dora di Rhêmes torrent	716.28 258.27	*Ex-post*	2018	Ongoing	32%
11	Electrorhêmes S.r.l. F.lli Ronc S.r.l. Electrorhêmes S.r.l.	Dora di Rhêmes torrent	2349.9 2166.18 3457.8	*Ex-post*	2018	Ongoing	32%
12	SIVO S.r.l.	Buthier d'Ollomont torrent	1445.88	*Ex-post*	2018	Ongoing	32%
13	BKW Hydro Italia S.r.l.	Lys torrent	2541.9	*Ex-post*	2018	Ongoing	44%

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N.	Applicant(s)	Affected watercourse(s)	Average nominal power (kW)	*Ex-ante*/ *ex-post*	Start date	End date	% of concluded steps
14	Idroelettrica Arvier S.r.l.	Dora di Valgrisenche torrent	2533.29	*Ex-post*	2018	Ongoing	56%
15	Messuere Energie S.r.l.	Messuère torrent	421.09	*Ex-post*	2018	Ongoing	28%
16	Hydro Electrique Clavalité S.p.A.	Clavalité torrent	6651.25	*Ex-post*	2018	Ongoing	64%
	ALGA S.r.l.		2955.42				
17	Aosta Gas S.r.l., C.M.F. Ru Chevrère et Montjovet	Chalamy torrent	244.37 *	*Ex-ante*	2018	Ongoing	16%
	Euriver S.r.l.		808.01				
	C.V.A. S.p.A.		2907.57				
	C.M.F. Ru Grenze et Ru Fabbrica Viéring		472.59				
	CAPE S.r.l.		266.67				
18	Idrora S.r.l.	Ruitor torrent	912.95	*Ex-post*	2018	Dismissed	100%
19	C.V.A. S.p.A.	Evançon and Graines torrents	25941.45	*Ex-post*	2018	Ongoing	36%
		Chalamy torrent	2907.57				
		Savara and Grand'Eyvia torrents	30545.54				
		Evançon torrent	9124.57				

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N.	Applicant(s)	Affected watercourse(s)	Average nominal power (kW)	*Ex-ante/ ex-post*	Start date	End date	% of concluded steps
19	C.V.A. S.p.A.	Dora Baltea river	13657.35				
		Dora Baltea river	3803.65				
		Marmore torrent	11849.43				
		Grand'Eyvia torrent	6195.45				
		Ayasse, Crest, and Brenve torrents	10174.99				
		Marmore torrent	8545.69				
		Dora Baltea river	16394				
		Dora di Rhêmes torrent	13991.17				
		Marmore torrent	20902.58				
		Artanavaz, Buthier, and Buthier d'Ollomont torrents	27687.52				
		Lys torrent	5821.36				
		Lys torrent	15102.99				
		Buthier torrent and Dora Baltea river	22711				
		Lys torrent	29833.11				
		Lys torrent	2758.91				

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N.	Applicant(s)	Affected watercourse(s)	Average nominal power (kW)	*Ex-ante*/ *ex-post*	Start date	End date	% of concluded steps
19	C.V.A. S.p.A.	Dora Baltea river and Dora di Valgrisenche torrent	21622.6				
		Urthier torrent	820.819				
		Dora Baltea river	1193.04				
		Dora Baltea river	23272.22				
		Dora Baltea river	30639				
		Saint-Barthélemy torrent	3658.25				
20	Municipality of Cogne, Pila S.p.A.	Valnontey torrent	/ (snowmaking)	*Ex-post*	2018	Ongoing	48%
21	Rialca Due S.n.c. C.E.A.B. S.r.l. Idroelettrica Quinson S.r.l.	Colombaz torrent	214.63 * 248.37 162.92	*Ex-ante*	2019	Ongoing	24%
22	Valdena S.r.l. C.V.A. S.p.A.	Dora Baltea river	Not defined * 16394	*Ex-ante*	2019	Ongoing	8%
23	Società idroelettrica Vargno S.r.l.	Pacoula torrent	488.57 *	*Ex-ante*	2019	2020	100%
24	Michaud H2O S.r.l. Duemila S.r.l.	Evançon torrent	498.54 280.93	*Ex-post*	2021	Ongoing	12%

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N.	Applicant(s)	Affected watercourse(s)	Average nominal power (kW)	*Ex-ante/ ex-post*	Start date	End date	% of concluded steps
25	BKW Hydro Italia S.r.l.	Lenteney torrent	986.15 461.1	*Ex-post*	2021	Ongoing	16%
26	S.e.v.a. S.r.l.	Dora Baltea river	3553.33	*Ex-post*	2021	Ongoing	32%
27	Herren & figli S.n.c.	Valnontey torrent	477.4 *	*Ex-ante*	2021	Ongoing	12%
28	Energy Urtier S.r.l.	Urtier torrent	498.95 *	*Ex-ante*	2021	Ongoing	12%
29	ALENERGY S.R.L. Società Idroelettrica Verrès S.r.l.	Evançon torrent	422.54 * 429.85 *	*Ex-ante*	2021	Ongoing	12%
30	Andrea Cesare Gadin	Vertosan torrent	4052.58 *	*Ex-ante*	2021	Ongoing	12%
31	Società Idroelettrica Laures S.r.l.	Les Laures lake	1673.62	*Ex-post*	2021	Ongoing	16%
32	St Barth Alto S.r.l.	Saint-Barthélemy torrent	397.75 *	Ex-ante	2021	2021	100%
33	Carlo Jeantet	Urthier torrent	478.43	*Ex-post*	2021	Ongoing	16%
34	Verra Energie S.r.l.	Verra torrent	2101.43	*Ex-post*	2021	Ongoing	8%
35	Idroelettrica Quinson S.r.l.	Arpy torrent	366.04 *	*Ex-ante*	2021	2021	100%
36	C.V.A. S.p.A.	Ayasse, Mandaz, and Brenve torrents	14114.68 *	*Ex-ante*	2021	Ongoing	16%

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N.	Applicant(s)	Affected watercourse(s)	Average nominal power (kW)	*Ex-ante*/ *ex-post*	Start date	End date	% of concluded steps
37	Blu Energie S.r.l.	Clevya Groussa torrent	522.78 *	*Ex-ante*	2022	Ongoing	4%
38	Idroelettrica Quinson S.r.l.	Colombaz torrent	492.45 * 52.01 * 929.15 *	*Ex-ante*	2022	Ongoing	4%
39	Hydro Electrique Clavalité S.p.A.	Clavalité torrent	995.54 *	*Ex-ante*	2022	Ongoing	4%
40	Blu Energie S.r.l.	Chavannes torrent	654 *	*Ex-ante*	2022	Ongoing	4%
41	Blu Energie S.r.l.	Dora di La Thuile torrent	824 *	*Ex-ante*	2022	Ongoing	4%
42	Blu Energie S.r.l.	Dora di Veny torrent	2999 *	*Ex-ante*	2022	Ongoing	4%
43	C.V.E. S.r.l.	Dora di Ferret torrent	Not defined *	*Ex-ante*	2022	Ongoing	4%
44	Sostener S.r.l.	Dora di Veny torrent	Not defined *	*Ex-ante*	2022	Ongoing	4%
45	S.e.v.a. S.r.l.	Ghiacciaio torrent	398.84 *	*Ex-ante*	2022	Ongoing	4%

The water withdrawal dams involved in the decision-making processes concluded and ongoing in Aosta Valley are represented in Figures 6.2, 6.3, and 6.4. Figure 6.2 illustrates the case studies involving existing water diversions. For each case study, the corresponding number (indicated in the first column of Table 6.1) is highlighted, as well as a graph showing the percentage of concluded steps of the decision-making process. It can be noticed that the procedure is not only used for a single withdrawal but also to optimize the ecological flows of multiple water diversions in the same watershed, sometimes involving different water bodies (e.g., case studies 3 and 10).

In particular, the most complex decision-making process (case study 19) concerns 32 existing HP withdrawals managed by the main regional hydroelectric company, i.e., Compagnia Valdostana delle Acque (C.V.A. S.p.A.), distributed over the regional territory and supplying water to 25 HP plants, among the largest in Aosta Valley. These water diversions are thus represented in another figure (Figure 6.3), where the affected water bodies are highlighted in orange and the average nominal licensed capacity of the involved HP plants is indicated. The decision-making process officially began in 2018 and phase C is currently being implemented (36% of the steps have already been concluded). The simultaneous MADM application to numerous withdrawal sites spread across a relatively large area, but functionally interconnected (e.g., some withdrawal dams are immediately downstream of the tailrace of another HP station) and managed by the same company, is rather complex. However, it also allows the implementation of *ex-situ* mitigation measures. Indeed, water withdrawal management, in this case, can be based not only on the specific definition of ecological flows for the single bypassed stretches but also on the implementation of cumulative flow releases from different diversions located, for example, in the same valley.

Figure 6.4, on the contrary, shows the location of the new water diversions, i.e., for which the corresponding HP plant is not yet in operation. In all these case studies the MADM procedure is applied *ex-ante*, i.e., to assess the suitability of new licenses for water withdrawal, during the planning phase. Also in this figure, for each case study, the corresponding number and a graph indicating the percentage of concluded steps of the decision-making process are shown. It can be noticed that, in some cases, the MADM procedure has already been concluded even if the withdrawal is not yet in operation because the corresponding HP plant is under construction (case studies 23, 32, and 35). Nevertheless, most of these decision-making processes are

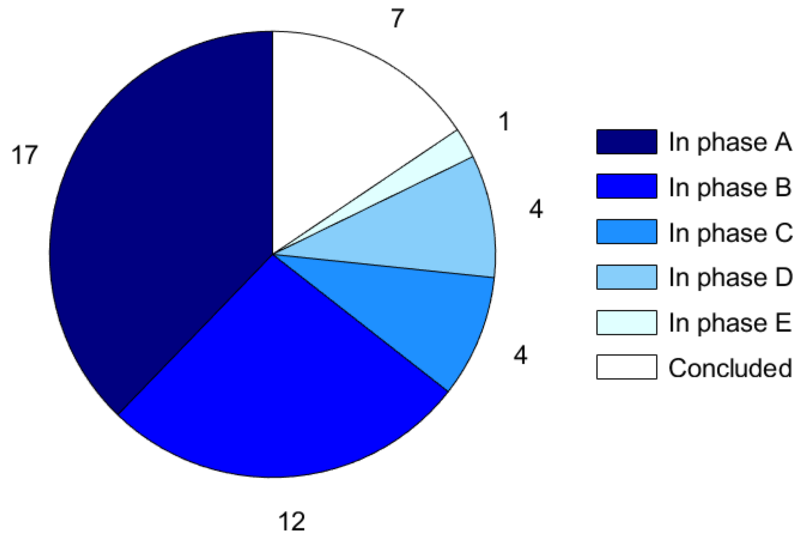

Fig. 6.1 Number of case studies carrying out the different phases of the decision-making process for water withdrawal assessment: A) beginning; B) problem structuring and MADM model building; C) analysis of the initial set of alternatives; D) sensitivity analyses; E) end of the decision-making process (data updated to March 2022)

still carrying out the initial steps of the procedure, including the 9 case studies that have just started (case studies from 37 to 45).

Overall, 46.7% of the decision-making processes are *ex-ante* MADM applications, but the majority of the case studies (i.e., 53.3%) are carried out *ex-post*, i.e., to evaluate the renewal, variation, or strengthening of licenses for existing water diversions. Furthermore, some withdrawals are involved in different decision-making processes. For example, some water diversions managed by the hydropower company C.V.A. S.p.A., included in case study 19, are also involved in another decision-making process concerning multiple withdrawals (e.g., case studies 8 and 17).

The collaboration among various actors, with different water-related interests, throughout the decision-making process for water withdrawal assessment is not always easy. For example, some case studies concerning different water diversions also involve numerous applicants, i.e., different HP companies and farmers' consortia. In these cases (e.g., case studies 8 and 17), there are often some problems related to the coordination of the activities, even for the definition and beginning of the monitoring programs, due to the conflicts among the various applicants. Moreover, the development of alternatives defining the ecological flows for each involved water withdrawal, as well as the evaluation of their cumulative effects, can be rather complex. Consequently, these decision-making processes usually take longer periods.

Other case studies are still in the initial phases because the applicants are evaluating the opportunity to continue the activities, due to the costs (e.g., case study 22), or because there were some difficulties in starting the agreed monitoring programs, at the end of phase A (e.g., case studies 11 and 12). On the contrary, case study 3 is the only one that has concluded phase D but is still implementing phase E. The reason is that a final decision on the flow release alternative to be adopted in the bypassed watercourse stretch, representing a mediation solution among the various stakeholders, has not yet been achieved. This is the only case study, so far, in which, despite the complete MADM implementation, the whole decision-making process could not be yet officially concluded through the release of the final authorization measure.

6.2.2 Main features of the involved water withdrawals

The first complete decision-making process carried out in Aosta Valley using the presented methodological framework concerned a small run-of-the-river HP plant (see Chapter 3 – section 3.3). Afterward, the procedure has been extended to decision problems also involving other types of water withdrawals, besides those for HP production, i.e., agricultural diversions for the irrigation of fields and industrial withdrawals for snowmaking in the skiing areas during the winter.

The 29 decision-making processes currently ongoing in Aosta Valley involve a total of 70 HP plants (11 of which are not yet in operation), 12 farmers' consortia (6 of which, mentioned in Table 6.1, are formally involved in the decision-making process, while the others do not take part in the TAB meetings even if they are directly affected by the TAB results), and 1 water withdrawal for snowmaking. Moreover, the 9 case studies that are beginning concern other 11 HP plants, whereas 9 HP plants were involved in the 7 concluded case studies (3 of which are not yet in operation and 1 is also included in an ongoing case study). Figure 6.5 shows the number of HP plants, farmers' consortia, and industrial water withdrawals concerned by all the decision-making processes started in Aosta Valley since 2012.

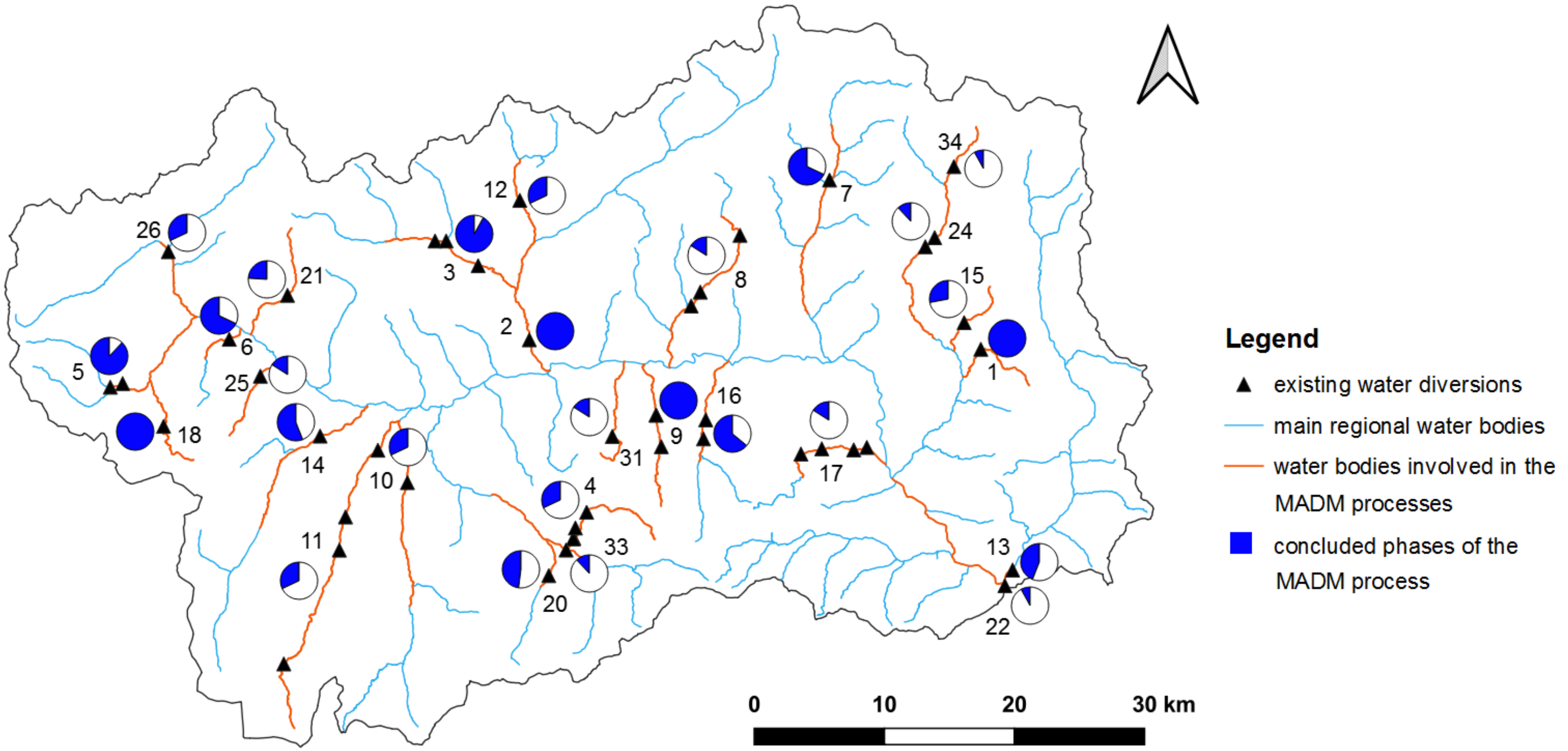

Fig. 6.2 Existing water withdrawals involved in the decision-making processes for the definition of the ecological flows: the numbers indicate the case studies (as in Table 6.1), while the graphs show the percentage of concluded steps of the decision-making processes

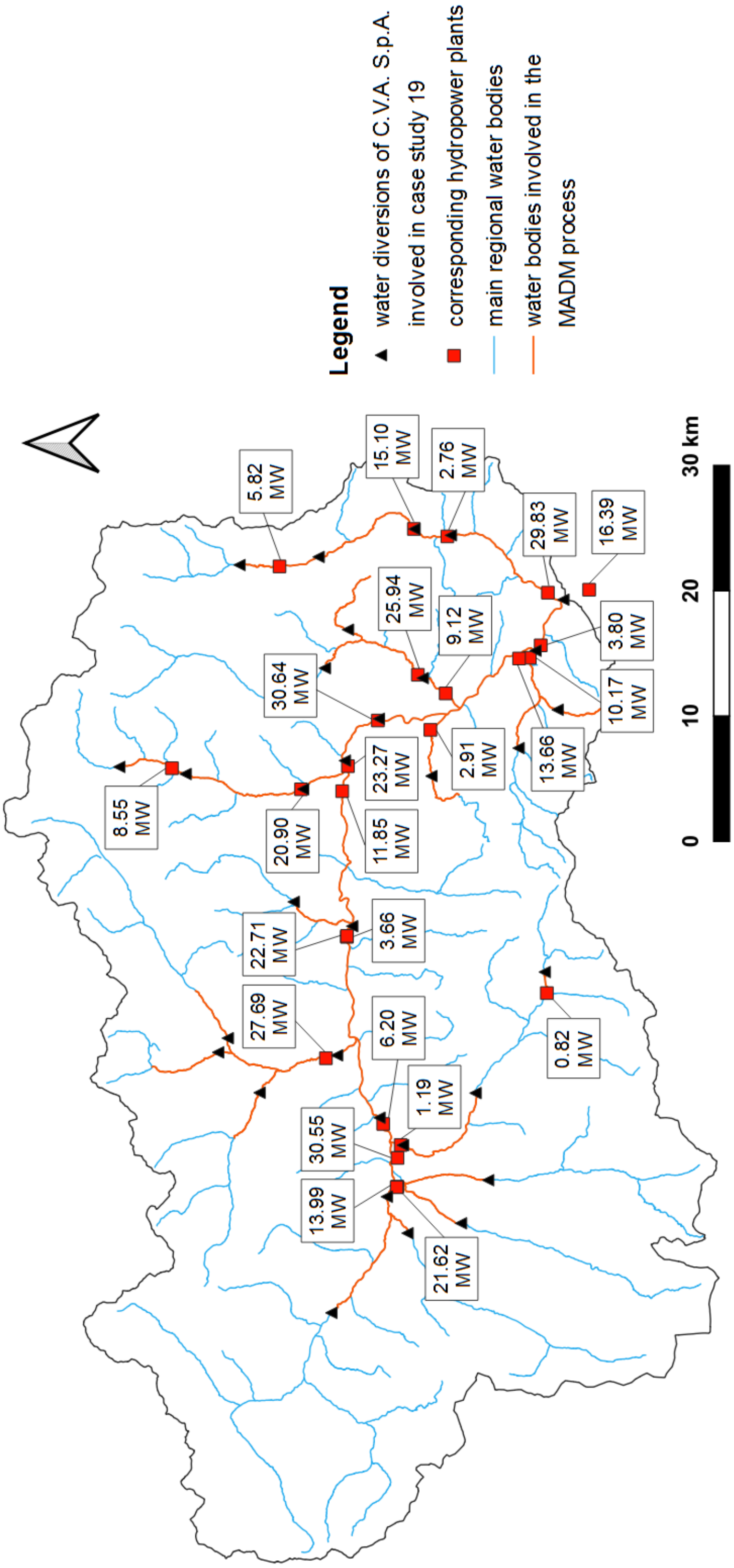

Fig. 6.3 Water withdrawals and corresponding hydropower plants, managed by the main regional hydropower company (C.V.A. S.p.A.), involved in a decision-making process for the definition of the ecological flows (case study 19). Next to each hydropower plant, its average nominal licensed capacity is indicated

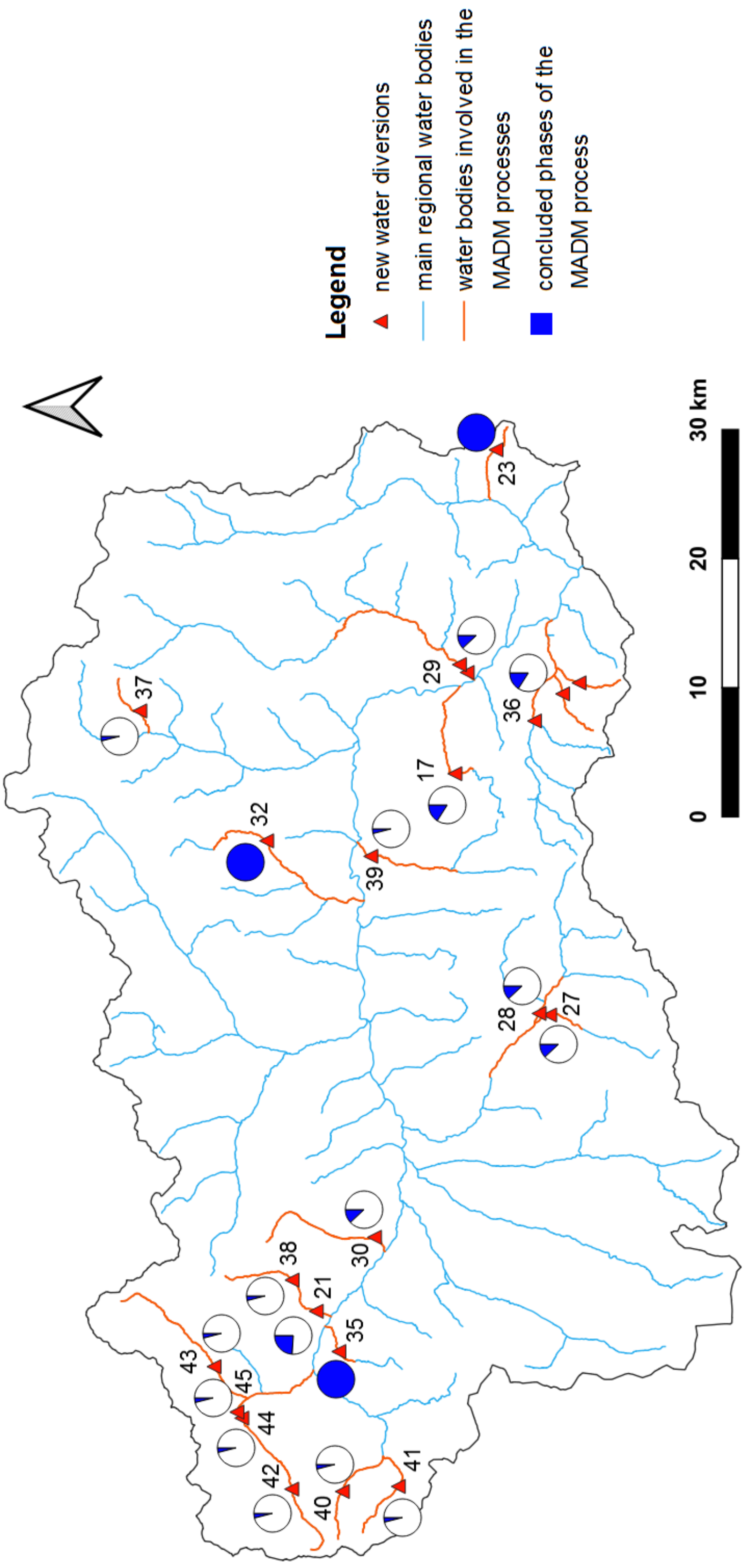

Fig. 6.4 New water withdrawals involved in the decision-making processes for the definition of the ecological flows: the numbers indicate the case studies (as in Table 6.1), while the graphs show the percentage of concluded steps of the decision-making processes

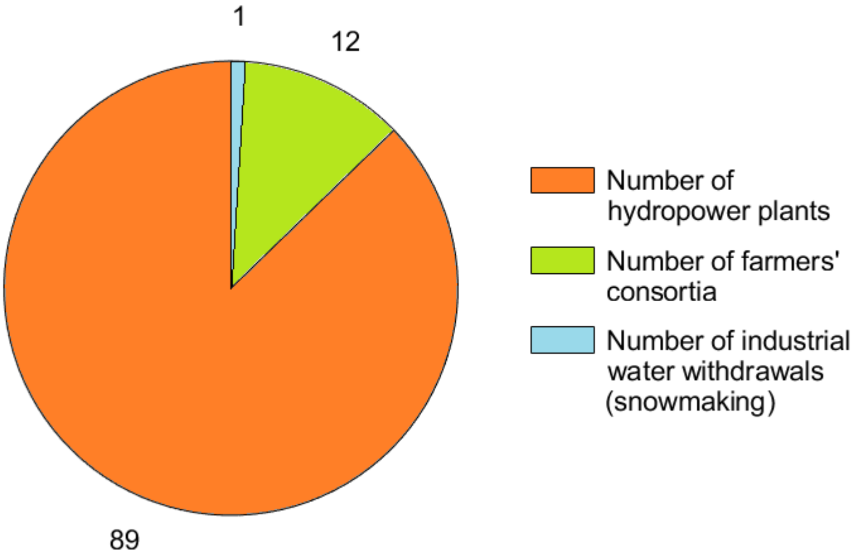

Fig. 6.5 Number of hydropower plants, farmers' consortia, and industrial water withdrawals involved in all the decision-making processes started in Aosta Valley since 2012

It has to be highlighted that the considered agricultural water diversions, so far, are involved in case studies also concerning other withdrawals for HP production. On the contrary, a specific decision-making process has been started to assess the sustainability of the only water diversion for snowmaking (case study 20).

Looking at Figures 6.2, 6.3, and 6.4, it is evident that the water withdrawals concerned by the decision-making processes are spread all over the regional territory, affecting most of the main surface water bodies. The altitude of the withdrawal points varies from 300 to more than 2000 m a.s.l., while the length of the bypassed watercourse stretches ranges between 1 km and 15 km.

As concerns the involved HP plants, the vast majority are run-of-the-river HP stations, but there are also some plants supplied by a reservoir (10.1%). Their size is highly variable, ranging from few kW to more than 30.5 MW. Figure 6.6 represents the classification of the HP plants involved in the decision-making processes, both in operation and planned, according to their average nominal licensed capacity. Only 3 planned HP stations were not included in the figure because their average nominal licensed capacity has not yet been defined, since they are still in the preliminary design phase. It can be noticed that most of the HP plants are small and, above all, mini-HP plants (i.e., their capacity usually varies between 100 kW and 10 MW).

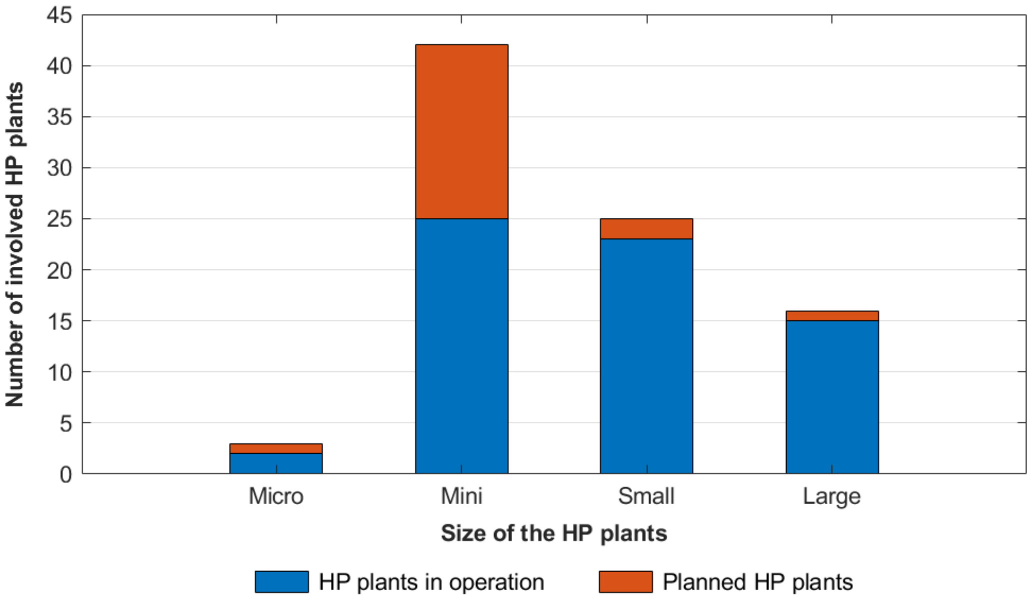

Fig. 6.6 Size of the hydropower plants, both in operation and planned, involved in all the decision-making processes started in Aosta Valley since 2012 (classification based on UNIDO [8]: micro = less than 100 kW of hydropower capacity, mini = between 100 kW and 1 MW, small = between 1 MW and 10 MW, large = more than 10 MW)

There are also 3 micro-HP plants (i.e., with a capacity lower than 100 kW). On the contrary, all the large-scale HP plants, including the one still in the design phase (case study 36), are managed by the main regional hydroelectric company (C.V.A. S.p.A.).

Furthermore, both public and private HP plants are involved in the case studies. The stations managed by C.V.A. S.p.A. are entirely public, while the other HP plants are either totally private or, in some cases, majority-owned by public institutions.

6.3 Stakeholders' feedback on the revised MADM framework

Part of the information presented in this section is based on the work described in the paper [1].

Stakeholders' feedback on the revised methodological approach for water withdrawal assessment has been collected during the decision-making processes carried out in Aosta Valley. In particular, for each case study, stakeholders' satisfaction with the final set of indicators (represented in Figure 3.4) has been assessed, based on the opinions expressed during the meetings of the TAB and recorded in the related minutes. The aim is to evaluate whether the considered indicators are reactive and representative of the different stakes.

Five main characteristics are usually analyzed for each indicator [1]:

- reactiveness, i.e., the causal relationship between the indicator and the different flow release alternatives;
- compliance with the related stakeholders' needs;
- compliance with the legislative framework;
- transferability to different river contexts, i.e., the possibility to adapt the indicator to different contexts, locations, and scales. Nevertheless, the indicator's suitability to assess the objective of the study in the context of the investigation is essential to provide significant information [16];
- availability of the dataset necessary for the elaboration of the indicator. The difficulties related to data collection, management, and elaboration (e.g., the time needed and costs) should also be considered.

The feedback resulting from the minutes of the TAB meetings was compared with the opinions of stakeholders involved in the first test applications of the experimental approach introduced by the regional River Strategic Plan, where the initial MADM framework (Figure 3.1) had been used. As explained in Chapter 3 (section 3.2.4), in fact, most of the initial indicators were modified and refined over the years to better represent the related stakeholders' interests. A comparison table was thus generated, illustrating how the revised procedure is perceived by the concerned actors.

Indeed, many of the representatives of the regional technical bodies involved in the decision-making processes have taken part in all the TAB meetings of the different case studies listed in Table 6.1 and they also collaborated in the first test case studies carried out in Aosta Valley. Therefore, they have gained a large experience in the procedure implementation and they have a clear idea of the improvements generated through the revision of the MADM framework. Their feedback on the adopted MADM methodology has already been discussed in Chapter 5.

Results of the stakeholders’ feedback analysis

The results of the stakeholders’ feedback analysis are summarized in Table 6.2. For each indicator, the five characteristics listed above are assessed, comparing the initial decision tree (indicated as “Previous”) and the final set of indicators (indicated as “Revised”). The following judgments are used: bad, poor, moderate (“mod.”), good, or high.

From a first look at the table, a general improvement of stakeholders’ opinions on the final set of indicators, compared to the previous one, is observed for almost all the analyzed characteristics. Only for the “availability of the dataset”, a worse judgment was assigned to some revised indicators. This feature, in fact, also considers the difficulties related to data collection, management, and elaboration, usually associated with increased time extension and costs. In particular, the need to collect reliable flow data series for the calculation of the scores of all the revised indicators requires the implementation of a continuous hydrological monitoring plan for several years. Nevertheless, this ensures a higher quality of data used in the MADM and emphasizes the importance of watercourse discharge, which is the main parameter of the decision-making process. Furthermore, the hydrological monitoring system also supports direct controls carried out by the Regional Water Authority to assess the compliance of water withdrawal with the license requirements.

More specifically, considering the environmental and fishing indicators, a significant improvement in stakeholders’ satisfaction was observed by replacing the previous WFD biological indicators and the indicator Fish and fishing activities protection with the Index of river Habitat integrity, which represents the stakes related to both the criteria Environment and Fishing. In particular, for the characteristics “reactiveness” and “compliance with stakeholders’ needs”, the judgment varies from bad to high for the environmental indicators. The reason is that, as explained in Chapter 3, the initial biological indicators did not respond reliably to variations of flow release alternatives and may overestimate the ecological status of the affected watercourse. Hence, they did not allow proper quantification of the withdrawal impacts on river ecosystems. On the contrary, the IH indicator is directly related to watercourse discharge alterations. Moreover, it assesses in a reliable and predictable way the effects of flow releases on the environment.

Table 6.2 Summary of stakeholders' feedback on the revised methodological approach used for water withdrawal assessment, comparing the initial set of indicators ("Previous") and the final decision tree ("Revised") (mod. = moderate; modified from [1])

Indicators	Reactiveness		Compliance with stakeholders' needs		Compliance with the legislative framework		Transferability		Availability of the dataset	
	Previous	Revised	Previous	Revised	Previous	Revised	Previous	Revised	Previous	Revised
Energetic indicator	good	high	good	high	good	good	mod.	good	mod.	mod.
Environmental indicator(s)	bad	high	bad	high	good	high	high	high	good	mod.
Fishing indicator	mod.	high	good	high	poor	high	high	high	high	mod.
Landscape indicator	poor	high	poor	high	good	good	mod.	mod.	good	mod.
Economic indicators	good	high	good	high	good	good	good	good	mod.	mod.

The reactiveness improves also according to the fishing stakeholders (from moderate to high). Indeed, the previous indicator, Fish and fishing activities protection, was a hydromorphological proxy indicator, essentially based on expert judgment and not directly related to flow release quantification. Furthermore, although it usually well represented the fishermen's needs, its compliance with the legislative framework was poor. On the contrary, the IH indicator has an explicit reference to recent national decrees (i.e., DD 29/2017 [30] and DD 30/2017 [31]). The compliance with the legislative framework has also improved according to the environmental stakeholders (from good to high). The previous biological indicators, in fact, were required by the regional environmental regulations, based on the European WFD, while the IH indicator fully complies with a more recent national set of laws, ensuring the achievement of environmental quality objectives defined by the WFD for surface water bodies.

As concerns the transferability, no relevant differences have been observed between the previous environmental and fishing indicators and the IH index (the judgment is always high). All the indicators, in fact, can be applied to different river contexts and for different types of water withdrawals. On the contrary, the opinions of environmental and, above all, fishing stakeholders on the availability of the dataset have worsened. Indeed, the initial fishing indicator was essentially based on expert judgment, not requiring regular and organized data collection. The biological indicators previously associated with the environmental criterion were also based on datasets that can be quite easily collected and elaborated. Instead, for the IH indicator, morphological data can be gathered using a common gear (laptop and rangefinder) and an available software tool, but hydrological data collection requires several years of monitoring, increasing the time extension necessary to implement the MeshoHABSIM methodology.

As mentioned in Chapter 4, the landscape indicator was also characterized by extensive modifications in recent years, mainly aimed at including visual effects of flow release amounts on the river landscape downstream of the withdrawal point. Therefore, both the reactiveness and the compliance with stakeholders' needs have considerably improved compared to the initial indicator (the judgment changed from poor to high). Indeed, the previous indicator did not vary significantly with flow releases, because a higher weight was assigned to regional landscape protection constraints. Moreover, neither visual effects of flow release amounts nor the visibility of the bypassed stretch was quantified. On the contrary, the current LPL indicator assesses in a reliable way the effects of flow releases on the river landscape, including the impacts on visual perception.

For this reason, the collection of representative images of the bypassed stretch, covering the entire variability of the hydrological regime, aligned with discharge data, is also required (for the assessment of the Visual Elements Factor). However, this process usually increases the overall time extension and the resources necessary to achieve the final LPL scores. Consequently, stakeholders' judgment on the "availability of the dataset" has worsened compared to the previous indicator, which required less time to be calculated.

On the contrary, no relevant changes have been noticed for the characteristics "Compliance with the legislative framework" and "Transferability". In fact, the same landscape protection constraints defined by national and regional laws (i.e., Legislative Decree n. 42/2004 [223] and Territorial Landscape Plan of Aosta Valley – PTP [224]) are considered for the calculation of both the indicators. Nevertheless, these constraints are typically referred to the Aosta Valley context, thus limiting the transferability of the indicators. To adapt the LPL indicator to different river contexts, for example, the Constraint Factor and the Visual Elements Factor should be updated according to the local regulations and the river landscape features typical of the area.

Finally, as concerns the energetic and economic indicators, no extensive changes in stakeholders' feedback have been observed comparing previous and revised indicators. As explained in Chapter 3 (section 3.2.4), the revised indicator Energy Index (IEn) is generally used in all the decision-making processes carried out in Aosta Valley (with the exception of case study 20, which does not involve any HP plants), considering the specific characteristics of the HP plant(s) involved in the case study. On the contrary, one or more economic indicators are usually defined for each case study by the related stakeholders involved in the TAB (i.e., members of the HP companies and, in case study 20, of the snowmaking company), taking into account the specific situations. For example, the HP company involved in case study 2 is a cooperative, which ensures a share of energy to its members. Therefore, a new economic indicator has been defined, quantifying the economic losses not only due to the lack of energy production but also to the purchase of energy to be supplied to the members. Instead, the HP company involved in case study 15 is developing an economic indicator that also considers the high costs associated with plant downtime caused by some flow release alternatives in winter. Moreover, for case study 20, an indicator evaluating the economic and tourist effects of the water diversion for snowmaking activities has been defined. In other case studies, an indicator that assesses the economic effects of different HP plants on the whole system (in particular, for C.V.A. S.p.A.) is also necessary.

For the energetic indicator, stakeholders' feedback has improved (from good to high) on both the "reactiveness" and "compliance with stakeholders' needs". Indeed, while the initial indicator had been defined to identify flow releases effects mainly on medium and large HP plants, the revised IEn takes into account the specific characteristics of the HP plant(s) involved in the case study (e.g., turbine typology, penstock characteristics, maximum turbine flow, etc.). Therefore, it also better quantifies the outputs of energy production and, thus, the related stakeholders' interests. Moreover, it can be more easily reused in different river contexts in Italy, thus improving also the transferability (from moderate to good).

Stakeholders' opinions on the other indicators' characteristics have not changed. Both the initial and revised indicators have good compliance with the legislative framework (i.e., European, national, and regional laws requiring the increase of energy production from renewable sources to reduce greenhouse gas emissions). On the contrary, the "availability of the dataset" has received a moderate judgment. In fact, energy production datasets are easily available in case of existing HP plants, while for new HP plants this information can be obtained only by referring to reliable streamflow time series, thus requiring significant time extension for hydrological data collection, processing, and validation.

Similar observations have been made for the economic indicators. The indicators currently considered in the decision-making processes are more reactive since they are directly related to watercourse discharge alterations. Their compliance with stakeholders' needs has also improved (from good to high). Indeed, the previous indicator well represented economic outcomes for the HP producer. However, the current economic indicators are usually directly developed by the related stakeholders involved in the specific case study, thus better quantifying the economic outcomes.

Instead, no relevant changes have been noticed in the compliance with the legislative framework and the transferability (economic indicators can be easily reused in other river contexts in Italy). Stakeholders' feedback on the availability of the dataset has also remained unvaried (moderate) for the previous and revised economic indicators. As for the energetic indicator, in fact, economic datasets are available for HP producers in case of existing HP plants, while, for new HP plants, this information is reliable only by collecting consistent hydrological series. Moreover, it may be possible that, for some financial data, trade secret can be applied. Similar observations can be made about the snowmaking company involved in case study 20. In addition, the quantification of economic outcomes at the local community level could be difficult due to the lack of clear methodological references.

6.4 Concluding remarks

The revised methodological framework presented in the previous Chapters is currently used in Aosta Valley for the definition of the ecological flows to be released downstream of one or more withdrawal dams. As explained in section 6.2, the procedure has been and is being applied to several real case studies over the regional territory. At present, 38 decision-making processes are ongoing in Aosta Valley, involving different types of water withdrawals (mainly run-of-the-river HP plants, but also water diversions for irrigation and, in one case study, for snowmaking). Moreover, other 7 decision-making processes are already concluded. The aim of the procedure is to identify a flow release alternative representing the best mediation scenario among ecosystem and landscape protection, HP production, and other water users' needs. The selected alternative is then officially approved by the Regional Government and implemented in the considered bypassed watercourses stretch.

The information provided in section 6.2 demonstrates that the methodological approach can be adapted to different types of decision problems, even particularly complex (e.g., case study 19). For example, it can be applied both *ex-ante*, i.e., to assess the suitability of new licenses for water diversions during the planning phase, and *ex-post*, i.e., to evaluate the renewal, variation, or strengthening of licenses for existing withdrawals. Moreover, the MADM procedure is not only used in case studies involving a single water diversion but also to optimize the ecological flows of multiple withdrawals located on the same watercourse and/or functionally interconnected.

Another important feature of the proposed methodology is the positive feedback of the involved stakeholders, who are required to collaborate throughout the decision-making process, overcoming conflicts. In particular, the analysis of stakeholders' opinions on the revised decision tree, illustrated in section 6.3, generally shows a further increase in their satisfaction compared to the initial set of indicators. In fact, almost all the analyzed characteristics have improved for the revised indicators, according to the involved stakeholders (as highlighted by the evaluation matrix represented in Table 6.2).

In particular, the final decision tree is more representative of the different interests, since all the revised indicators are considered highly compliant with the corresponding stakeholders' needs. Moreover, all the revised indicators are directly related to the watercourse discharge, withdrawn and released in the bypassed stretch. Therefore, they are also considered highly reactive. Furthermore, they all have explicit normative references and they can usually be easily applied to different river contexts. Only for the landscape indicator, the judgment on the "transferability" is moderate, because the landscape protection constraints and the visual metrics of riverscape perception considered for the calculation of the LPL score are typically referred to the Aosta Valley context.

On the contrary, stakeholders' feedback on the availability of the dataset has generally worsened for the revised indicators. This is due to the increased time extension and costs required for data collection, management, and elaboration. In particular, since discharge data are essential for the calculation of all the revised indicators, a continuous hydrological monitoring system is necessary to collect reliable streamflow time series. Therefore, the whole decision-making process usually covers a period of at least five years. This may appear as a drawback, especially for the stakeholders applying for the release of a water withdrawal license, since the final authorization measure is generally released after a long period. However, the applicants are directly involved in the MADM implementation, together with the other concerned stakeholders, trying to identify a flow release alternative that best represents the different water users' interests. Furthermore, during the decision-making process, temporary authorization measures can be released, allowing the applicant to adopt provisional flow release schemes, agreed by the members of the TAB. Hence, even the applicants usually acknowledge the advantages of the described approach.

A weakness that can be noticed considering the case studies ongoing in Aosta Valley, which also concern some agricultural water diversions, is the lack of a criterion representing the stakes of the involved farmers' consortia. Indeed, a reactive indicator quantifying the effects of flow release alternatives on irrigation activities is currently not available. However, work is ongoing, in collaboration with the representatives of the Regional Agriculture Service, to develop a new agricultural indicator, which will probably be introduced in the MADM decision tree, when needed, in future decision-making processes.

As discussed in this Chapter, the revised methodological framework used in Aosta Valley has proven to be a suitable tool to support decision-making problems concerning water withdrawal assessment. Recently, it has been formally adopted in the institutional water withdrawal licensing procedure for the definition of ecological flows. Moreover, due to the positive feedback of the involved stakeholders and decision-makers, the methodology will probably be officially endorsed in the regional River Strategic Plan as the primary method for the assessment of water withdrawal sustainability.

Chapter 7

Conclusions

The aim of this thesis was to present the innovative methodological framework, based on multi-criteria decision-making and refined during the PhD, for the overall assessment of water withdrawal sustainability in the Alpine region.

Indeed, most of the Alpine watercourses are affected by several anthropogenic alterations, generating significant impacts on freshwater ecosystems and river landscape. Moreover, the impacts of climate change on water availability will further intensify conflicts among different water users, e.g., hydropower, agriculture, and industry. Therefore, new approaches based on a collaborative and participatory framework are strongly recommended for water resources management in the Alps.

In Aosta Valley, a small Alpine region located in northwest Italy, most watercourses are significantly impacted by water withdrawals, mainly for hydropower production and agricultural irrigation. Water-related conflicts among different stakeholders have thus increased. Therefore, an experimental approach based on the application of multi-attribute decision-making (MADM) has been recently developed to identify the most appropriate scenario of ecological flows to be released downstream of a withdrawal dam. The aim is to achieve a decision that represents the best mediation among river environment and landscape protection and the other water users' interests.

Over the last decades, several studies have focused on the use of MADM methods to solve a variety of decision-making problems concerning surface water resources management, in different areas of the world, as demonstrated by the results of the literature review illustrated in Chapter 2. The use of these methods, in fact, can improve the understanding of problems characterized by a multi-dimensional and complex nature, facilitating the resolution of conflicts [45]. However, real applications with legally binding results are rare. Even in the reviewed scientific articles, although a real decision problem is often described, it is usually not specified whether the MADM results have been actually adopted to support the decision-maker in achieving the final solution.

On the contrary, the methodological framework presented in this thesis is officially used, in Aosta Valley, in the water withdrawal licensing procedure for the definition of ecological flows. Each decision-making process is based on the active participation of key stakeholders, representing the main concerned water uses, forming a Technical Assessment Board (TAB). The TAB, coordinated by the Regional Water Authority, includes the applicants asking for the release or renewal of a water withdrawal license and the representatives of the main concerned regional technical bodies. The involved stakeholders' interests are represented in the MADM decision tree by the different criteria, each quantified by one or more indicators. Furthermore, a set of alternatives, representing various scenarios of ecological flows, is developed by the members of the TAB and assessed through the SHARE MCA method.

The methodology has been refined during the PhD, mainly to improve the representativeness of the different interests involved in the decision-making process. An important achievement has been the revision of the MADM decision tree, which currently includes only reactive and representative indicators, based on the normative framework and related to the watercourse discharge.

Four criteria are usually considered in the revised decision tree, i.e., Energy, Environment & fishing, Landscape, and Economy. In particular, the Index of river Habitat integrity (IH), derived from the MesoHABSIM (Mesohabitat Simulation Model) methodology, has been associated with the Environment & fishing criterion to quantify the effects of water withdrawals on river ecosystems and fish communities. As explained in Chapter 3, the integration of this methodology into the MADM framework has allowed overcoming the limitations of the previous environmental and fishing indicators. Indeed, the criterion "Environment" was initially quantified through four biological indicators derived from the European Water Framework Directive (WFD). Nevertheless, these indicators were scarcely reactive to hydrological alterations, as demonstrated by different scientific articles and by local studies carried out in Aosta Valley. Moreover, also the indicator initially associated with the

Fishing criterion, essentially based on expert judgment, was not sufficiently reliable. The suitability of the new IH indicator, on the contrary, has been demonstrated by the satisfying results of the first complete decision-making process carried out in Aosta Valley, involving a small run-of-the-river HP plant on the Graines torrent (illustrated in section 3.3). Indeed, the selected flow release alternative is currently implemented downstream of the considered HP plant.

Furthermore, a new indicator, named Landscape Protection Level (LPL), has been developed to quantify the Landscape criterion. This indicator, described in Chapter 4, assesses the effects of water withdrawals on the river landscape of the affected watercourse. It takes into account the visibility of the bypassed stretch and the presence of landscape protection constraints, the amount of flow released downstream of the dam, and the impact on the visual perception. The main properties of the LPL indicator have been analyzed (in section 4.4), based on the results obtained in four real case studies, concerning different HP plants. In particular, the indicator has proven to be highly reactive and representative of the related stakeholders' interests.

As mentioned in Chapter 3, the energy and economic indicators have also been revised compared to the initial decision tree. The Energy Index, which quantifies the losses of HP production due to the flow releases, currently considers the specific characteristics of the involved HP plant(s). However, it is excluded from the decision tree when no HP plants are included in the decision-making process (only in rare cases). On the contrary, one or more economic indicators, directly related to flow releases, are defined for each case study by the related stakeholders involved in the TAB. Since they consider the specific situations and datasets, they quantify in a reliable way the economic incomes.

All the indicators included in the revised decision tree are directly related to the watercourse discharge, which is the main parameter of the decision-making process. Therefore, the need to collect reliable flow data series requires the installation of a continuous hydrological monitoring system in the affected watercourse. This system also supports direct controls carried out by the Regional Water Authority to assess compliance with the water license requirements. Moreover, by measuring discharge data upstream of the withdrawal dam, several recent HP plants have the possibility to implement real-time alternatives, which define the flow releases according to the natural watercourse discharge. These ecological flows are thus characterized by more natural variability, compared to fixed monthly flow releases, better supporting the riverine ecological processes.

Moreover, the effectiveness of the MADM technique adopted in Aosta Valley has been evaluated by comparing the method with other MADM techniques, among the most widely used in the literature. All the considered methods have been applied to the same real case study of hydropower management, using the revised decision tree, as explained in Chapter 5. The results of non-parametric correlation tests (i.e., Kendall's tau and Spearman's rho) and aggregation techniques (i.e., Borda and Copeland methods) have demonstrated that the results of SHARE MCA are in line with the results obtained by applying the most popular MADM methods (as illustrated in section 5.3). Besides, evaluating the overall methodological approach of the different MADM techniques, also based on the feedback of some stakeholders involved in the decision-making process, SHARE MCA has proven to be highly feasible and replicable.

Due to the positive results of the first complete decision-making process carried out in Aosta Valley, the revised methodological approach has been formally adopted in the institutional water withdrawal licensing procedure. Therefore, as explained in Chapter 6, over the last years, it has been applied to several real case studies over the regional territory (38 are currently ongoing, while 7 are already concluded).

The overview of the decision-making processes shown in Table 6.1 demonstrates that the methodology can be adapted to different contexts. For example, different types of water withdrawals are considered: water diversions for HP production are the most frequent, supplying water to HP plants characterized by highly variable sizes (from few kW to more than 30.5 MW), but agricultural and industrial withdrawals are also involved in some case studies. Moreover, the MADM procedure can be used both *ex-ante*, to assess the release of a new water withdrawal license, and *ex-post*, for the renewal, variation, or strengthening of an existing license. It can also be applied to different scales, i.e., either for a single water diversion or for multiple withdrawals, functionally interconnected, located in the same watershed, sometimes involving different watercourses. Case studies carried out at a larger scale are usually more complex, due to the need to optimize the ecological flows of multiple water diversions and, sometimes, to the involvement of different applicants. However, during each decision-making process, the collaboration among the members of the TAB generally allows the identification of a flow release alternative that represents the best mediation among the different water users' interests. The selected scheme of ecological flows is officially approved by the Regional Government and implemented in the affected watercourse stretch.

The stakeholders involved in the case studies carried out in Aosta Valley are usually satisfied with the revised methodological approach. In particular, their feedback on the final decision tree is generally good, as illustrated in section 6.3. Indeed, almost all the analyzed characteristics of the revised indicators have improved compared to the previous decision tree.

Nevertheless, since all the revised indicators are related to discharge data, the collection of reliable streamflow time series is necessary. This usually requires at least five years of hydrological monitoring, which increase the time extension of the whole decision-making process. Besides, the work and time needed for the calculation of some indicators' scores can also be significant (as in the case of the LPL indicator, which requires the collection and analysis of a set of images of the bypassed stretch, aligned with discharge data). However, the quality of the obtained data, used in the MADM framework, is higher. Moreover, during the decision-making process, temporary authorization measures can be released, allowing the applicant to adopt provisional ecological flows, agreed by the members of the TAB.

Another limitation of the methodological approach is the initial difficulty, for stakeholders and administrators without a technical background, to understand all the aspects of the decision-making procedure. For example, the MesoHABSIM methodology, used for the determination of the IH indicator, is usually more difficult to be explained, compared to other methods for environmental assessment. Besides, it is necessary to clearly explain to all the involved actors the strategic importance of hydrological monitoring, which contributes to increasing the quality of the MADM assessment. For these reasons, the possibility of directly involving more stakeholders (e.g., members of the local communities and river landscape users) in the decision-making process is currently limited. However, the main water users' interests are considered in the MADM framework by involving in each case study, in addition to the applicants, the representatives of the corresponding regional technical bodies. There is general satisfaction with the methodological approach and the decision-makers have also noticed an improvement in the decision-making quality. Therefore, the methodology will probably be officially endorsed in the regional River Strategic Plan as the primary method for the assessment of water withdrawal sustainability.

Future research

Based on the strengths of the described methodology and on some limitations highlighted in the previous Chapters, some ideas for future research are proposed in the following paragraphs.

First, a weakness highlighted in Chapter 6 is the lack of a criterion representing the stakes of the farmers' consortia involved in some decision-making processes currently ongoing in Aosta Valley. Therefore, an indicator assessing the effects of flow release alternatives on irrigation activities is being developed, in collaboration with the representatives of the Regional Agriculture Service. This indicator should be introduced in the MADM decision tree, associated with a new criterion "Agriculture", for case studies concerning agricultural water withdrawals.

Other activities could be carried out to involve other stakeholders in the described procedure, especially for a final assessment of the selected flow release alternative. For example, as mentioned in Chapter 4, in some case studies, a representative sample of the main river users (e.g., tourists, fishermen, members of the local community, etc.) could be interviewed to collect their impressions of the withdrawal effects on the considered watercourse stretch.

Furthermore, future research should also focus on the analysis of climate change effects on the hydrology of some Alpine watercourses. In fact, over the next years, the water withdrawal licenses of several hydropower plants will be revised in Aosta Valley, redefining the ecological flow requirements for a thirty-year period. At such a time scale, the potential effect of climate change on future water availability cannot be neglected. Therefore, a modeling approach could be used to support decision-makers in water withdrawal management. Historical and future flow time series could be modeled under different greenhouse gas scenarios for some watercourses in Aosta Valley to analyze changes in future runoff regimes. Moreover, the MesoHABSIM methodology could be applied to simulate the variations in habitat availability for the local fish population (i.e., brown and marble trout). The consequences for the main indicators considered in the MADM decision tree could also be simulated, thus supporting the decision-makers in future decisions concerning the release or renewal of water withdrawal licenses.

Finally, further work should be carried out to extend the application of the proposed methodological framework to different river contexts. Indeed, as explained in Chapter 6, most of the considered indicators can be easily used in other areas. However, for the landscape indicator, some revisions are necessary for the adaptation to another location. In fact, the landscape protection constraints and the visual metrics of riverscape perception currently considered for the calculation of the LPL score are typically referred to the Aosta Valley context. Therefore, these elements should be updated, by considering the local regulations in force and visual metrics typical of the watercourses present in the area before the adoption of the landscape indicator in another region. Moreover, further work would be necessary to adapt the decision-making process to local characteristics, e.g., considering the typical water-related conflicts, the main stakeholders to be directly involved in the procedure, or the possibility of actually implementing the selected alternative at the end of the MADM process, with the official endorsement of the local Water Authority.

Appendix A

Weighting methods for multi-attribute decision-making

Main subjective weighting methods

As explained in Chapter 2, subjective weighting methods determine criteria weights based on the decision-makers' preferences. The most popular subjective methods are:

- Direct rating
- Ranking method
- Point allocation
- Pairwise comparison
- Ratio method
- Swing method
- Delphi method
- Simple Multi-Attribute Ranking Technique (SMART)
- Simos' method

Direct rating method

The direct rating method is a popular subjective weighting method in which the decision-maker assigns a score to each criterion according to its importance. The procedure can be based on a questionnaire using an ordinal rating scale. The importance of a criterion can be varied without modifying the weight of another criterion [64].

Ranking method

The ranking method is one of the simplest techniques for the definition of criteria weights. Initially, the criteria are ranked from the most important to the least important. Then, the weights are calculated through one of the following methods: rank sum, rank exponent, or rank reciprocal [92].

In rank sum, the individual rank positions are divided by the sum of the ranks to determine the weights of criteria:

$$w_j = \frac{n - p_j + 1}{\sum_{k=1}^{n} (n - p_k + 1)} \tag{A.1}$$

where p_j is the rank of the j-th criterion and n is the number of the considered criteria.

The rank exponent is similar, but an exponent p has to be defined by the decision-maker, based on the most important criterion. The following formula is used:

$$w_j = \frac{(n - p_j + 1)^p}{\sum_{k=1}^{n} (n - p_k + 1)^p} \tag{A.2}$$

Finally, rank reciprocal uses the normalized reciprocal of the criterion rank position p_j:

$$w_j = \frac{1/p_j}{\sum_{k=1}^{n} (1/p_k)} \tag{A.3}$$

This weighting technique is appealing due to its simplicity, but it is not appropriate when there is a large number of criteria because, in this case, straight ranking is difficult [92].

Point allocation

Point allocation is another simple method for the definition of criteria weights. In this method, the decision-maker is asked to directly assign a certain number of points to each criterion, according to its relative importance. The sum of all criteria weights is 100.

This method is easy to normalize, but it is difficult to apply when the number of criteria is equal to or higher than 6. Moreover, the obtained weights are not very precise [92].

Pairwise comparison and Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a widely used MADM method developed by Thomas L. Saaty in the 1970s [73]. It is a flexible methodology that allows analyzing complex decision-making problems, structuring them into a hierarchical framework [13].

Pairwise comparison is the tool employed to estimate priorities among the different criteria. At each level of the hierarchy, a pairwise comparison matrix is developed and the elements are compared among themselves in pairs based on a 9-point rating scale developed by Saaty (Table A.1). 1 corresponds to equal importance between two criteria, while 9 means that a criterion is much more important than another [13].

Each pairwise comparison matrix P is a reciprocal square matrix:

$$P = (p_{ij}) = \begin{pmatrix} 1 & p_{12} & \dots & p_{1n} \\ p_{21} & 1 & \dots & p_{2n} \\ \dots & \dots & \dots & \dots \\ p_{n2} & p_{n2} & \dots & 1 \end{pmatrix} \tag{A.4}$$

Table A.1 Rating scale for pairwise comparison developed by Saaty (adapted from [13])

Intensity of importance	Verbal judgment of preference
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values

where p_{ij} is the relative importance of the i-th element over the j-th element, $i, j \in \{1, \ldots, n\}$, $p_{ji} = {p_{ij}}^{-1}$, and the main diagonal values are always equal to 1 [122].

Criteria weights are calculated from the pairwise comparison matrix by finding the eigenvector with the largest eigenvalue (λ_{max}) [73]. To assess the consistency of the judgments provided by the decision-maker, two indexes are calculated, i.e., the consistency index (CI):

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{A.5}$$

and the consistency ratio (CR):

$$CR = \frac{CI}{RI} \tag{A.6}$$

where RI is the consistency index of a randomly generated matrix of the same size [240]. A CR value lower than 0.1 indicates a reasonable level of consistency in the pairwise comparison; otherwise, the pairwise comparison should be re-evaluated [92].

Ratio method

The ratio method requires the judgment of the decision-maker to rank the criteria according to their importance. A value of 10 is assigned to the least important criterion, while multiples of 10 are assigned to the other criteria. Then, the resulting weights are normalized so that their sum is equal to 1 [64].

Swing method

The Swing method [241] is a well-known method for weight elicitation. The decision-maker is asked to select an alternative with the worst outcome and select the criterion whose change (or swing) from the worst to the best score would result in the largest improvement of the overall value [242]. This criterion is the most important and 100 points are allocated to it.

The process is repeated for the remaining criteria, to which points between 0 and 100 are assigned based on the importance of their score change in relation to the score change of the most important criterion. The final weights are obtained by normalizing the assigned points so that their sum is equal to 1 [118].

Delphi method

The Delphi method is based on a structured process that allows a group of experts to deal with complex problems by collecting information through a series of questionnaires combined with controlled opinion feedback [188]. It is often used in decision problems concerning water resources management to select appropriate criteria and to estimate their weights (e.g., [157, 243].

During the Delphi process, a series of iterative questionnaires are sent to a group of selected experts, who remain anonymous. The results of the previous questionnaires are returned to the respondents, who are required to examine and possibly modify their responses. By the second or third round of this process, the experts usually reach a consensus on the estimation problem [244].

An advantage of the Delphi method is that there are no members of the team of experts that can influence other members in an inappropriate way [188]. Moreover, the iteration process allows the participants to refine their views, also based on the controlled feedback which informs them of the other experts' perspectives [245]. The most difficult part of the Delphi process is the selection of the panel of experts, which should be carried out carefully in order to include the opinion of all the affected stakeholders [188].

Simple Multi-Attribute Ranking Technique (SMART)

The Simple Multi-Attribute Rating Technique (SMART) is a compensatory method for multi-criteria decision-making. The weighting technique used in this method requires the decision-maker to rank the criteria from the worst to the best, according to their importance. 10 points are assigned to the least important criterion. Then, an increasing number of points is allocated to the other criteria, with 100 points to the most important one. The criteria weights are calculated by normalizing the sum of the points to one [92].

Simos' method

This method, proposed by Simos [246], is based on a simple procedure that uses "playing cards" to define the criteria weights. The procedure is characterized by the following steps [136]:

1. *n* cards are given to the decision-maker (corresponding to the *n* criteria). On each card, the name of the criterion and its objective are indicated. Some black cards are also provided to the decision-maker.
2. The decision-maker is asked to rank the *n* cards from the least important to the most important. If some criteria have the same importance according to the decision-maker, the cards are grouped together, i.e., they have the same rank position.
3. Moreover, the decision-maker can place blank cards between two consecutively ranked cards (or groups of cards) to represent a higher difference of importance between the criteria.

Figueira and Roy [247] proposed a revision of the Simos' method, the "Revised Simos' procedure", including an additional step to the procedure described above [67]:

4. The decision-maker is asked to answer the question "How many times more important is the first ranked criterion (or group of criteria), compared to the last ranked criterion (or group of criteria)?"

The ranking of criteria is then transformed using an algorithm that assigns a numerical value to the weights of each criterion [67].

An advantage of this weighting method, is the possibility to express the weighting preferences on an ordinal scale, instead of using a numerical scale [67]. Moreover, the active participation of the decision-maker increases his/her understanding of the method. However, a drawback was observed when the direct response of the decision-maker to the question of step 4 was completely different from the total number of cards used (including blank cards). In this case, the obtained normalized weights of criteria showed a distortion of the initial ranking of criteria defined by the decision-maker [136].

Main objective weighting methods

Objective weighting methods determine criteria weights by means of mathematical models, without considering decision-makers' preferences. The most popular objective methods are:

- Entropy method
- Criteria Importance Through Inter-criteria Correlation (CRITIC)
- Mean weight
- Standard deviation

Entropy method

Shannon entropy [248] is a measure of uncertainty in information formulated in terms of probability theory [249]. The entropy method can be used for assessing objective weights using the data contained in the normalized decision matrix [141].

The entropy (e_j) of each criterion C_j is calculated by the following equation:

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} r_{ij} \cdot \ln(r_{ij}) \tag{A.7}$$

The degree of deviation (d_j) of the average internal information included in each criterion is calculated as:

$$d_j = 1 - e_j \tag{A.8}$$

Finally, the objective weight of each criterion is obtained through the following equation:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{A.9}$$

Criteria Importance Through Inter-criteria Correlation (CRITIC)

The CRITIC (CRiteria Importance Through Inter-criteria Correlation) method, proposed by Diakoulaki et al. [250], uses correlation analysis to detect contrasts among criteria [138].

Considering the j-th criterion of the normalized decision matrix, a vector r_j can be generated with the normalized scores r_{ij} of all the m alternatives:

$$r_j = (r_{1j}, r_{2j}, \ldots, r_{mj}) \tag{A.10}$$

Each vector r_j is characterized by the standard deviation σ_j, quantifying the contrast intensity of the corresponding criterion [250].

Afterward, a symmetric $n \times n$ matrix is obtained, whose elements l_{jk} represent the linear correlation coefficients between the vectors r_j and r_k. Lower values of l_{jk} indicate a higher discordance between the scores of the alternatives in criteria j and k. Eq. A.11 represents a measure of the conflict generated by criterion j with respect to the decision situation defined by the other criteria:

$$\sum_{k=1}^{n} (1 - l_{jk}) \tag{A.11}$$

Therefore, the amount of information C_j conveyed by the j-th criterion can be determined by combining the measures of the two previous notions through the following equation [250]:

$$C_j = \sigma_j \sum_{k=1}^{n} (1 - l_{jk}) \tag{A.12}$$

Higher values of C_j indicate a larger amount of information conveyed by the corresponding criterion and, thus, higher importance of this criterion for the decision-making process. Objective weights w_j are then calculated by normalizing these values [250]:

$$w_j = \frac{C_j}{\sum_{k=1}^{n} C_k} \tag{A.13}$$

Mean weight

This objective method is based on the assumption that all the criteria have the same importance. It is generally used when decision-makers' preferences are not known or when there is not enough information to reach a decision [92]. This technique is the most widely applied due to its simplicity but assigning equal importance to all the criteria is usually unrealistic [67]. The following equation is used:

$$w_j = \frac{1}{n} \tag{A.14}$$

where n is the number of criteria.

Standard deviation

The standard deviation method determines the criteria weights w_j based on their standard deviation σ_j, using the following equations [92]:

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{m} (x_{ij} - \bar{x}_j)^2}{m}} \tag{A.15}$$

$$w_j = \frac{\sigma_j}{\sum_{j=1}^{n} \sigma_j} \tag{A.16}$$

where m is the number of alternatives, n the number of criteria, and x_{ij} is an element of the decision matrix (i.e., the score of the i-th alternative when it is evaluated in terms of the j-th criterion).

Appendix B

Main multi-attribute decision-making (MADM) methods

Methods based on value measurement

As explained in Chapter 2, the methods based on *value measurement* aim to obtain a true value for each alternative by aggregating the value functions of each considered criterion, according to their relative importance. The most popular methods included in this category are:

- Multi-Attribute Value and Utility Theories
- Simple Additive Weighting
- Weighted Product Method
- Analytic Hierarchy Process
- Weighted Linear Combination

Multi-Attribute Value and Utility Theories

Multi-Attribute Value and Utility Theories (MAVT and MAUT) [76] are among the most widely applied MADM methods. Since their origin in the late 1960s, the use of these methods has increased the focus on the actual implementation of multi-criteria decision-making, influencing developments in the field [3].

Multi-Attribute Value Theory (MAVT) is based on the definition of a measurable value function to include the preferences of the decision-maker or stakeholders. The value theory is used to transform the initial scores of alternatives against the different criteria (x_{ij}) into dimensionless values, usually varying between 0 and 1 [165]. The multiple attributes are then aggregated to obtain a single, overall value for each alternative [251]. Additive aggregation is usually adopted to aggregate the value functions defined for each attribute (v_j):

$$V(A_i) = \sum_{j=1}^{n} w_j \cdot v_j(x_{ij}) \tag{B.1}$$

where n is the number of criteria, w_j is the weight of each criterion, x_{ij} is the initial score of alternative A_i with respect to criterion j, and $v_j(x_{ij})$ is the corresponding normalized score. The overall performance of the i-th alternative is given by its overall value function $V(A_i)$. The preferred alternative is the one with the highest performance $V(A_i)$ [251]. Moreover, larger differences between the overall values of two alternatives correspond to stronger differences in preference [252].

MAVT is strictly valid under two axioms, i.e., completeness and transitivity. Completeness means that, for any pair of alternatives, the decision-maker can define which one is preferred or whether they are equivalent. Transitivity, on the contrary, implies that, if the decision-maker prefers A_1 to A_2 and A_2 to A_3, then he/she necessarily prefers A_1 to A_3 [252].

Multi-Attribute Utility Theory (MAUT) can be considered as an extension of MAVT, including information about the risk attitudes of the decision-maker or stakeholders [3]. In this case, probability distributions, usually defined as “lotteries”, are associated with each alternative and preferences between these probability distributions can be considered to elicit a utility function [252]. The overall utility function $U(A_i)$ is usually obtained through an additive aggregation:

$$U(A_i) = \sum_{j=1}^{n} w_j \cdot u_j(x_{ij}) \tag{B.2}$$

where u_j is the utility function of criterion j.

A further axiom in the *expected utility theory*, apart from completeness and transitivity of MAVT, is the independence assumption. According to this axiom, the preference between two lotteries is not affected by the introduction of another alternative [3].

Simple Additive Weighting

Simple Additive Weighting (SAW) [72] is a full compensatory method. Due to its simplicity, it is very popular also among practitioners [71]. For each alternative, the method calculates a global value based on a weighted sum [253, 179]:

$$P(A_i) = \sum_{j=1}^{n} w_j \cdot r_{ij} \tag{B.3}$$

where $P(A_i)$ is the final performance value for the i-th alternative and r_{ij} is the normalized score of alternative A_i with respect to criterion j.

In this method, the criteria should be all numerical, expressed in the same unit, and with the same preference direction (maximization or minimization). Therefore, if the attributes are not comparable, they have to be normalized, so that they can be added up [254]. The preferred alternative corresponds to the higher performance value $P(A_i)$ for a maximization decision problem (and to the lowest $P(A_i)$ for a minimization problem) [138].

Weighted Product Method

The Weighted Product Method (WPM) [230] is very similar to the SAW, but multiplication is used, instead of addition, to aggregate the elements of the decision matrix. In particular, for each criterion, a ratio is calculated and raised to the corresponding criterion weight. The ratios are then multiplied to determine the overall value of each alternative. Therefore, to compare the alternatives A_k and A_l (where $1 \leq k, l \leq m$), the following equation is used [255]:

$$R\left(\frac{A_k}{A_l}\right) = \prod_{j=1}^{n} \left(\frac{x_{kj}}{x_{lj}}\right)^{w_j} \tag{B.4}$$

where x_{ij} is the value of the i-th alternative in terms of the j-th criterion.

Alternative A_k is considered better than alternative A_l if the value $R\left(\frac{A_k}{A_l}\right)$ is higher than or equal to 1, in a maximization decision problem (lower than 1 in the minimization case). The preferred alternative is the one that is better than (or at least equal to) all the other alternatives [255].

An advantage of this method is that, considering relative values, the different units of measure are directly removed. Therefore, the WPM method can be used in multi-dimensional decision problems, without requiring the normalization of the decision matrix. Nevertheless, all the criteria have to be of the same type, i.e., benefit or cost [238].

Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) [73] is one of the most widely used MADM methods, in different fields. It is a flexible methodology, which allows the breakdown of complex decision-making problems into a hierarchical structure [13]. The AHP application is characterized by the following steps.

1. Definition of the hierarchical structure of the problem. The goal is at the top level, criteria and (if present) sub-criteria at the intermediate levels, and the alternatives at the lowest level [256]. An example of such a hierarchical structure is shown in Figure B.1.

2. Collection of the decision-maker's preferences, by means of pairwise comparisons. As explained in Appendix A (page 183), different pairwise comparison matrices are obtained, for each level of the hierarchical structure, by comparing in pairs the elements based on the Saaty's scale. For each pairwise comparison matrix, a vector of priorities, representing the relative importance of the compared elements, is defined. This vector can be approximated by considering the eigenvector with the largest eigenvalue (λ_{max}) of the matrix [122].

3. Evaluation of the consistency of the pairwise comparison, at each level of the hierarchy. Two indexes are calculated:

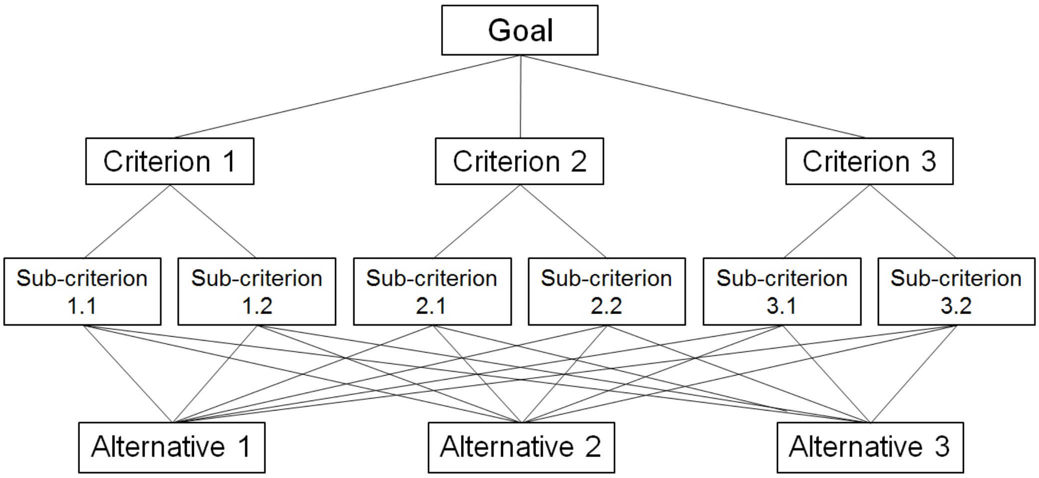

Fig. B.1 Example of the hierarchical structure of a decision-making problem [7]

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{B.5}$$

$$CR = \frac{CI}{RI} \tag{B.6}$$

where *CI* is the consistency index, *CR* is the consistency ratio, and *RI* is the consistency index of a randomly generated pairwise comparison matrix of the same size. A *CR* value lower than 0.10 indicates an acceptable level of consistency [13].

4. Aggregation of the weights of the elements throughout the hierarchical structure to obtain an overall performance value for each alternative. An additive aggregation is generally used. Based on these values, the final ranking of the alternatives is obtained [256]: the alternative with the highest performance value is the preferred one.

Weighted Linear Combination

The Weighted Linear Combination (WLC) method is one of the most often used techniques in the GIS environment for spatial multi-criteria decision-making [257]. The method is frequently employed for land use and suitability assessment or site selection, and it allows the production of composite maps [172]. Its popularity is due to the simplicity of the procedure, which is intuitive to decision-makers and can be easily implemented in GIS using map algebra operations [147].

The WLC method can be described by the following formula:

$$V(A_i) = \sum_{j=1}^{n} w_j \cdot r_{ij} \tag{B.7}$$

where $V(A_i)$ is the final performance value of the i-th location (map cell), w_j is the weight of the j-th criterion, and r_{ij} is the normalized value of the i-th location in terms of the j-th criterion [258].

The alternatives (i.e., the map cells) can be ranked according to their overall performance value: the preferred alternative is characterized by the highest value of $V(A_i)$. Furthermore, this overlay technique allows aggregating the attribute map layers (i.e., different input maps) into a composite map layer, i.e., the output map [172].

Methods based on goal, aspiration, or reference level

The MADM methods that can be included in the category of *goal, aspiration, or reference level models* rank the alternatives according to their distance from an "ideal" solution, measured through an aggregating index. The most popular methods in this category are:

- Compromise Programming
- Technique for Order Preference by Similarity to Ideal Solution
- VIKOR method

Compromise Programming

Compromise Programming (CP) [78] is a method that ranks the alternatives according to their closeness to the ideal solution. The preferred alternative is the nearest to the ideal solution [138].

The ideal value for each criterion (x_j^*) can be defined by the decision-maker. However, if the ideal solution is too difficult to be identified, it can be approximated by considering the elements of the decision matrix, i.e., for benefit criteria, $x_j^* = \max_i x_{ij}$ (while $x_j^* = \min_i x_{ij}$ for cost criteria) [94]. Moreover, the anti-ideal values, for benefit criteria, are defined as $x_j^- = \min_i x_{ij}$. The weighted distance measure used in CP is calculated by the following equation [227]:

$$L_{p,i} = \left[\sum_{j=1}^{n} \left(w_j \frac{x_j^* - x_{ij}}{x_j^* - x_j^-} \right)^p \right]^{1/p} \tag{B.8}$$

where $L_{p,i}$ is the distance of the i-th alternative from the ideal solution, and p is a parameter varying between 1 and ∞. The value of the parameter p indicates the decision-maker's intent to balance the criteria ($p = 1$) or to find a completely dominant solution ($p = \infty$). A frequent value assigned to this parameter is $p = 2$, where higher distances from the ideal solution are penalized more than lower distances [138]. The preferred alternative is the one associated with the minimum value of $L_{p,i}$.

Technique for Order Preference by Similarity to Ideal Solution

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is a MADM method proposed by Hwang and Yoon [11]. This method ranks the alternatives according to their closeness to the ideal solution (A^*) and their distance from the negative-ideal solution (A^-). The TOPSIS procedure can be described through the following steps [239].

1. Calculate the normalized decision matrix, using the following equation:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} (x_{ij})^2}} \tag{B.9}$$

2. Calculate the weighted normalized values $v_{ij} = w_j \cdot r_{ij}$, where w_j is the weight of the j-th criterion, assigned by the decision-maker.

3. Determine the ideal solution (A^*) and the negative-ideal solution (A^-):

$$A^* = \{v_1^*, \ldots, v_n^*\} = \left\{ \left(\max_i v_{ij} | j \in I^* \right), \left(\min_i v_{ij} | j \in I^- \right) \right\} \tag{B.10}$$

$$A^- = \left\{ v_1^-, \ldots, v_n^- \right\} = \left\{ \left(\min_i v_{ij} | j \in I^* \right), \left(\max_i v_{ij} | j \in I^- \right) \right\} \tag{B.11}$$

where I^* and I^- are sets of benefit and cost criteria, respectively.

4. Calculate the distance of each alternative from the ideal solution (D_i^*) and the negative-ideal solution (D_i^-), using the n-dimensional Euclidean distance:

$$D_i^* = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^* \right)^2} \tag{B.12}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^- \right)^2} \tag{B.13}$$

5. Calculate the relative closeness of each alternative to the ideal solution (RC_i):

$$RC_i = \frac{D_i^-}{\left(D_i^* + D_i^- \right)} \tag{B.14}$$

6. The value of RC_i varies between 0 and 1: the closer this value is to 1, the closer the alternative is to the ideal solution [194].

7. Rank the alternatives according to the value of RC_i in descending order.

VIKOR method

VIKOR (*VIšekriterijumsko KOmpromisno Rangiranje* – multicriteria optimization and compromise ranking) [231] was developed to solve complex decision problems, characterized by conflicting criteria. The method introduces the multi-criteria ranking index based on the closeness to the ideal solution [239]. The L_p-metric, also used in Compromise Programming, is adopted to represent the relative distance of each alternative from the ideal solution [259]. The following form of the L_p-metric is considered:

$$L_{p,i} = \left[\sum_{j=1}^{n} \left(w_j \frac{x_j^* - x_{ij}}{x_j^* - x_j^-} \right)^p \right]^{1/p} \qquad 1 \leq p \leq \infty \tag{B.15}$$

The compromise ranking algorithm VIKOR is characterized by the following steps [239].

1. Determine the best (x_j^*) and the worst (x_j^-) values of each criterion. If the j-th criterion represents a benefit, they can be calculated as follows:

$$x_j^* = \max_i x_{ij} \, , \qquad x_j^- = \min_i x_{ij} \tag{B.16}$$

2. Calculate the values S_i and R_i, using the following relations:

$$S_i = \sum_{j=1}^{n} \frac{w_j \left(x_j^* - x_{ij} \right)}{x_j^* - x_j^-} \tag{B.17}$$

$$R_i = \max_j \left[\frac{w_j \, (x_j^* - x_{ij})}{x_j^* - x_j^-} \right] \tag{B.18}$$

3. Calculate the values Q_i through the equation:

$$Q_i = \frac{\upsilon (S_i - S^*)}{S^- - S^*} + \frac{(1-\upsilon)(R_i - R^*)}{R^- - R^*} \tag{B.19}$$

   where:

$$S^* = \min_i S_i \, , \qquad S^- = \max_i S_i \tag{B.20}$$

$$R^* = \min_i R_i \, , \qquad R^- = \max_i R_i \tag{B.21}$$

   Coefficient υ is a weight for the strategy of “the majority of criteria”, while $(1-\upsilon)$ is the weight of “the individual regret”. This coefficient is defined by the decision-maker in the interval $[0,1]$. These strategies can be compromised considering $\upsilon = 0.5$ [260].

4. Rank the alternatives, based on the values of S, R, and Q, in decreasing order. Therefore, the results are three ranking lists.

5. Propose as a compromise solution the alternative $A^{(1)}$, which is the alternative with the minimum value of Q, if the following two conditions are satisfied:

   C_1) "Acceptable advantage":

   $$Q(A^{(2)}) - Q(A^{(1)}) \geq DQ \tag{B.22}$$

   where $A^{(2)}$ is the alternative with the second position in the ranking by Q and $DQ = 1/(m-1)$;

   C_2) "Acceptable stability in decision-making": alternative $A^{(1)}$ must also be the best ranked by S or/and R.

If condition C_1 or C_2 is not satisfied, the preferred solution cannot be directly selected, but a set of compromise solutions can be defined, including:

- alternatives $A^{(1)}$ and $A^{(2)}$, if only condition C_2 is not satisfied, or
- alternatives $A^{(1)}, A^{(2)}, \ldots, A^{(k)}$, if condition C_1 is not satisfied, where $A^{(k)}$ is the last alternative, in the ranking by Q, for which the relation $Q(A^{(k)}) - Q(A^{(1)}) < DQ$ is valid.

Therefore, the main result of the VIKOR method is represented by the compromise ranking of the alternatives and the compromise solution (one or a set) with the "advantage rate" [239].

Outranking methods

As explained in section 2.2.3, the *outranking* methods are based on the pairwise comparison of alternatives, to identify their outranking relation, and on concordance/discordance analysis. The most popular methods in this category are:

- the methods of the ELECTRE family (e.g., ELECTRE III)
- the methods of the PROMETHEE family (e.g., PROMETHEE II)

Methods of the ELECTRE family

The acronym ELECTRE stands for ELimination Et Choix Traduisant la RÉalité (i.e., elimination and choice expressing the reality). ELECTRE methods are a family of MADM techniques developed in France in the 1960s by Bernard Roy [75].

Different methods of this family have been developed to solve various types of decision problems. For example, ELECTRE I (the first version) and ELECTRE IS (which can model situations with imperfect data) are used for choice problems, i.e., to choose the best alternative(s) from a set of given alternatives. ELECTRE II, ELECTRE III (considering pseudo-criteria and fuzzy outranking relations), and ELECTRE IV (which does not use criteria weights), on the contrary, have been developed for ranking problems, i.e., to rank alternatives from the best to the worst. Finally, ELECTRE A and ELECTRE TRI are used for sorting problems, i.e., to classify alternatives into different predefined categories [58].

One of the ELECTRE methods most frequently used for ranking problems is **ELECTRE III** [232]. The novelty of this method is the introduction of pseudo-criteria, instead of true criteria, to deal with inaccurate, imprecise, or uncertain information [58]. Thus, three thresholds are introduced: indifference threshold q_j, preference threshold p_j, and veto threshold v_j. Their values, for each criterion, have to be defined by the decision-maker considering the following rule: $q_j < p_j < v_j$ [186].

As explained in Chapter 2 (section 2.2.3), the preference model is based on an outranking binary relation between the alternatives, denoted as S, which means “at least as good as”. The outranking relation $A_1 \, S \, A_2$ is true if a sufficient majority of criteria is in favor of it (concordance) and none of the criteria opposes it too strongly (non-discordance or non-veto). Concordance and discordance are assessed through the following indexes [58].

1. The concordance index $C_j(A_i,A_k)$ of the alternatives A_i and A_k, for each criterion j, is calculated as:

$$C_j(A_i,A_k) = \begin{cases} 0 & \text{if } g_j(A_i) \leq g_j(A_k) - p_j \\ 1 & \text{if } g_j(A_i) > g_j(A_k) - q_j \\ \frac{p_j - \left[g_j(A_k) - g_j(A_i)\right]}{p_j - q_j} & \text{otherwise} \end{cases} \tag{B.23}$$

where $g_j(A_i)$ and $g_j(A_k)$ are the scores of alternatives A_i and A_k, respectively, in terms of the j-th criterion;

2. The global concordance index $C(A_i,A_k)$ is calculated through the following equation:

$$C(A_i,A_k) = \frac{\sum_{j=1}^{n} w_j \cdot C_j(A_i,A_k)}{\sum_{j=1}^{n} w_j} \tag{B.24}$$

3. The discordance index $D_j(A_i,A_k)$, for each criterion j, is defined as:

$$D_j(A_i,A_k) = \begin{cases} 0 & \text{if } g_j(A_i) > g_j(A_k) - p_j \\ 1 & \text{if } g_j(A_i) \leq g_j(A_k) - v_j \\ \frac{\left[g_j(A_k) - g_j(A_i)\right] - p_j}{v_j - p_j} & \text{otherwise} \end{cases} \tag{B.25}$$

4. Finally, the credibility index $\sigma(A_i,A_k)$ is calculated:

$$\sigma(A_i,A_k) = C(A_i,A_k) \prod_{j \in J(A_i,A_k)} \frac{1 - D_j(A_i,A_k)}{1 - C(A_i,A_k)} \tag{B.26}$$

where $J(A_i,A_k) = \left\{ j \in J \mid D_j(A_i,A_k) > C_j(A_i,A_k) \right\}$.

Based on the credibility indexes, two pre-orders of the alternatives are obtained by means of two ranking procedures, named “distillations”. The descending distillation classifies the alternatives in descending order, from the best to the worst. The ascending distillation, on the contrary, ranks the alternatives in ascending order, from the worst to the best. The final ranking of the alternatives is then obtained by combining the two pre-orders [58].

Methods of the PROMETHEE family

PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluations) is a family of methods developed by Brans and Vincke [79]. Different techniques are included in this family, e.g., PROMETHEE I (providing a partial ranking), PROMETHEE II (providing a complete ranking), PROMETHEE III (providing a ranking based on intervals), PROMETHEE IV (for the continuous case), and PROMETHEE V (including segmentation constraints) [9].

Compared to other outranking techniques, PROMETHEE methods are considered easier to understand and they are thus more appreciated by end-users [160]. The preference structure of PROMETHEE is based on pairwise comparisons of the alternatives. In this case, the difference between the evaluations of two alternatives (A_i and A_k) for each criterion is considered. The larger such difference, the higher the preference for the best alternative. These preferences can be translated into real numbers varying between 0 and 1 by means of preference functions [67]. Therefore, for each criterion j, a preference function P_j has to be defined:

$$P_j(A_i,A_k) = F_j\left[g_j(A_i) - g_j(A_k)\right] \tag{B.27}$$

where $g_j(A_i)$ is the score of alternative A_i with respect to criterion j, F_j, for benefit criteria, is a non-decreasing function of the observed deviation between $g_j(A_i)$ and $g_j(A_k)$, and:

$$0 \leq P_j(A_i,A_k) \leq 1 \tag{B.28}$$

The pair $\left\{g_j(\cdot), P_j(A_i,A_k)\right\}$ is called “generalized criterion”, associated with criterion $g_j(\cdot)$, and it has to be defined for each criterion. Six types of particular preference functions have been proposed, as shown in Figure B.2 [9]. Some functions also require the definition of one or two additional parameters, i.e., an indifference threshold (q), a strict preference threshold (p), or a value s varying between p and q.

The aggregated preference indexes can be calculated through the following equation:

$$\pi(A_i,A_k) = \sum_{j=1}^{n} w_j \cdot P_j(A_i,A_k) \tag{B.29}$$

where $\pi(A_i,A_k)$ represents the outranking degree of alternative A_i over alternative A_k for all the criteria [9].

Since each alternative is compared with $(m-1)$ other alternatives, the following positive (ϕ^+) and negative (ϕ^-) outranking flows can be defined:

$$\phi^+(A_i) = \frac{1}{m-1} \sum_{k=1}^{m} \pi(A_i,A_k), \quad k \neq i \tag{B.30}$$

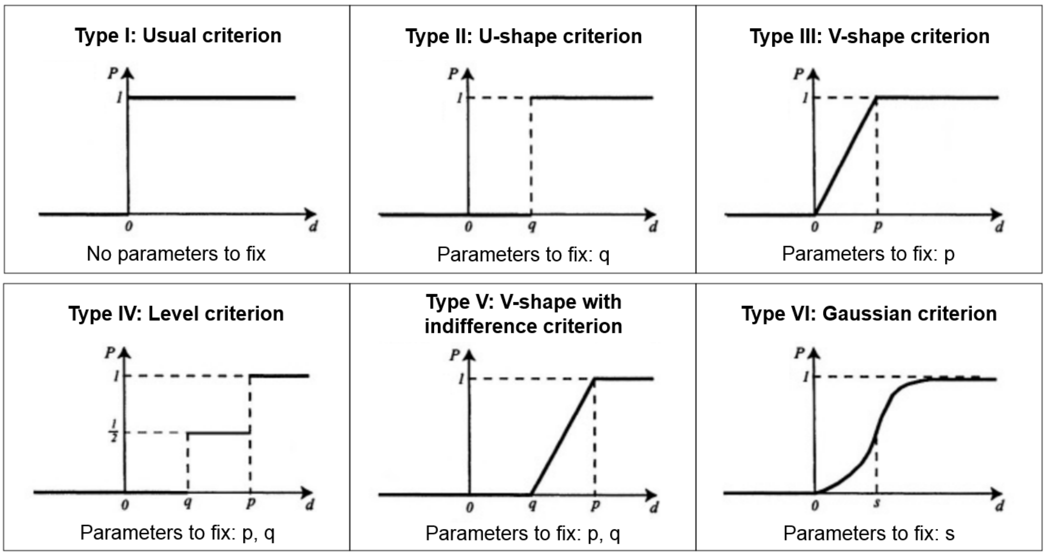

Fig. B.2 Types of generalized criteria, with the corresponding preference function P and the parameters to be defined (q = threshold of indifference, p = threshold of strict preference, s = intermediate value between p and q) (adapted from [9])

$$\phi^{-}(A_i) = \frac{1}{m-1} \sum_{k=1}^{m} \pi(A_k, A_i), \quad k \neq i \tag{B.31}$$

The positive outranking flow expresses how an alternative A_i is outranking all the others (i.e., its strength), while the negative outranking flow indicates how the alternative is outranked by all the others (i.e., its weakness) [9]. Therefore, the higher $\phi^{+}(A_i)$ and the lower $\phi^{-}(A_i)$, or the greater their difference, the more the alternative A_i is preferred to the others [160].

From these flows, a partial or complete ranking of the alternatives is obtained. For a complete ranking, **PROMETHEE II** calculates a net flow for each alternative:

$$\phi(A_i) = \phi^{+}(A_i) - \phi^{-}(A_i) \tag{B.32}$$

A higher value of the net flow is associated with a better alternative. Thus, the alternatives are ranked according to the value of $\phi(A_i)$ in descending order [67].

Appendix C

Correlation tests and aggregation methods

Correlation tests

As demonstrated by the results of the review presented in Chapter 2 (section 2.3.2), some authors apply different multi-attribute decision-making (MADM) methods to the same case study and perform a comparative analysis of the obtained results. In these cases, correlation tests can be used to statistically analyze the degree of agreement between the different rankings. Spearman and Kendall correlation tests are among the most used.

Spearman correlation test

Spearman correlation test is used to describe the degree of correlation between two different rankings [188]. Conceptually, Spearman's rank correlation coefficient (ρ) is equal to Pearson's linear correlation coefficient applied to the rankings of two measured variables, which in this case are two sets of alternatives (x and y) [229]. Spearman's rho is calculated as:

$$\rho = 1 - \frac{6 \sum_{i=1}^{m} d_i^2}{m\left(m^2 - 1\right)} \tag{C.1}$$

where m is the number of alternatives and $d_i = x_i - y_i$ is the difference between the ranks of alternative i according to the two considered ranking methods.

The values of ρ vary between –1, indicating a perfect negative correlation between the two rankings, and +1, corresponding to a perfect positive correlation. When ρ is close to zero, there is no association between the considered rankings [137].

Kendall correlation test

Kendall correlation test is a statistical measure that indicates the correlation between two compared rankings [229]. Kendall's tau coefficient (τ) is calculated using the following equation:

$$\tau = \frac{C - D}{\frac{m\ (m-1)}{2}} \tag{C.2}$$

where $C = \{(i,k)|(x_i < x_k \wedge y_i < y_k) \vee (x_i > x_k \wedge y_i > y_k)\}$ is the number of concordant pairs and $D = \{(i,k)|(x_i < x_k \wedge y_i > y_k) \vee (x_i > x_k \wedge y_i < y_k)\}$ is the number of discordant pairs, with x and y representing two compared ranking methods, and i and k two alternatives [227].

The value of τ varies between –1, for 100% negative associations, and +1, for 100% positive associations (i.e., perfect match). A value of zero indicates the absence of any association [229]. Therefore, higher values of τ denote higher similarity between the compared rankings.

Aggregation methods

Some authors use aggregation methods to combine the rankings obtained with different MADM methods. Generally, the similarity of each ranking with the achieved aggregated order is then analyzed to compare the results of the considered MADM methods. Moreover, aggregation methods are also used to combine the rankings obtained by different decision-makers or by considering different sets of weights. Borda and Copeland methods are usually adopted in these cases.

Borda method

Borda method [191] determines the final ranking of candidates (in this case, alternatives) by assigning, for each ranking, a number of points to each alternative according to its position in the ranking. If m alternatives are considered, for each ranking, a value between $(m-1)$ and zero is assigned to each alternative (i.e., $m-1$ points to the preferred alternative and zero to the worst alternative). These points are then added up to obtain the aggregated score of the alternative [228]. Therefore, the Borda sum for the alternative A_i (i.e., $B(A_i)$) can be calculated through the following equation:

$$B(A_i) = \sum_{k=1}^{R} m - \sigma_k(i) \tag{C.3}$$

where R is the number of considered rankings, m is the number of alternatives, and $\sigma_k(i)$ is the ordinal position of alternative A_i in the ranking k [261].

The alternatives are thus ranked according to their value of $B(A_i)$, in decreasing order.

Copeland method

Copeland method [192] allows aggregating different rankings by pairwise comparing the alternatives and defining their aggregated rank according to the difference between the number of pairwise victories and the number of pairwise defeats in the considered rankings [194]. More formally, the Copeland score of an alternative A_i with respect to the set A of alternatives and the preference configuration $P = \{P_1, \dots, P_n\}$ can be defined as:

$$s(A_i, A, P) = |\{A_k \in A | A_i M A_k\}| - |\{A_k \in A | A_k M A_i\}| \tag{C.4}$$

where $A_i M A_k$ indicates that the majority of voters prefer A_i to A_k, i.e., in most of the rankings A_i has a better position than A_k [193].

The alternatives are then ranked according to their Copeland score $s(A_i, A, P)$, in decreasing order.

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