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Use of multicriteria analysis (MCA) for sustainable hydropower planning and management

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Abstract Multicriteria analysis (MCA) is a decision-making tool applied to a wide range of environmental management problems, including renewable energy planning and management. An interesting field of application of MCA is the evaluation and analysis of the conflicting aspects of hydropower (HP) exploitation, affecting the three pillars of sustainability and involving several different stakeholders. The present study was aimed at reviewing the state of the art of MCA applications to sustainable hydropower production and related decision-making problems, based on a detailed analysis of the scientific papers published over the last 15 years on this topic. The papers were analysed and compared, focusing on the specific features of the MCA methods applied in the described case studies, highlighting the general aspects of the MCA application (purpose, spatial scale, software used, stakeholders, etc.) and the specific operational/technical features of the selected MCA technique (methodology, criteria, evaluation, approach, sensitivity, etc.). Some specific limitations of the analysed case studies were identified and a set of "quality indexes" of an exhaustive MCA application were suggested as potential improvements for more effectively support decision-making processes in sustainable HP planning and management problems.

Keywords: Multicriteria analysis · Sustainable hydropower · Renewable energy · Water resources management · Decision-making process · Stakeholders involvement

1 Introduction

Hydropower (HP) is one of the most important renewable energy sources (RES), having the highest electricity production share (66.4 % in 2008 in EU-27) (Šantl and Steinman, 2015) among RES and contributing approximately with the 16% to the global electricity production (IHA, 2015). Moreover, the trend for new HP plants is increasing, especially in regions with a relevant hydropower potential. For example in the Alps there is a highly strategic interest in the exploitation of this potential with the aim of providing a future-proof energy supply and clear advantages for the global CO_2 balance and the generation of several socio-economic benefits. However, despite its advantages, HP implementation causes several impacts on the affected watercourses, such as changes in river morphology and flow alterations (river impoundment, flow reduction, hydro-peaking, etc.), with a consequent loss of habitats (Alpine Convention, 2011b) and biodiversity of aquatic biota (Vezza et al., 2014a). Negative impacts of hydropower generation are not only associated with large dams, reservoirs and related hydropower facilities, but also with small hydropower plants (SHP) originating cumulative effects impacting several river stretches (Vezza et al., 2014b).

In recent years, the increased awareness by public opinion and governments about sustainable hydropower development started to involve with almost equal importance all the three interdependent pillars of sustainability, i.e. economic development, environmental protection and social justice (Kumar and Katoch, 2015), and local community is now being recognized as a key stakeholder (Diduck et al., 2013).

In order to face the problem of conflicting objectives due to multiple purposes and stakeholders, the use of a method that adds structure, auditability, transparency and rigour to the decision making process (Šantl and Steinman, 2015), like multicriteria analysis (MCA), is strongly required.

MCA is a decision-making tool used to carry out a comparative assessment of different alternatives, on the basis of a set of evaluation criteria, taking into account the opinions of the different actors concerned. It allows involved stakeholders to assign a score to each alternative, in order to quantify

its performance in relation to the selected criteria. The method consists of five main steps: alternatives selection, criteria selection, utility function choice, weight allocation and final ranking. At the end of the analysis, a vector of the performances is produced, which represents the final ranking of the alternatives: the one characterized by the highest score is considered the best alternative for the problem in question (Mammoliti Mochet et al., 2012).

Due to its intrinsic features, MCA is then recognized as an important tool in addressing issues related to environmental management, since it enables to evaluate and analyse conflicting aspects from multiple perspectives, with a general overall goal of determining a preference order among a number of available options (Steele et al., 2009).

In particular, for the planning, management or policy assessment of renewable energy projects, including hydropower, several multicriteria decision analysis (MCDA) methods have been developed over the last few decades. Sustainable water management requires a proper understanding of the context by the policy decision maker and MCA can bring in a rigorous structure to decision models for the integrated management of water resources (Šantl and Steinman, 2015) and the multiplicity of metrics and the complexity of energy planning and projects can be easily handled during the decision-making process (Carriço et al., 2014). Therefore, MCA can be considered a very useful tool especially in regions where HP developments are significantly increasing, since it allows the incorporation of socio-environmental considerations into hydropower project assessments; with MCA decision makers can identify a sustainable balance between economic growth, facilitated by hydropower, and socio-environmental targets, linked to sustainable energy production (Morimoto, 2013).

The strong need and, on the other hand, the difficulty of integrating ecological, socio-economic and hydropower companies objectives in a sustainable manner have been recognised by the EU. Some guidelines, in fact, were elaborated to provide a methodological approach to support decision-making processes on regional and strategic levels (Alpine Convention, 2011a; Swiss Confederation,

2011). However, a concrete and shared MCA method for the evaluation of watercourses hydropower exploitation is still missing (Šantl and Steinman, 2015).

Under the above scenario, the objective of this paper is to analyse the main features of the different existing MCA methods, reviewing the state of the art of MCA applications to sustainable hydropower production and related decision-making and operational management problems. The analysis was based on a critical review of scientific papers related to the field of interest (MCA applications to hydropower), selected among the academic articles present in *Scopus* and *Web of Science* databases and published over the last 15 years.

The review was aimed at (i) analysing in detail the nature of MCA application to the HP sector, (ii) focusing on the most important technical features applied in several specific case studies proposed by different authors and (iii) identifying some limitations that still characterise current evaluations. On the basis of this critical review, a set of "quality indexes" of an exhaustive MCA application to a real case study were identified and some proposals were made to improve future applicative research.

2 Materials and methods

The selection of papers to be analysed was carried out using *Scopus* and *Web of Science* databases of peer-reviewed literature and completed in October 2015 focusing on scientific works published over the last 15 years. The articles were selected first searching the following keywords and their combinations: "multicriteria", "MCA", "AHP", "renewable energies", "hydropower", "HP", "hydroelectricity", and then reading the abstract of the papers returned by the databases. In this way it was possible to select only the scientific papers that really described the application of one or more multicriteria approaches to hydropower use, thus excluding, for example, the ones in which hydropower was compared to other renewable energy sources in order to find the best type of plant or energy production method in a specific context. Articles whose full paper resulted unavailable in the above databases or from other online sources were excluded from the sample.

The full papers of the selected sample were critically analysed with a two phases approach: in a first phase general aspects of the MCA application were analysed, while afterwards specific operational/technical features of the selected MCA technique were investigated.

In the analysis the following general parameters of the MCA application were considered in order to understand where and at which spatial scale MCA is applied and to identify tools, purposes and actors involved:

- the country in which the case study was set;
- the spatial scale, i.e. the extension of the area of application (for example national, regional or more specific scale);
- the description of the case study, differentiating real case studies (single site or multi-sites) from theoretical/illustrative examples;
- the software used to implement the method;
- the nature and the context of the decisional problem, i.e. the purpose for which MCA was used;
- the actors involved in the decision-making process, e.g. experts or stakeholders.

The analysis of these parameters was aimed at understanding where MCA is mainly applied and at which spatial scale, identifying tools, purposes and actors involved.

In order to draw an exhaustive and detailed picture of the main technical characteristics of the MCA applications in the sample, the following specific operational/technical features of the selected MCA technique were considered in the analysis:

- the methodology used (e.g. linear additive, multi-attribute utility theory MAUT, etc.);
- the number and the list of selected criteria, namely the elements that allow to reflect performance in meeting the objectives;
- the number and the list of selected sub-criteria (or indicators), i.e. the components in which criteria are decomposed to convey a more specific information and on the basis of which the score is determined (it has to be outlined that not all the analysis require the presence of both

criteria and indicators: in some decisional problems the scores may be directly assigned on the basis of criteria);

- the number of selected alternatives, i.e. the different options that may contribute to the achievement of the decisional problem's objectives;
- the number and the typology of hydropower plants involved in the study (such as dams, run-of-river plants, pumped-storage systems and their size).

In relation to the parameter "methodology used" the following classification was adopted, partially based on the guidelines proposed by Dodgson et al. (2009):

1) *Linear additive methods*, the most popular of which are SAW – Simple Additive Weighting (Hwang and Yoon, 1981) and AHP – Analytic Hierarchy Process (Saaty, 1980), which can be applied when criteria are independent of each other and when uncertainty is not formally integrated into the MCA structure;
2) *Multi-attribute utility theory* (MAUT), also defined multi-attribute value theory (MAVT) (Keeney and Raiffa, 1976), a decision model that requires procedures to determine whether criteria are independent of each other or not;
3) *Outranking methods*, the most known of which are ELECTRE (Elimination and Choice Translating Reality) (Roy, 1968), and PROMETHEE (Preference Ranking Organisation Method for Enrichment Evaluation) (Brans, 1982), which are based on the *outranking* concept (the possibility of an alternative to outperforms another on enough criteria without being significantly outperformed by the other alternative on any one criterion) and on the possibility to consider two alternatives as "incomparable" (Mendoza and Martins, 2006);
4) *Decision models based on fuzzy sets* (i.e. sets without sharp boundaries), which have been developed to give a response to the imprecision characterising much of the data on which public decision making is often based (Jamali et al., 2014) and which use weights that are sometimes also represented as fuzzy quantities, considering the degree of error due to subjectivity in the assessment process (Kucukali, 2011);

5) *Other methods*, which include MCA techniques not falling into the previous classes.

Analysing the MCA applications found in the sample, four other technical parameters were investigated. The first two relate to the approach used: it was examined if the analysis described in the paper was an *ex-ante* evaluation, implemented during the planning process, before building a new hydropower plant (or a group of new plants), or an *ex-post* evaluation, reviewing a situation which followed a particular decision, in this case after the construction of a hydropower plant to evaluate different management alternatives. Furthermore, the analysis focused on whether the case study was based on a *top-down* approach, i.e. entirely implemented by the experts, or on a *bottom-up* approach, involving different stakeholders from the very beginning of the method preparation.

Another analysed aspect was the application of *sensitivity analysis*, an analytic methodology that provides a mean for examining the extent to which imprecision about the inputs or disagreements between subjects involved in a decision-making process cause any difference to the final overall results (Dodgson et al., 2009).

Finally it was checked if a *cartographic analysis*, usually through GIS, was associated with the MCA approach.

In order to analyse in detail all the above parameters, allowing a subsequent comparison of all the papers of the sample, a specific checklist was used (Appendix S1) and compiled for each paper during its critical reading.

3 Results and discussion

The selected sample consists of 45 scientific papers which cover the range of MCA applications to sustainable hydropower production and management decision-making problems since the early 2000s until October 2015 (for the analysis 2 papers dated 2016 already available online as per the previous cut-off date were considered as published in 2015). A total of 10 articles, 8 of which belonging to conference proceedings and all of them related to China or other Asian countries, were excluded from the sample because of the unavailability of the full papers.

An increasing trend over time of MCA applications to the hydropower sector is evident (Fig. 1).

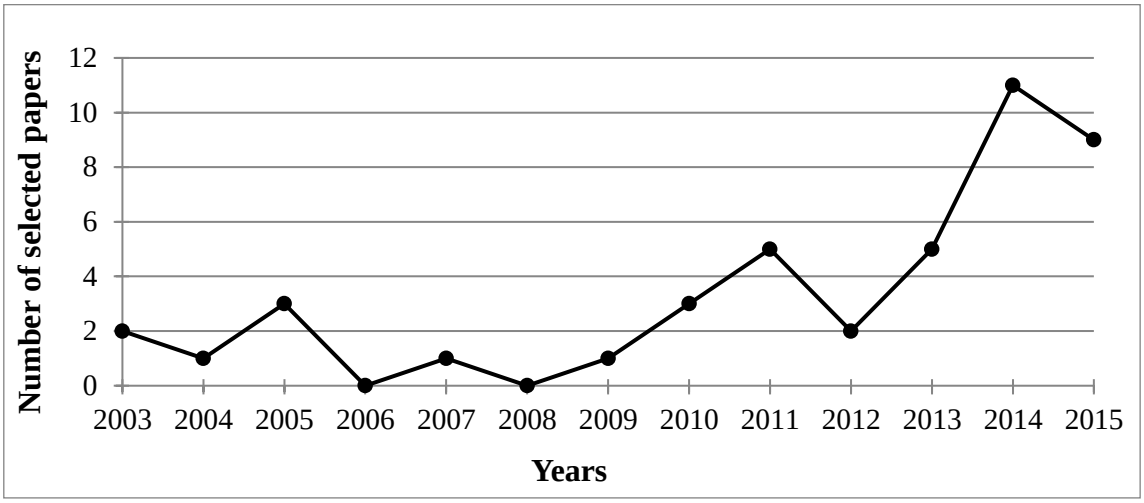

Fig. 1 Trend over time of MCA applications to hydropower sector.

In the following paragraphs results of the analysis of the general and technical features of the MCA applications are presented; detailed data referred to each paper are listed in Appendix S2 and Appendix S3 respectively.

3.1 General features of the MCA application

Selected papers refer to MCA applications carried out in different parts of the world, including developing countries. The geographic areas where MCA is more used are Europe and Asia, with 18 papers each, while the main countries of application of the method are China (4 papers), Italy (4 papers), Turkey (4 papers) and India (3 papers).

With regards to the spatial scale of the case studies analysed in the sample, most of the papers (48.9%) are referred to a specific river or watershed (e.g. Brown and Joubert, 2003; Stević et al., 2014); for the others the spatial scale resulted highly heterogeneous, with some MCA applications related to a single hydropower plant (Alipour, 2015; Hadjibiros et al., 2005; Kucukali 2011; Zhang et al., 2013), and some others referred to a broader scale, such as a whole province or nation (e.g. Canales et al., 2014; Cowan et al., 2010; Kucukali, 2014b; Vučijak et al., 2013; Wang et al., 2014).

The majority of papers (86.7%) refers to real case studies in which MCA is carried out with real data (e.g. Arthington et al., 2003; Larson and Larson, 2007; Tzimopoulos et al., 2013), while in the remaining ones the authors proposed an illustrative example or simulation tests (Brown and Joubert, 2003; Chew Hernández et al., 2015; Dong et al., 2015; Rosso et al., 2012; Vučijak et al., 2013) or no descriptions of a specific case study (Marttunen et al., 2010). However, no paper describes if MCA results were actually applied to support the decision-making process, not only at a theoretical level, but also leading in practice to economical and political decisions (Srdjevic and Srdjevic, 2014).

The software used to implement the MCA process is specified in several papers (53.3%): *Excel* (Marttunen and Suomalainen, 2005; Morimoto, 2013; Saracoglu, 2015), *Expert Choice* (Fuentes-Bargues and Ferrer-Gisbert, 2015; Rosso et al., 2014; Singh and Nachtnebel, 2016), *ArcGIS* (Goyal et al. 2015; Jamali et al. 2014; Jiménez Capilla et al. 2016) and *Super Decisions* (Cowan et al., 2010; Rosso et al., 2012) are the most frequently used.

The diversity of models and methodological approaches identified within the sample also highlights that the application of MCA is related to a broad range of hydropower use and management problems. In particular, the main purposes for which the multicriteria analysis is applied within the sample can be referred to the following eight main categories:

1. Establishing a ranking of different hydropower projects (11 papers): to evaluate different proposed HP projects establishing a ranking or selecting the most appropriate one, considering the typology of hydropower plants (technical and operational parameters, installed capacity, etc.), their positive and negative impacts (e.g. de Almeida et al., 2005), or the best way to optimize the distribution of limited financial resources (e.g. Canales et al., 2014).
2. Carrying out risk assessment/feasibility analysis of hydropower projects (7 papers): to support the risk identification or assessment of hydropower projects, investigating the probability of failure induced by potential risk factors (e.g. Ji et al., 2015); in other cases MCA is used to

assess the suitability of some watercourse sections for HP implementation (Šantl and Steinman, 2015) or to evaluate the technical-economic feasibility of a project (Adhikary et al., 2014).

3. Locating suitable sites for hydropower use (6 papers): to locate suitable sites for the construction of new HP projects or to determine the optimal location of the upper reservoir for pumped-storage facilities (Jiménez Capilla et al., 2016; Kucukali, 2014b) or to find the best site for a habitat protection area within a watershed where several hydropower stations have been constructed (Yuan et al., 2011).
4. Determining the optimal management of existing hydropower plants (6 papers): to compare different water management policies, e.g. to implement a rational management of a multipurpose reservoir (Hadjibiros et al., 2005), to determine the water volume to be released from a system of hydroelectric diversions or reservoirs (Girardi et al., 2011; Moosavian et al., 2010) or the best framework for reservoir operation during flooding events (Alipour, 2015).
5. Assessing the consequences of hydropower use (5 papers): to evaluate the impact of hydropower development on the environment, for example considering runoff and sediment changes (Liu and He, 2012) or the relationship between economic, environmental and social impacts (Morimoto, 2013) or to analyse the overall efficiency of HP generation, considering its profitability, environmental and social benefits (Wang et al., 2014).
6. Selecting the optimal distribution of a water system or HP/electricity network (4 papers): to design a network of different hydropower plants for hydro potential exploitation of a region (Chew Hernández et al., 2015; Stević et al., 2014), to select the optimal reconfiguration scenario of a power network which include a HP plant (Bernardon et al., 2014) or to determine the best energy efficient option for a water supply system where a HP plant is installed (Carriço et al., 2014).
7. Determining measures for environmental restoration related to hydropower exploitation (3 papers): to support the generation of a regulatory practice (Marttunen and Suomalainen, 2005), to plan the restoration of migratory routes for fish (Karjalainen et al., 2013) in rivers affected by

HP exploitation, or to control waste management and treatment originated during the construction of hydropower plants (Zhiyong et al., 2011).

8. Selecting the best hydropower scheme (3 papers): to select the most sustainable installed capacity range of hydropower plants (Kumar and Katoch, 2015) or their most appropriate capacity (micro, small, medium, big or large) (Singh and Nachtnebel, 2016), but also to determine an optimal mix of technologies to achieve sustainability objectives in a region (such as pumped hydroelectric storage, incremental HP, small HP, micro-HP, etc.) (Cowan et al., 2010).

With regards to the number and typology of involved decision makers, in several articles (37.8%) there are no references to the participation of experts and stakeholders to the decision-making process or, even if authors declared a participatory approach, the subjects actually involved in the case study are unspecified. Even in the other papers, the information is often not explicit: only in few cases (4.4%) there is a specific list with the number and the typology of subjects involved in the attribution of weights to criteria and sub-criteria or in the final decision (e.g. Alberti et al., 2004; Carriço et al., 2014). Usually the decision makers are experts in a specific sector, such as engineers, developers, experts in electricity generation, socio-economics, environment (e.g. Singh and Nachtnebel, 2016; Supriyasilp et al., 2009), power companies, university researchers (e.g. Karjalainen et al., 2013), local authorities representatives; just in a limited number of cases local community representatives (e.g. people living nearby the site, farmers, fishermen, recreational users) were involved (Marttunen and Suomalainen, 2005). Moreover, in some papers it is evident that real stakeholders were not involved, being the DM process carried out exclusively by the authors (e.g. Canales et al., 2014; Chew Hernández et al., 2015).

3.2 Technical features of the MCA methodologies

The most applied MCA technique resulted the Analytic Hierarchy Process – AHP (19 papers, 42.2%), which sometimes is used in conjunction with other methodologies or is applied in a fuzzy

environment (Dong et al., 2015). Figure 2 shows which class of MCDA methodology (linear additive, MAUT, outranking, fuzzy, others) was used in the analysed papers; in some articles (17.8%) two or more (Saracoglu, 2015) techniques are compared or applied together while in one third of the sample the methodology used is not specified. Linear additive methods (AHP and in one paper, by Carriço et al. 2014, SAW) are the most recurrent ones. ELECTRE (outranking class) is applied in 3 papers, whereas decision models based on fuzzy sets are described in 4 articles (fuzzy TOPSIS, TFAHP, IFEMCDM and an unspecified fuzzy rating tool). MAUT is used only by Karjalainen et al., 2013. Finally, in 11 papers the MCA technique used falls within the "other methods" class (REGAIM, ERCA, Factor Analysis Method, Swing, TOPSIS, VIKOR, Compromise programming, FIM, Entropy).

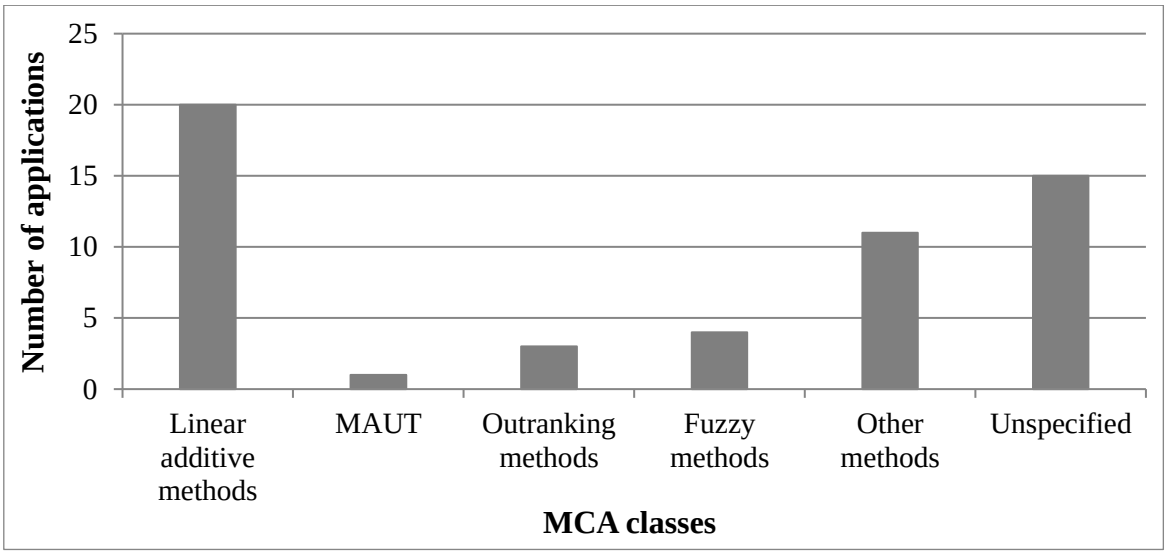

Fig. 2 Number of applications of the different MCA classes.

The number of criteria and sub-criteria (or indicators) used were highly variable: the mean number of criteria is 5.3±4.2, while the mean number of indicators is 15.3±10.1. The number of criteria is generally low: in most cases it is between 3 and 5 (31 papers), the most recurrent ones being the three basic sustainability criteria: economic, environmental and social (e.g. Kumar and Katoch, 2015; Morimoto, 2013), to which technological or political aspects are sometimes added (e.g. Cowan et al., 2010; Singh and Nachtnebel, 2016). However, some authors use only 2 criteria (3

papers) or even more than 10 (3 papers); sometimes (3 papers) the number is not specified, because there is not a description of a real case study (Marttunen et al., 2010) or there are just some examples of important parameters to be taken into account, without providing a specific list (Adhikary et al., 2014; Goyal et al., 2015). Indicators are absent in 18 papers, since the model is single level and scores are directly assigned based on selected criteria. In the other papers indicators are often less than 10 (40%), but in several cases (28%) are more than 20 (up to 44 in Kucukali, 2011), showing that a wide variety of approaches can be found. Appendix S4 provides a complete list of criteria and sub-criteria/indicators, divided according to the nature and context of the decision-making process.

Most of the articles list the alternatives considered in the analysed case study, often represented by different proposed HP projects or investments (e.g. de Almeida et al., 2005; Saracoglu, 2015), potential sites for hydropower development within a watershed (e.g. Supriyasilp et al., 2009) or different management strategies for existing HP plants (Srdjevic and Srdjevic, 2014). Usually the number of alternatives varies between 3 and 6 (21 papers, 60% of papers in which this information is specified), ranging up to 22 in Morimoto, 2013, while in 4 articles alternatives are not specified, because MCA assesses environmental risks (Kucukali, 2011, 2014a), solves an objective function (Hernández et al., 2011) or determines indicators weights (Liu and He, 2012).

Information about the number and characteristics of HP plants are available in the 71.1% of the sample; usually only one plant is examined (17 papers), but sometimes the number is higher than 10 (7 papers), up to 64 potential sites in Supriyasilp et al., 2009. Some authors specify the typology of HP plants (dams in 12 articles, run-of-river in 3, pumped-storage in 2) or their size (usually small HP plants, in 9, mini or micro in 2, medium/large in 1).

In the analysed case studies, *ex-ante* evaluations are typically applied to select the most appropriate HP project or plant management among several alternatives, to identify the most suitable site for the location of a new HP plant or to carry out a feasibility analysis, while *ex-post* ones mainly evaluate consequences of HP exploitation or management of HP plants in operation. Figure 3a shows that in

the sample *ex-ante* and *ex-post* evaluations have almost equal numbers; only in one paper this characteristic is not evident, since a method to improve planning and decision support practices is presented without describing a real case study (Marttunen et al., 2010).

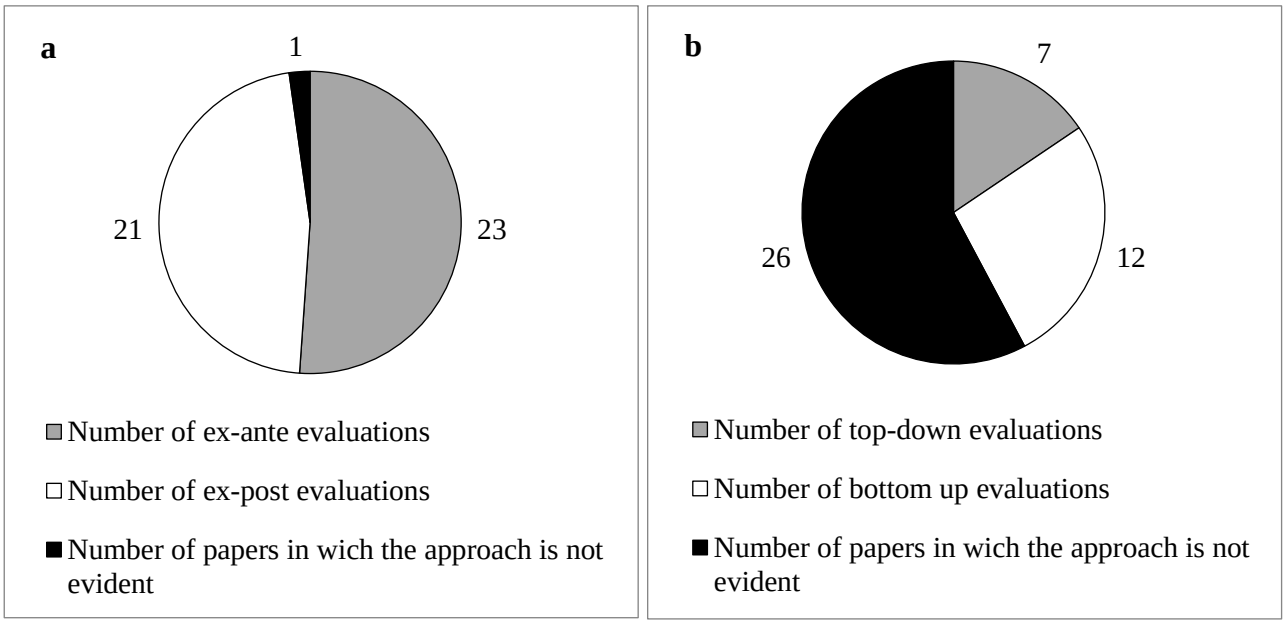

Fig. 3 Distribution of (**a**) *ex-ante* or *ex-post* evaluations and (**b**) *top-down* or *bottom-up* approaches.

The MCA approach was considered "*top-down"* only when the weighting procedure was implemented by the authors, without involving any stakeholders or experts (e.g. Canales et al., 2014), or involving them only for the final decision (e.g. Jiménez Capilla et al., 2016) and "*bottom-up*" when different stakeholders and specialists were involved not only for the weighting procedure, but also during the preparatory stage of MCA (e.g. selection of criteria, indicators, alternatives) (e.g. Marttunen and Suomalainen, 2005). In all other cases it was defined as "not evident", and Figure 3b shows that it applies to most articles (57.8%), while *bottom-up* approach prevails in the remaining sample.

Figure 4a shows that sensitivity analysis was applied in 12 papers, in order to investigate the results consistency, usually by changing the weights of some indicators to observe if this modified alternatives' preference. Just in few cases the sensitivity analysis results were clearly presented (e.g.

de Almeida et al., 2005; Jamali et al., 2014), while some authors suggested a sensitivity analysis for future MCA applications, without applying it to their case study (e.g. Rosso et al., 2014).

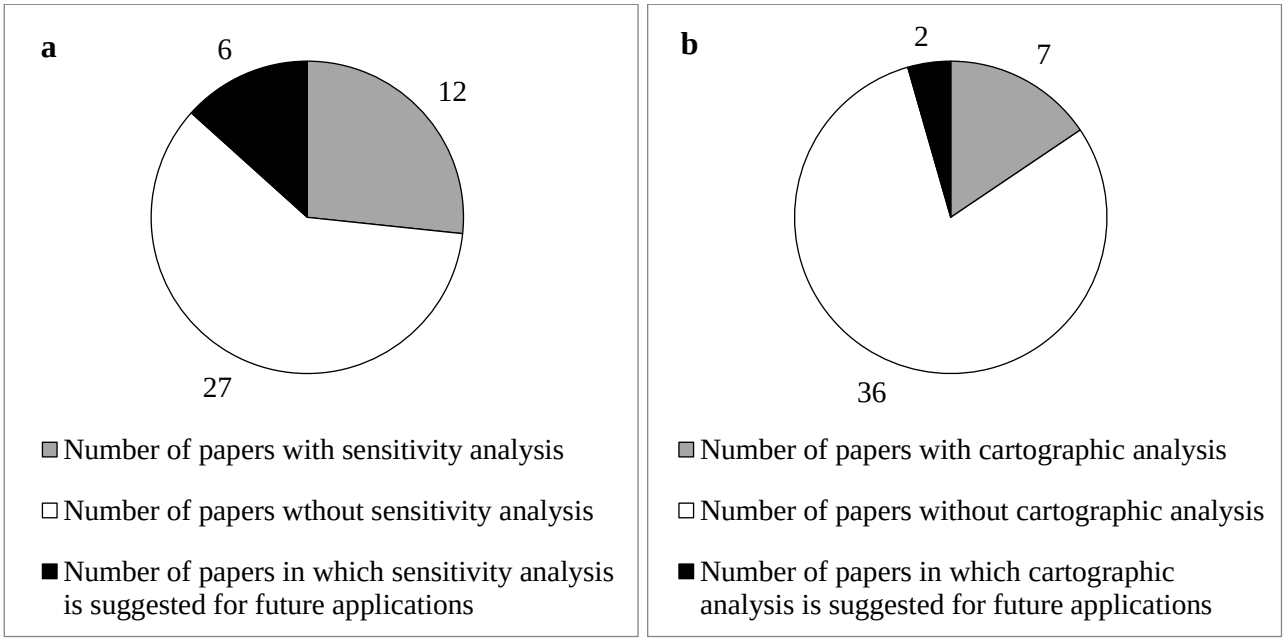

Fig. 4 Occurrence of (**a**) sensitivity analysis and (**b**) cartographic analysis.

Finally, in some papers (15.6%) MCA is integrated with cartography, often by means of the *ArcGIS* software (Fig. 4b), usually when the purpose is the identification of suitable sites to locate new HP plants (e.g. Jamali et al., 2014, Jiménez Capilla et al., 2016). Again, some authors considered it a key feature for MCA applications without performing it (e.g. Marttunen et al., 2010; Rosso et al., 2014).

3.3 Identification of "quality indexes"

A major weakness identified during the review is the lack of several significant information in many papers, such as: MCA methodology used, type and number of criteria and indicators, alternatives considered, actors involved in the decision-making process, use of MCA results in the real case study.

Therefore, the most important elements to be considered as "quality indexes" of an MCA application to a real case study of HP planning or management were identified. Firstly, the real

problem addressed by MCA shall be presented, fully describing the HP plants or sites to which MCA is applied and providing a list of the actors (or categories of involved subjects) taking part in the decision-making process. Besides, the most relevant technical features of the MCA application must be fully disclosed, highlighting at least the adopted methodology and the description of selected criteria, indicators and alternatives. Another key feature is the "sensitivity analysis" to test the robustness of the method, since the decision model implies the use of parameters which may be subject to changes and errors.

Finally, the operational impacts of the MCA application should be clearly described, displaying the results obtained through the analytic process and their adoption by policy makers to solve the real decision-making problem. Possibly, when applicable, an ex-post evaluation of the real impacts of the choice made based on the MCA results should be carried out, highlighting mismatches between its expected and real outcomes.

Considering all the above "quality indexes" and examining the results of the review, only 6 papers were deemed appropriate, despite none of them exactly satisfies all the above parameters: Supriyasilp et al. (2009), Kucukali (2011), Jamali et al. (2014), Stević et al. (2014), Fuentes-Bargues and Ferrer-Gisbert (2015) and Singh and Nachtnebel (2016). However, in none of them the authors explain if the method actually had an impact in the real case study and provide a specific list of the actors involved in the decision-making process (instead the typology of these subjects is always cited).

Besides, in Kucukali (2011) and Jamali et al. (2014) the number of alternatives is unspecified and it is not evident if the approach is *bottom-up* or *top-down*, while in Singh and Nachtnebel (2016) the number of HP plants is not specified.

Hence, the most exhaustive approach can be ascribed to the following 3 papers: Supriyasilp et al. (2009), Stević et al. (2014) and Fuentes-Bargues and Ferrer-Gisbert (2015). However each of them presents some limitations: while the first presents an apparently excessive number of sub-

criteria (30) and alternatives (64), the other two papers do not disclose a list of the involved actors, just explaining that a team of experts was involved in the process.

The three papers describe a *bottom-up* approach, where actors were involved in the decision-making process since the preparatory stage of MCA. They also provide some information about the proposed alternatives: Supriyasilp et al. (2009) present a table with a comparison of electricity generation, engineering and economic aspects of 64 potential sites for HP use; Stević et al. (2014) show the main technical parameters of 15 small HP plants and a description of 8 alternatives; Fuentes-Bargues and Ferrer-Gisbert (2015) highlight a scheme of the project with a description of 3 alternatives .

4 Conclusions

In recent years MCA applications have been often used as a suitable decision-making tool for hydropower planning and management, with case studies in several areas of the world where HP exploitation is already significant (e.g. China, Europe, etc.) or is increasing (e.g. Vietnam, Laos, etc.). The analysis of the 45 selected papers revealed that the most applied MCA technique is AHP, because it is flexible, user-friendly and its results can be clearly explained and justified (Supriyasilp et al., 2009). Almost all the examined papers describe a real case study, whose spatial scale is often a specific river or watershed, facing a wide range of HP decision-making problems.

However, some drawbacks emerged from the critical review. In many papers some significant information is unspecified (e.g. the criteria and indicators used, the list of the alternatives considered during the decision-making process, the MCA technique used, the involved stakeholders, etc.), not allowing to perform statistical analyses on the selected sample and to fully understand how MCA supported the decision-making process. Although almost all papers describe the application of MCA to a real case study, it is never specified if it was actually adopted to support the real decision-making process for the specific case study or, at least, if the MCA results were taken into account by decision makers. Furthermore, the review showed that a *bottom-up*

approach is generally difficult to be carried out (e.g. the choice of criteria and indicators is usually made by the authors of the paper, sometimes based on a literature review or on expert consultation), probably because it is not easy to promote the participation of different stakeholders, taking into account their concerns and interests and facing the divergence of their perspectives, point of view and values (HarmoniCOP, 2005).

On the basis of the critical review of the selected sample, some "quality indexes" of an exhaustive MCA application to a real case study were identified: indication of the spatial scale, list of the subjects involved in the decision-making process, disclosure of operational/technical features of the MCA technique, application of sensitivity analysis, actual implementation of MCA in the real DM process. Only 6 papers, among the selected sample, were recognized as describing the most complete approach, even if none totally satisfies all the above parameters, in particular the last one, which is not evident in any of the 45 selected articles. The 3 papers estimated as the most exhaustive (Supriyasilp et al., 2009; Stević et al., 2014; Fuentes-Bargues and Ferrer-Gisbert, 2015) also contain a description of the proposed alternatives and are characterized by a bottom-up approach.

These "quality indexes" should be implemented in future MCA applications to sustainable HP planning and management problems, especially for real decision-making problem solving, in which MCA results may have legally binding operating impacts, trying to bridge the gap between researchers and policy makers (Srdjevic and Srdjevic, 2014). Moreover, sensitivity analysis should always be performed in order to test the consistency or the variation of the results in response to any modification in the input data (Chakhar and Mousseau, 2008; Pannell, 1997).

In order to increase the quality of the decision-making process, future MCA applications should also adopt a more participatory attitude at all levels of the modelling procedure. Stakeholders, experts or decision makers involved in the process should represent the diversity of issues at stake and they should be able to participate and contribute actively to the modelling, although this may require time to absorb and discuss new information and to present the different interests and points

of view (HarmoniCOP, 2005). Hence, more transparent, simple and easily accessible participatory patterns should be developed, in order to enable a fruitful *bottom-up* approach (Mendoza and Martins, 2006) for applications to HP projects, which can impact all the three sides of sustainability (environment, society, economy).

Besides, in order to gain more accurate results, perhaps some new MCA techniques should also be proposed in the future (Zhang et al., 2013), or more methodologies could be used simultaneously, in a multi-methodology framework (Mendoza and Martins, 2006), to improve the quality of HP use and management analysis.

Finally, future applicative research could further focus on improving MCA application to support HP suitability on a large scale level, for example using the method to identify the optimum management of a system of several HP plants located in an entire watershed or region. The aim of the decision-making process should always be to integrate hydropower exploitation and ecological water-related objectives, including considerations about socio-economic aspects, in order to provide an even more sustainable management of water resources.

Appendix A. Supplementary data

Supplementary data related to this paper (the checklist used for the analysis of the sample, the detailed data resulting from the analysis of all the selected papers and the complete list of criteria and subcriteria) are available online.

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References

Adhikary, P., Roy, P.K., Mazumdar, A., 2014. Multi-dimensional feasibility analysis of small hydropower project in India: a case study. ARPN J Eng Appl Sci 9 (1), 80–84.

Alberti, M., Montanari, A., Montesi, M., Severino, C., Spada, G., Zanotti, P., 2004. Un metodo multi criterio per la stima della portata di progetto di centrali idroelettriche ad acqua fluente, in: XXIX Convegno di Idraulica e Costruzioni idrauliche. Editoriale BIOS, Cosenza, vol. 3, pp. 313–320.

Alipour, M.H., 2015. Risk-informed decision making framework for operating a multi-purpose hydropower reservoir during flooding and high inflow events. Case study: Cheakamus River system. Water Resour Manage 29 (3), 801–815. doi:10.1007/s11269-014-0844-3.

Alpine Convention, 2011a. Common guidelines for the use of small hydropower in the Alpine region. Permanent Secretariat of the Alpine Convention, Innsbruck.

Alpine Convention, 2011b. Situation report on hydropower generation in the Alpine region focusing on small hydropower. Permanent Secretariat of the Alpine Convention, Innsbruck.

Arthington, A.H., Rall, J.L., Kennard, M.J., Pusey, B.J., 2003. Environmental flow requirements of fish in Lesotho rivers using the drift methodology. River Res Appl 19 (5–6), 641–666. doi:10.1002/rra.728.

Bernardon, D.P., Mello, A.P.C., Pfitscher, L.L., Canha, L.N., Abaide, A.R., Ferreira, A.A.B., 2014. Real-time reconfiguration of distribution network with distributed generation. Electr Pow Syst Res 107, 59–67. doi:10.1016/j.epsr.2013.09.011.

Brans, J.P., 1982. L'ingénierie de la décision; Élaboration d'instruments d'aide à la décision. La méthode PROMETHEE, in: Nadeau, R., Landry, M. (editors), L'aide à la décision: Nature, Instruments et Perspectives d'Avenir. Presses de l'Université Laval, Québec, Canada, pp. 183–213.

Brown, C.A., Joubert, A., 2003. Using multicriteria analysis to develop environmental flow scenarios for rivers targeted for water resource management. Water SA 29 (4), 365-374.

Canales, F.A., Mendes, C.A.B., Beluco, A., 2014. Prioritizing small hydropower projects in scenarios with limited financial resources. Journal of Renewable and Sustainable Energy 6 (4), 043130. doi:10.1063/1.4893076.

Carriço, N.J.G., Veríssimo Gonçalves, F., Covas, D.I.C., do Céu Almeida, M., Alegre, H., 2014. Multi-criteria analysis for the selection of the best energy efficient option in urban water systems. Procedia Engineering 70, 292–301. doi:10.1016/j.proeng.2014.02.033.

Chakhar, S., Mousseau, V., 2008. Spatial multicriteria decision making, in: Shekhar, S., Xiong, H. (editors), Encyclopedia of GIS. Springer, New York, pp. 747–753.

Chew Hernández, M.L., Pérez Pantoja, E.E., García Reyes, B.C., 2015. A framework for the optimal multicriteria design of networks of small hydro turbines in polluted streams. International Journal of Multicriteria Decision Making 5 (1–2), 109–128. doi:10.1504/IJMCDM.2015.067944.

Cowan, K., Daim, T., Anderson, T., 2010. Exploring the impact of technology development and adoption for sustainable hydroelectric power and storage technologies in the Pacific Northwest United States. Energy 35 (12), 4771–4779. doi:10.1016/j.energy.2010.09.013.

de Almeida, A.T., Moura, P.S., Marques, A.S., de Almeida, J.L., 2005. Multi-impact evaluation of new medium and large hydropower plants in Portugal centre region. Renew Sust Energ Rev 9 (2), 149–167. doi:10.1016/j.rser.2004.01.015.

Diduck, A.P., Pratap, D., Sinclair, A.J., Deane, S., 2013. Perceptions of impacts, public participation, and learning in the planning, assessment and mitigation of two hydroelectric projects in Uttarakhand, India. Land Use Policy 33, 170–182. doi:10.1016/j.landusepol.2013.01.001.

Dodgson, J.S., Spackman, M., Pearman, A., Phillips, L.D., 2009. Multi-criteria analysis: a manual. Department for Communities and Local Government, London. https://www.gov.uk/government/publications (accessed 05-10-15).

Dong, M., Li, S., Zhang, H., 2015. Approaches to group decision making with incomplete information based on power geometric operators and triangular fuzzy AHP. Expert Syst Appl 42 (21), 7846–7857. doi:10.1016/j.eswa.2015.06.007.

Fuentes-Bargues, J.L., Ferrer-Gisbert, P.S., 2015. Selecting a small run-of-river hydropower plant by the analytic hierarchy process (AHP): a case study of Miño-Sil river basin, Spain. Ecol Eng 85, 307–316. doi:10.1016/j.ecoleng.2015.10.020.

Girardi, P., Garofalo, E., Brambilla, P.C., Maran, S., 2011. Implementation of a multi criteria analysis for the definition of environmental flow from hydroelectric diversions within an IWRM (integrated water resources management) framework. La Houille Blanche (6), 11-16. doi:10.1051/lhb/2011055.

Goyal, M.K., Singh, V., Meena, A.H., 2015. Geospatial and hydrological modelling to assess hydropower potential zones and site location over rainfall dependent Inland catchment. Water Resour Manage 29 (8), 2875–2894. doi:10.1007/s11269-015-0975-1.

Hadjibiros, K., Katsiri, A., Andreadakis, A., Koutsoyiannis, D., Stamou, A., Christofides, A., Efstratiadis, A., Sargentis, G., 2005. Multi-criteria reservoir water management. Global Nest J 7 (3), 386–394.

HarmoniCOP [Harmonising Collaborative Planning], 2005. Learning together to manage together – Improving participation in water management. University of Osnabrück, Institute of Environmental Systems Research, Osnabrück.

Hernández, J.G., Schleiss, A.J., Boillat, J., 2011. Decision Support System for the hydropower plants management: the MINERVE project, in: Proceedings of the International Symposium on Dams and Reservoirs under Changing Challenges - 79th Annual Meeting of ICOLD, Swiss Committee on Dams, Lucerne, Switzerland; 1st June, 2011, pp. 459–468.

Hwang, C.L., Yoon, K.S., 1981. Multiple attribute decision making: Methods and applications. Springer-Verlag, New York.

IHA [International Hydropower Association], 2015. 2015 Hydropower Status Report. Sutton, London. http://www.hydropower.org/2015-hydropower-status-report (accessed 19-11-15).

Jamali, I.A., Mörtberg, U., Olofsson, B., Shafique, M., 2014. A spatial multi-criteria analysis approach for locating suitable sites for construction of subsurface dams in Northern Pakistan. Water Resour Manage 28 (14), 5157–5174. doi:10.1007/s11269-014-0800-2.

Ji, Y., Huang, G.H., Sun, W., 2015. Risk assessment of hydropower stations through an integrated fuzzy entropy-weight multiple criteria decision making method: a case study of the Xiangxi River. Expert Syst Appl 42 (12), 5380–5389. doi:10.1016/j.eswa.2014.12.026.

Jiménez Capilla, J.A., Carrión, J.A., Alameda-Hernandez, E., 2016. Optimal site selection for upper reservoirs in pump-back systems, using geographical information systems and multicriteria analysis. Renew Energ 86 (7065), 429-440. doi:10.1016/j.renene.2015.08.035.

Karjalainen, T.P., Marttunen, M., Sarkki, S., Rytkönen, A.M., 2013. Integrating ecosystem services into environmental impact assessment: an analytic–deliberative approach. Environ Impact Asses 40, 54–64. doi:10.1016/j.eiar.2012.12.001.

Keeney R.L., Raiffa, H., 1976. Decisions with multiple objectives: Preferences and value trade-offs. Wiley, New York.

Kucukali, S., 2011. Risk assessment of river-type hydropower plants using fuzzy logic approach. Energ Policy 39 (10), 6683–6688. doi:10.1016/j.enpol.2011.06.067.

Kucukali, S., 2014a. Environmental risk assessment of small hydropower (SHP) plants: a case study for Tefen SHP plant on Filyos River. Energy for Sustainable Development 19 (1), 102–110. doi:10.1016/j.esd.2013.12.010.

Kucukali, S., 2014b. Finding the most suitable existing hydropower reservoirs for the development of pumped-storage schemes: an integrated approach. Renew Sust Energ Rev 37, 502–508. doi:10.1016/j.rser.2014.05.052.

Kumar, D., Katoch, S.S., 2015. Sustainability assessment and ranking of run of river (ROR) hydropower projects using analytical hierarchy process (AHP): a study from Western Himalayan region of India. J Mt Sci 12 (5), 1315–1333. doi:10.1007/s11629-014-3156-4.

Larson, S., Larson, S., 2007. Index-based tool for preliminary ranking of social and environmental impacts of hydropower and storage reservoirs. Energy 32 (6), 943–947. doi:10.1016/j.energy.2006.09.007.

Liu, X., He, D., 2012. A new assessment method for comprehensive impact of hydropower development on runoff and sediment changes. J Geogr Sci 22 (6), 1034–1044. doi:10.1007/s11442-012-0981-7.

Mammoliti Mochet, A., Rovere, S., Saccardo, I., Maran, S., Fercej, D., Steinman, F., Schneider, J., Füreder, L., Lesky, U., Belleudy, P., Ruillet, M., Kopecki, I., Evrard, N., 2012. SHARE handbook. A problem solving approach for sustainable management of hydropower and river ecosystems in the Alps. http://www.greenalps-project.eu/infoservice/related-projects (accessed 17-09-15).

Marttunen, M., Ignatius, S.M., Sarkkula, J., Hämäläinen, R.P., 2010. Sustainable development of hydropower involving the private sector in research collaboration in the Lower Mekong Region - The results of the Internet questionnaire and interviews related to multi-criteria decision analysis. Final report of the project "Water and Energy: Sustainable development of hydropower involving the private

sector in research collaboration in the Lower Mekong region", Ministry for Foreign Affairs of Finland, November 2010. http://splash-era.net (accessed 05-10-15).

Marttunen, M., Suomalainen, M., 2005. Participatory and multiobjective development of watercourse regulation – creation of regulation alternatives from stakeholders' preference. Journal of Multi-Criteria Decision Analysis 13 (1), 29-49. doi:10.1002/mcda.374.

Mendoza, G.A., Martins, H., 2006. Multi-criteria decision analysis in natural resource management: a critical review of methods and new modelling paradigms. Forest Ecol Manag 230 (1–3), 1–22. doi:10.1016/j.foreco.2006.03.023.

Moosavian, S.A.A., Ghaffari, A., Salimi, A., 2010. Sequential quadratic programming and analytic hierarchy process for nonlinear multiobjective optimization of a hydropower network. Optim Contr Appl Met 31 (4), 351–364. doi:10.1002/oca.909.

Morimoto, R., 2013. Incorporating socio-environmental considerations into project assessment models using multi-criteria analysis: a case study of Sri Lankan hydropower projects. Energ Policy 59, 643–653. doi:10.1016/j.enpol.2013.04.020.

Pannell, D.J., 1997. Sensitivity analysis of normative economic models: theoretical framework and practical strategies. Agr Econ 16 (2), 139-152. doi:10.1016/S0169-5150(96)01217-0.

Rosso, M., Bottero, M., Comino, E., La Ferlita, S., Pommarico, S., 2012. Approccio metodologico per la valutazione di progetti per la realizzazione di impianti idroelettrici nei bacini montani. Geoingegneria Ambientale e Mineraria 136 (2), 39-50.

Rosso, M., Bottero, M., Pomarico, S., La Ferlita, S., Comino, E., 2014. Integrating multicriteria evaluation and stakeholders analysis for assessing hydropower projects. Energ Policy 67, 870–881. doi:10.1016/j.enpol.2013.12.007.

Roy, B., 1968. Classement et choix en présence de points de vue multiples (la méthode ELECTRE). Rev Fr Inform Rech O 8, 57-75.

Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw-Hill, New York.

Šantl, S., Steinman, F., 2015. Hydropower suitability analysis on a large scale level: inclusion of a calibration phase to support determination of model parameters. Water Resour Manage 29 (1), 109–123. doi:10.1007/s11269-014-0830-9.

Saracoglu, B.O., 2015. An experimental research study on the solution of a private small hydropower plant investments selection problem by ELECTRE III/IV, Shannon's entropy, and Saaty's subjective criteria weighting. Advances in Decision Sciences 2015 (548460), 1–20. doi:10.1155/2015/548460.

Singh, R.P., Nachtnebel, H.P., 2016. Analytical hierarchy process (AHP) application for reinforcement of hydropower strategy in Nepal. Renew Sust Energ Rev 55, 43–58. doi:10.1016/j.rser.2015.10.138.

Srdjevic, Z., Srdjevic, B., 2014. Modelling multicriteria decision making process for sharing benefits from the reservoir at Serbia-Romania border. Water Resour Manage 28 (12), 4001–4018. doi:10.1007/s11269-014-0723-y.

Steele, K., Carmel, Y., Cross, J., Wilcox, C., 2009. Uses and misuses of Multicriteria Decision Analysis (MCDA) in Environmental Decision Making. Risk Analysis 29 (1), 26–33. doi:10.1111/j.1539-6924.2008.01130.x.

Stević, S., Milošević, H., Stević, I., Hadrovic, S., 2014. Sustainable management of water resources in Prokletije region. Industrija 42 (1), 47–61.

Supriyasilp, T., Pongput, K., Boonyasirikul, T., 2009. Hydropower development priority using MCDM method. Energ Policy 37 (5), 1866–1875. doi:10.1016/j.enpol.2009.01.023.

Swiss Confederation, 2011. Recommendations for developing cantonal conservation and exploitation strategies for small hydropower plants, Bern. http://www.environment-switzerland.ch/ud-1037-e (accessed 22-09-15).

Tzimopoulos, C., Balioti, V., Evangelides, C., 2013. Fuzzy multi-criteria decision making method for dam selection, in: Proceedings of the 13th International Conference on Environmental Science and Technology, CEST, Athens, Greece; 5–7 September, 2013.

Vezza, P., Parasiewicz, P., Calles, O., Spairani, M., Comoglio, C., 2014a. Modelling habitat requirements of bullhead (*Cottus gobio*) in Alpine streams. Aquat Sci 76 (1), 1–15. doi:10.1007/s00027-013-0306-7.

Vezza, P., Parasiewicz, P., Spairani, M., Comoglio, C., 2014b. Habitat modeling in high-gradient streams: the mesoscale approach and application. Ecol Appl 24 (4), 844–861. doi:10.1890/11-2066.1.

Vučijak, B., Kupusović, T., Midžić-Kurtagić, S., Ćerić, A., 2013. Applicability of multicriteria decision aid to sustainable hydropower. Appl Energ 101, 261–267. doi:10.1016/j.apenergy.2012.05.024.

Wang, B., Nistor, I., Murty, T., Wei, Y.M., 2014. Efficiency assessment of hydroelectric power plants in Canada: a multi criteria decision making approach. Energ Econ 46, 112–121. doi:10.1016/j.eneco.2014.09.001.

Yuan, J., Lu, B., Kang, Y., Lv, Y., Zhang, H., Qin, Y., 2011. Optimization of habitat protection area based on Analytic Hierarchy Process (AHP) at Chongqing Reach in Wujiang Basin, in: Proceedings of International Conference on Remote Sensing, Environment and Transportation Engineering, RSETE, Nanjing, China; 24–26 June, 2011. 5964110, pp. 8379–8382. doi:10.1109/RSETE.2011.5964110.

Zhang, S., Sun, B., Yan, L., Wang, C., 2013. Risk identification on hydropower project using the IAHP and extension of TOPSIS methods under interval-valued fuzzy environment. Nat Hazards 65 (1), 359-373. doi:10.1007/s11069-012-0367-2

Zhiyong, H., Dan, L., Qibin, L., Guangwu, X., Jian, L., Luliang, Z., 2011. A study on the integrated MSW management technologies of work zone in the hydropower station of Yangtze basin, in: Proceedings of International Conference on Computer Distributed Control and Intelligent Environmental Monitoring, CDCIEM, Changsha, Hunan, China; 19–20 February, 2011. 5748310, pp. 2416–2419. doi:10.1109/CDCIEM.2011.332.