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A systematic review of application of multi-criteria decision analysis for aging-dam management

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ABSTRACT

Decisions for aging-dam management requires a transparent process to prevent the dam failure, thus to avoid severe consequences in socio-economic and environmental terms. Multiple criteria analysis arose to model complex problems like this. This paper reviews specific problems, applications and *Multi-Criteria Decision Making* techniques for dam management. Multi-Attribute Decision Making techniques had a major presence under the single approach, specially the Analytic Hierarchy Process, and its combination with Technique for Order of Preference by Similarity to Ideal Solution was prominent under the hybrid approach; while a high variety of complementary techniques was identified. A growing hybridization and fuzzification are the two most relevant trends observed. The integration of stakeholders within the decision making process and the inclusion of trade-offs and interactions between components within the evaluation model must receive a deeper exploration. Despite the progressive consolidation of *Multi-Criteria Decision Making* in dam management, further research is required to differentiate between rational and intuitive decision processes. Additionally, the need to address benefits, opportunities, costs and risks related to repair, upgrading or removal measures in aging dams suggests the Analytic Network Process, not yet explored under this approach, as an interesting path worth investigating.

Keywords

Ageing dams; Dam management; Decision making; Multiple criteria analysis; Risk

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1. Introduction

It is estimated that by 2050 the population will have increased by 130 million, much of the increase being located downstream from reservoirs contained by dams that are aging and presenting therefore significant potential risk **[1]**.

Today, owners of dams face a significant challenge in allocating limited financial, human and material resources to ensure adequate operating conditions in old dams. The absence of proper investment in conservation of the dam condemns it to the very likely event of failure, with particularly severe consequences in socio-economic, environmental and heritage terms **[2]**. It is necessary, therefore, to provide a transparent decision process so as to facilitate public participation in decision-making on dams that are deteriorated or aging **[3]**. Assessing the status of an aging dam requires the bringing together of quantitative and qualitative information, since the factors that determine the state of the dam (structural, geological, environmental, etc.) are deterministic, stochastic or fuzzy in nature **[4].**

Deterioration may appear throughout the whole dam life cycle, from its construction phase to its completion, demolition or abandonment phase. Ageing can be defined as the deterioration process that occurs more than five years after the beginning of the operation phase, so that deterioration occurring before that time is attributed to inadequacy of design, construction or operation. Even beyond that time, dam ageing can be considered as a class of deterioration associated with time-related changes in the properties of the materials of which the structure and its foundation are constructed. Besides the type of structure, other factors significant to the ageing problems are the environmental conditions, dimensions, design and construction standards, nature of operation and maintenance and congenital and early age deterioration of structures **[5].**

The problem of deterioration through aging is one that also applies to the reservoir contained by the dam, where environmental degradation may be observed (within the short and medium terms of the life of the structure, <50 years), in the form of: (i) alterations in the flow system, (ii) loss of longitudinal and floodplain connectivity, (iii) altered sediment system, (iv) changes in the composition of the substrate and, (v) degradation of the downstream channel. The environmentally-related problems in the long term (> 50 years) of the dam-reservoir system is, still today, even less well-known; therefore, new decision-making processes must be developed for the management of these systems in a situation of deterioration through aging **[6]**.

There is a close connection between Climate Change and managing the operation of ageing dams. Hydrological changes brought about by the former lead to the need to reassess the safety conditions of dams in general, but even more so in older dams; many of them already considered unsafe in periods before the onset of Climate Change. There are a great number of existing dams, at an advanced stage of deterioration, that are especially vulnerable to extreme natural phenomena linked to Climate Change. The determination of the vulnerability index as a means of diagnosing the real state of the dam serves as a clear support to decision-making on its conservation, maintenance and rehabilitation **[7].**

Generally, decision-making processes in dam management use a combination of decision bases ranging from technical codes and standards-based ways of assessing alternatives to values-based assessments based on company or wider societal values and stakeholder expectations and perceptions. The inclusion of social sustainability criteria and factors within the evaluation model to be developed must be guaranteed by addressing social and cultural impacts on human populations derived from the decisions undertaken on an ageing dam during its operational phase. The decision-maker must weigh and balance community, owner and other stakeholder interests and make all necessary value judgments, including those needed to weigh different types of risks: monetary loss, environmental degradation, etc. In parallel, political risks and resources allocation among competing societal needs must be considered. These are all subjective tasks to which knowledge-based disciplines can give little assistance **[8]**.

The inclusion of social sustainability criteria and factors within the evaluation model must be guaranteed by addressing the social and cultural impacts derived from the decisions undertaken on an ageing dam during its operational phase **[9].** Essentially, sustainability applied to aging-dam management must be understood as the reconciliation of the economic, environmental and social aspects intrinsically related to complex decisions **[10].** Ultimately, from a cognitive perspective, the adequate approach to aging-dam management must be to improve knowledge on the decision-making process and to make it possible for the stakeholders participating in the resolution process and its integrated systems to learn from the experience **[11-13].**

Decision-making in water resources management is driven by multiple objectives. Multi-Criteria Decision Analysis (MCDA) has been used in areas such as watershed management, groundwater management, selection of hydraulic infrastructure (mainly urban water supply), watershed management, water policy planning and management, water quality management and the management of protected coastal areas **[14].** Over a long time scale, with a variety of decision-makers, the use of MCDA reveals itself to be more suitable compared with other techniques usual in water resources management such as multi- or mono-objective optimization or cost benefit analysis (CBA) **[15].** MCDA provides an excellent support to prioritize rehabilitation activities in ageing dams. Therefore, this review analyzes the application of Multi-Criteria Decision Making (MCDM) methods and techniques to the comprehensive management of dams throughout the whole infrastructure lifecycle and identifies the specific treatment given to these methods in its application to ageing dams during its operational phase.

2. Search strategy and methodology

The purpose of the literature review was to identify trends and gaps in research and to propitiate further progress upon the foundation developed by others. A systematic, objective review contains a five-stage structure **[16]**. The first stage is the formulation of the problem, the second stage deals with the determination of the data collection strategy, the third stage revolves around evaluating the retrieved data, the fourth stage points to the analysis and interpretation of the literature and finally, and the fifth stage presents the resulting conclusions.

2.1. Formulation of the problem

The study formulated two main questions. First: What specific types of decisional problems and applications in dam management have been addressed throughout Multi-Criteria Decision Analysis techniques. Second: How these techniques have been applied to solve each problem and application to explore the reasons of their adequacy.

2.2. Determination of the data collection strategy

An extensive computerized search was the central axis for the data collection strategy. Articles were identified by the internationally-recognized bibliographic database SCOPUS. Among the main advantages of this database are the depth of its coverage and its ability to search both forward and backward from a particular citation **[17]**. Electronic databases searches were supplemented by searching conference proceedings and relevant journals.

A preliminary search was conducted to collect any article within the database clearly related to the study object. The objective was to create the framework for a later filtering that would finally produce the set of articles on which the qualitative and quantitative analysis would be performed. The preliminary search was developed using the Boolean operators ‘AND’ and ‘OR’ with specific search terms especially selected to produce the optimum search algorithm that would track all the relevant articles in respect of

MCDA applied to dam management. Logically, a previous literature examination, based upon the knowledge of the research team within the area, facilitated the configuration of the best preliminary search algorithm. The review covered the 1992-2015 period (24 years), as no relevant article prior to 1992 was found in the database. This preliminary search resulted in the identification of 6.217 studies.

Finally, a five steps filtering process was conducted as follows: (1) exclusion of keywords not related to the search (terms from the oil and gas and hydraulic fracture industry, artificial intelligence and neural networks); (2) limitation of the research disciplines involved in the study to the following areas classified in SCOPUS: Agricultural and Biological Sciences, Chemical Engineering, Computer Science, Decision Sciences, Earth & Planetary Sciences, Energy, Engineering, Environmental Science, Materials Science, Mathematics and Social Sciences; (3) elimination of those articles identified in more than one of the application areas or disciplines finally selected in filter 2; (4) 'search within the search', as SCOPUS permits a further detailed identification of articles within an initial search throughout keywords, and; (5) a final filtering to eliminate articles that, despite having close association with the study goal, were finally considered to be not at the core of the investigation (articles from energy, procurement, commodities and enterprise management, as well as, articles from underground water resources, land uses and watershed strategic planning). As a result of this structured filtering process, a final set of 128 articles was settled upon for further analysis and interpretation'.

3. Evaluation of data

The publication of studies increased dramatically in 2009, with a clear sustained upward trend (Fig. 1). Over 80% of the publications in the field of MCDA applied to dams were made in the 2009-2015 period. The year 2012 stand as the year with the highest number of publications (26 studies). Chinese authors played a key role in the investigation on MCDA applied to dams, having published up to 70 studies in the 1992-2015 period. Authors from Iran (9 studies), USA (6 studies) and Taiwan (5 studies) significantly contributed to the investigation as well. Netherlands, USA, Germany, United Kingdom and China were the sources of the journals more active in MCDA research related to dams, totaling respectively, 35, 32, 20, 14 and 12 studies between 1992 and 2015. 32% of the total studies published -41 articles- were concentrated in six journals: Water Resources Management (11 studies), Advanced Materials Research (10 studies), Applied Mechanics and Materials (8 studies), Natural Hazards (5 studies), Stochastic Environmental Research and Risk Assessment (4 studies) and Journal of Water Resources Planning and Management (3 studies).

The evaluation of the obtained data permitted the identification of nine main applications or topics that are described as follows:

1. *Flooding* (5 studies, 4%). These studies used MCDA specifically to model and simulate multi-objective decision-making for flood control and mitigation. This application is closely related to the 7th and 9th applications, 'Reservoir Operation' **[18-20]** and 'Risk Analysis' -dam break analysis- **[21, 22]** -both under extreme flood conditions-, respectively.
2. *Water quality* (5 studies, 4%). This involved applications of MCDA to problems of reservoir water quality evaluation. Most of the cases were focused on the eutrophication assessment **[23-25],** while two studies focused on the determination of the water quality contamination factors **[26]** and the weighting of different reservoir water quality indexes **[27].**
3. *Dam location* (6 studies, 5%). These papers covered applications of MCDA to decide the ideal location for a dam in a specific site **[28-33].**
4. *Seismicity and Geology* (11 studies, 9%). These applications involved one of the two following purposes: (i) reservoir-induced seismicity analysis **[34-37]** and, (ii) large-scale debris flows susceptibility analysis, landslide hazard assessment, stability rock study, rock burst prediction or rock mass quality evaluation -reservoir/dam surroundings- **[38-44].**
5. *Hydropower* (18 studies, 14%). These studies used MCDA for three main objectives: (i) planning, evaluation and prioritization –projects, portfolio, technologies, energy sector, benefits, project financing- **[45-55]**, (ii) construction procedures safety evaluation, project risk analysis and project management **[56-60]**, (iii) impact assessment of Climate Change on hydropower projects **[61]** and, (iv) hydropower generation efficiency **[62]**.
6. *Environmental Impact Assessment* (17 studies, 14%). The cases included in this group can be divided into two sub-groups of applications: (i) development of a new EIA method or improvement of existing EIA methods **[63-68]**, and, (ii) environmental planning and ecological risk analysis of specific dam-reservoir systems **[69-79]**.
7. *Reservoir operation* (20 studies, 15%). These studies used MCDA for three main purposes: (i) reservoir operation evaluation -mainly oriented to its optimization- **[80-92]**, (ii) analysis of risks on the reservoir operation -principally due to the human factor and flood vents- **[93-96]**, and, (iii) assessment of the environmental dimension related to the reservoir operation **[97-99]**.

8. *Water resources management* (21 studies, 16%). These papers applied MCDA for four goals: (i) comparative study or literature review of methods, techniques and tools for water resources management **[100-102]**, (ii) development of methods for conflict resolution, equal distribution, constraints evaluation and water uses prioritization **[103-107]**, (iii) development of models for sustainable management mainly oriented to dam optimum location, drought mitigation, flood control and hydropower projects evaluation **[7, 108-115]**, and, (iv) reservoir operation optimization to address adequate water resources management **[116-119]**.

9. *Risk analysis* (25 studies, 19%). This involved applications of MCDA to: (i) dam break risk assessment –regardless the dam typology- **[120-129]**, (ii) risk assessment for earth fill dams **[130-133]**, (iii) risk assessment for hydropower projects **[134-136]**, (iv) risk assessment for tailing dams **[137,138]**, (v) risk assessment for cascade reservoirs **[139]**, (vi) risk assessment for river-way levees **[140]**, and, (vii) other purposes as rock stability analysis **[141]**, risk assessment for dam demolition **[142,143]** and, construction equipment allocation **[144]**.

Fig. 2 shows the interannual progression of MCDA studies in each of the nine applications fields, Fig. 3 specifies the contribution of each MCDA approach –(1) single MADM (Multi-Attribute Decision Making) method, (2) single MODM (Multi-Objective Decision Making) method and (3) hybrid MADM/MODM- and 'fuzzification' in each of these same nine application fields, Fig. 4 presents the total number of studies under each MCDA approach and Table 1 categorizes current literature according to type of decisional problem, application and MCDM approaches and techniques.

4. Presentation of the results

Firstly, problems, applications and techniques were explored in a two steps process: (1) a detailed analysis of types of decisional problems faced and MCDA approaches and techniques employed in each of the nine applications, based on a sound categorization of problems and techniques; and (2) an overall diagnosis that permits the identification of the main patterns and tendencies to gain perspective particularly on the adequacy of methods in each case. Secondly, a statistical analysis was developed to identify relevant correlations between specific MCDA techniques and applications.

4.1. Problems, applications and techniques

Table 1 served as a key basis for the in-depth analysis of the different decisional problems faced by scholars, as well as the distinct approaches, methods or techniques employed and how they were applied to each decisional problem in each on the nine identified applications. The fitness or adequacy of methods around decisional problems and applications was our major concern. We firstly categorized all the studies according to three basic dimensions: (1) types of decisional problems; (2) applications; and (3) approaches and techniques. Regarding the first dimension, we initially distinguished four kinds of decision making problems **[145]**: (1) ALPHA (Choice problem) -choicing the best alternative or selecting a limited set of the best or most preferred alternatives-; (2) BETA (Classification problem) -classifying/sorting the alternatives into predefined alternatives homogeneous groups-; (3) GAMMA (Prioritization problem) -ranking-ordering of the alternatives from the best to the worst-; and (4) DELTA (Description problem) -describing the major features of the alternatives and their consequences-. Additionally, with the purpose of broadening the decisional spectrum, we considered other decisional typologies proposed by the MCDM community: (5) 'Design' -creating new alternatives that will meet the goals and aspirations of the decision maker- **[146]**; (6) 'Elimination' -a particular branch of sorting problem- **[147]**; and (7) KAPPA (Cognitive problem) -educating the actors involved in the resolution process by providing the arguments (knowledge) that support the scientific resolution of the problem, the different positions of the actors and the final decision- **[148]**.

Regarding the third dimension (approaches and techniques), we established three main Multi-Criteria Decision Making (MCDM) approaches: (1) MADM-based single approach; (2) MODM-based single approach; and (3) MADM-MODM hybrid approach. This approach categorization was based on previous academic research that dealt with systematic literature review in related areas **[149, 150].** Furthermore, as the fuzzification of different nuclear MCDM methods is a clear trend initially detected, we included an additional parameter in the third dimension demonstrative of the fuzzified studies for each decisional problem and application. We classified multi-criteria techniques under the 'single' approach as follows (the 'hybrid' approach has been considered as a combination of MADM and MODM methods): A) Multi-Objective Decision Making (MODM) methods: A.1. 'Efficient Solutions' (Weighting, Epsilon-Constraint, Simplex Multi-Criteria, etc.); A.2. 'Goal, Aspiration or Reference-level' techniques: A.2.1 Compromise Programming (CP); A.2.2 TOPSIS; A.2.3 VIKOR; A.2.4 Goal Programming (GP); and A.2.5 Data Envelope Analysis (DEA). B) Multi-Attribute Decision Making (MADM) methods: B.1. 'Aggregation methods': B.1.1 Direct (MAUT, MAVT, UTA, GRIP, etc.); B.1.2 'Hierarchy or Network' (AHP, ANP, SMART, MACBET, etc.); and B.2. 'Outranking methods': B.2.1 ELECTRE and B.2.2 PROMETHEE. C) Complementary techniques: CT.1 'Statistical' Techniques: CT.1.1 Discriminant analysis; CT.1.2 Logit and Probit analysis; CT.1.3 Cluster analysis; and CT.1.4 Other Multivariate

Techniques. CT.2 ‘Non-parametric’ Techniques: CT.5.1 Neural Networks (NN); CT.5.2 Machine Learning; CT.5.3 Fuzzy Set Theory (FSs); CT.5.4 Rough Sets (RS); and CT.5.5 ENTROPY.

4.1.1. Flooding

The main decisional problem treated was the GAMMA type and almost all the studies were developed under the hybrid approach. In this case, AHP was the MCA method primarily chosen although ANP and MAUT had also a significant presence. The few studies under the hybrid approach combined AHP and TOPSIS, so that the first was used to establish the objective weights of criteria and factors and the second was employed for the final ranking. Singularly, DEMATEL was valued by its capacity to deal with the indirect relationships between model components and to solve the ANP’s drawback derived from assuming equal weights for each cluster **[21]**. Scholars were especially concerned by the idiosyncrasy of information within this application, essentially the difficulty of data standardization due to the diverse data sources, different formats, time periods and data processing **[20]**.

4.1.2. Water Quality

Despite the variety of decisional problems treated was relevant, the GAMMA type showed great relevance. The single approach was dominant and AHP was the preferred MCA method, while FSs and ENTROPY were principally selected by authors as complementary techniques. Scholars took advantage of AHP’s capacity to adequately structure the assessment model (hierarchy) and to determine the subjective weights of criteria and factors, whereas ENTROPY contributed to calculate the objective weights and FSs handled the vagueness and ambiguity that characterizes the water quality evaluation problems in reservoirs **[24]**.

4.1.3. Dam Location

ALFA and GAMMA types were the solely decisional problems attended by scholars. The single approach was the path chosen while AHP was used in almost all the studies, where remarkably no complementary technique was used. Certain authors decided to fuzzify the nuclear AHP (FAHP) to make the convenient sensitivity analysis based on different levels of uncertainty **[29]**. Interestingly, GIS was scarcely used in comparison with neighboring areas where Spatial Multi-Criteria Decision Analysis (SMCDA) is being repetitively explored (Solid Waste; Sustainable Urban Development; etc.) **[151, 152]] or** even other applications within this review (primarily Seismicity and Geology).

4.1.4. Seismicity and Geology

The main decisional problems faced by scholars were the GAMMA, BETA and DELTA types. The single approach was the path chosen by all the authors, in which AHP was the nuclear method and ENTROPY and FSs were the complementary techniques selected, especially the second. Authors valued AHP's capacity to comprehensively structure the problem and to compute the model components weights, based on the subjective human experience **[38]**. Considering this application, the dam-reservoir system is characterized by its high turbulence degree (e.g., debris flows), whose quantification is an authentic challenge. Accordingly, ENTROPY was chosen in some studies to enable this quantification based on objective data without the influence of subjective factors, thus avoiding personal interference to a large extent. In this case, weights from AHP (subjective) and ENTROPY (objective) were rationally combined while the principle of minimum deviation of subjective and objective results was used to construct a combination weighting optimality model **[38]**.

Additionally, a significant number of studies proceeded to fuzzify the nuclear AHP (FAHP) to deal with the complexity, impreciseness and uncertainties present in this application, Lastly, GIS-based multicriteria -even accompanied by Remote Sensing (RS)- had its major prominence in this application.

4.1.5. Hydropower

The majority of studies focused on GAMMA type decisional problems. The hybrid approach slightly appeared (AHP and GP), so again the leading path was the single approach in which AHP was mostly employed as the nuclear method. VIKOR, DEA and TOPSIS were the MODM alternative to AHP. The interactions and dependencies between model components were poorly explored -a behavior extensible to all the review-, as ANP was scarcely used. However, it raised our attention the presence of a couple of studies facing KAPPA type decisional problems, especially one that explored three methods for knowledge acquisition in a multi-criteria environment (Value Focused Thinking; Knowledge Elicitation Techniques; and, Repertory Grid) for planning hydropower plant reconditioning assessment **[56]**. The fuzzification of models was moderate and a higher variety of complementary techniques were used to deal with the imprecise, uncertain and incomplete information (RS), to finally synthesize the problem (RBF) or to impute relationships between unobserved constructs (latent variables) from observable variables (SEM) **[51]**. Essentially, scholars concluded with the same main AHP's advantages (simplicity, flexibility, intuitive appeal and ability to handle both qualitative and quantitative criteria) and disadvantages (time consuming; risk and uncertainty not handled; and the conversion from verbal to numerical judgements given by fundamental Scale of 1-9, which tends to overestimate preferences estimates) **[54]**.

4.1.6. Environmental Impact Assessment

Practically all the studies solved GAMMA type decisional problems -mainly ecological safety or environmental vulnerability at a watershed scale-, although a significate number of ALFA type problems were faced. The single approach led the research, so that half of the models were developed around MADM methods (principally AHP, except punctual cases with PROMETHEE, ANP and RATINGS) and the other half of studied throughout MODM methods (TOPSIS, DEA and VIKOR). The fuzzification in this application was relevant (half of the studies), pursuing to adequately deal with the complexity and non-quantitative nature of the environmental data. Scholars felt the necessity of overcoming the disadvantages of traditional models (subjectivity and complexity) through FSs, SPA and others.

4.1.7. Reservoir Operation

ALFA and GAMMA type decisional problems were mostly evaluated, given the concern of researchers around the optimization of the reservoir operation, which requires identifying the optimal functional alternative or prioritizing different scenarios of functional operability. In this application, it is given a slight prominence of MOMD on MADM methods. In the latter case, even AHP was no longer the most widely chosen method, participating ELECTRE, PROMETHEE, MAUT and ANP. The presence of hybrid models was nonexistent, but it must be stressed the abundant use of complementary techniques (especially SFs, but also ENTROPY, Neural Networks and NSGA-II -Non-Denominated Sorting Genetic Algorithm-). TOPSIS and Multi-Objective Programming (both Linear -MOLP- and Dynamic -MODP-) highlighted as the most commonly used MODM methods. The use of MOLP or MODP was motivated by the achievement of the operational effectiveness in an environment of uncertainty, randomness and interaction between factors, characteristics all of this application. For this reason, the fuzzification played a central role in several studies.

4.1.8. Water Resources Management

The decisional problem of prioritizing or ordering of alternatives (GAMMA type) was the most commonly chosen by the researchers. The assessment models were developed around both MADM methods (primarily AHP, but also other MADM methods: ELECTRE, PROMETHEE, MAUT and ANP) and MODM methods (Weighting method, CP, VIKOR, TOPSIS, DEA and MOLP). It must be stressed the almost absence of hybrid models as well as a minimum fuzzification of the nuclear methods.

4.1.9. Risk Analysis

Half of the research in this application dealt with GAMMA type decisional problems. It must be pointed out the profuse use of AHP, regardless of the type of decisional problem faced. There were many studies that propose, under a single approach, a comprehensive methodology for risk assessment of the dam-reservoir system supported on the usual practice of risk analysis along with the classic multi-criteria analysis (primarily AHP, except a few cases through ANP and TOPSIS). In the few studies that opted for the hybridization process, the AHP-TOPSIS combination was mostly chosen so that AHP was used for structuring the model and obtaining the weights of the criteria and factors, and TOPSIS facilitated the final prioritization. The fuzzification process had a very relevant presence, a path particularly chosen by Chinese authors in the risk assessment of dams. In parallel, other complementary methods like CLOUD MODEL, GREY THEORY, Average Ranking, Borda, Copeland and CBR (Case-Based Reasoning) were explored. Finally, we have detected a slight attempt to explore the modeling of interactions between components of the evaluation model by ANP.

4.1.10. Overview

Our examination moved us to infer that 66% of studies used the MADM single approach, 24% of studies employed the MODM single approach and 10% of studies were based on the MADM/MODM hybrid approach. Clearly, under the single approach, studies were principally constituted on MADM methods. In this case, when MODM methods were chosen, they were basically used to solve optimization problems in the applications ‘Reservoir Operation’, ‘Water Resources Management’, and ‘Environmental Impact Assessment’, particularly through Multi-Objective Linear or Dynamic Programming (MOLP, MODP, respectively) and TOPSIS. As to the MADM methods, scholars plainly preferred AHP due to its known advantages while some authors dealt with AHP’s disadvantages by means of two alternatives: (1) other MADM methods (primarily ELECTRE, PROMETHEE, MAUT and ANP) or (2) a hybrid approach, where the AHP-TOPSIS combination was mostly visited by scholars, regardless the application. In this case, AHP was used for structuring the model (hierarchy) and obtaining the subjective weights of the criteria and factors, while TOPSIS facilitated both the objective weights determination and final evaluation (mostly, alternatives ranking or best alternative selection). 33% of the studies used FSs (Fuzzy Sets Theory) as the complementary technique to handle the complexity, imprecision, ambiguity and uncertainty that particularly characterize applications ‘Environmental Impact Assessment’, ‘Risk Analysis’, ‘Reservoir Operation’, ‘Hydropower’ and ‘Water Resources Management’. The significant presence of AHP determined this was the majorly fuzzified method, a combination (AHP+FSs: FAHP) well established in

Multi-Criteria Decision Analysis applied to different fields. Essentially, the fuzzification trend is clearly more relevant than the hybridization trend; in terms of the number of studies we detected any of them, a fact demonstrative of a major concern on the treatment of uncertainty and imprecision than on the handling of classical AHP's disadvantages. The two major decisional problems were GAMMA (62%) and ALFA (21%), i.e., ranking of alternatives and selection of the best alternative, respectively. According to the classification previously established, no 'Design' nor 'Elimination' problem was detected. Regarding the use of complementary techniques their use was determined by different reasons: (1) the need of dealing with vagueness; (2) the presence of uncertain and incomplete information; (3) the analysis of correlations between model components; (4) the very nature of the decisional problem (temporal or spatial); (5) the final step of synthesizing the problem; and (6) the purpose of overcoming the disadvantages of subjectivity and complexity of traditional methods. Very few studies focused on the analysis of interactions, dependencies, loops and feedbacks between criteria, factors and alternatives. In this case, ANP was the path chosen by scholars. Additionally, Spatial Multi-Criteria Decision Analysis (SMCDA) had certain relevance in the application D (Seismicity and Geology) but few significance at the level of the dam management field when compared with other fields or areas.

The study detected a less systematic inclusion of stakeholders in the model than in other similar areas, such as Transport, where the participation of stakeholders has been the subject of increased attention with different techniques or approaches -MAUT, MACBETH, ANP, GIS, TOPSIS, SAW (Simple Additive Weighting), AHP, PROMETHEE, ELECTRE, etc. **[153]-** or the area of Environmental, where the inclusion of stakeholders in complex decisions in the context of natural resource management has been addressed in depth **[14]**. In the majority of the 128 analyzed studies the stakeholder engagement was not consistently set out, so input from stakeholders was mainly used at the MCDM first stages to collect enough information in order to build an initial framework. The DELPHI technique was widely used by experts for that case **[69].** Therefore, participation of stakeholders was primarily identified in the following stages: (i) decisional problem definition and contextualization; (ii) alternatives identification; (iii) criteria elucidation; (iv) criteria weighting and; (v) scoring alternatives. Very uniquely, some studies ensured stakeholder involvement at the final phase to provide feedback on the evaluation results. The multiple-actors involvement, the building of an extension of the decision process to a group decision level and the methodological challenges of capturing stakeholders preferences must receive a more consistent treatment when applied to dam management.

In the operational management of dams, decision-making is a complex problem since there are many interrelationships between the various factors involved. Of the 128 studies examined, only four **[95, 96, 135, 136]** formally addressed the modeling of the dependencies between the different components of the evaluation model. To do this, in all the cases authors opted for ANP, and applied it mainly to the risk assessment of hydroelectric projects in China. In parallel, we noted that no author developed the BOCR (Benefit-Cost-Opportunity-Risk) variant of the ANP, a variant that has been developed successfully in other areas of application. The current strategy to integrated management of dams during the operational phase requires a holistic approach to identify, analyze and quantify the benefits, opportunities, costs and risks of maintenance, operation and rehabilitation measures. This is especially critical in old dams, with observable problems related to aging-based deterioration. The BOCR-variant of the ANP method opens up a line of research for aging-dam management, which must be considered of great interest in the near future.

Essentially, the findings of this study confirm what was pointed out by previous authors: (i) different methods establish different prioritization **[154]**; (ii) the choice of one method over another is subjective, depending on how the decider feels about one or the other **[155]**; (iii) the choice of MCDM is in itself a multi-objective problem **[156]** and; (iv) this choice depends on the particular conditions of the problem.

4.2. Statistical analysis

In parallel to the literature review, a statistical analysis was developed to detect correlations between specific MCDM and applications for aging-dam management. Firstly, the data were structured in the form of a contingency table composed of rows (Applications) and columns (Methods). Secondly, a correspondence analysis was carried out throughout IBM SPSS Statistics 22.0 software, with the goal of reducing the original interactions between both variables, according to their frequencies. According to the values obtained from standard deviation and correlation, those elements achieving an extreme score in dimensions were discarded, limiting the spectrum of analysis to the range ([− 0.5, 1.0]; [− 1.5, 2.5]). The results are graphically depicted in Fig. 5.

The information shown in Fig. 5 must be treated carefully, since the frequency of application of a certain MCDA method to an application is not a sure value, i.e. even though data were sought through an extensive bibliometric search in a digital database so reliable as SCOPUS is, this literature review might not cover all the studies of application of MCDA methods in dams. Moreover, one cannot issue categorical judgments based on enough punctual or non-representative observations. Under these premises, and whereas the variables under study are dichotomous, the Phi's correlation coefficients were calculated for each pair of elements Application/Method. The results show that two interactions were statistically significant –see Table 2-: (i) a tendency to use ENTROPY in studies evaluating the quality of reservoir water and, (ii) a tendency to use ELECTRE in studies evaluating the operation of the dam-reservoir system.

The ENTROPY theory measures uncertainties and the extent of useful information provided by data. It overcomes the subjectivity of expert evaluation and it is useful when dealing with missing data or unreliable information, such as is the case with Water Quality assessment, where imprecision and vagueness characterize the problem. ELECTRE method is a non-compensatory aggregation procedure with the ability to set pre-defined categories and to introduce thresholds. These characteristics explain the suitability of this method for ranking solutions of multi-objective Reservoir Operation optimization problems.

5. Conclusions

MCDA has gained importance to evaluate complex decisions in dam management, especially since 2009, when the literature on this subject surges with a clear uptrend. Between the nine applications identified in the review, Risk Analysis (dam/reservoir safety level assessment) was the topic more frequently explored by scholars, indicative of the serious concerns the problem of aging-dam management is arousing in Society. The majority of problems were focused on ranking of alternatives (GAMMA) or selection of the optimal alternative (ALFA). MADM techniques were mostly applied under the single approach (principally AHP or its fuzzified version, FAHP), while the MODM techniques were majorly used to solve optimization problems related to the reservoir-dam system operation. AHP-TOPSIS was the MADM/MODM hybrid model fundamentally visited by scholars due to the reinforcing aspect of their combination, oriented to deal with the classical AHP disadvantages. Models were complemented by a relevant variety of techniques to handle aspects shared by all the applications: imprecise, uncertain and incomplete information, and the subjectivity and complexity of traditional methods. Apart from those commonalities, the different problems in each application were treated in a very diverse way due to the author's preference or the particular conditions of the problem. Additionally, we discovered that Spatial Multi-Criteria Decision Analysis (SMCDA) has been less explored than other related fields. Essentially, two main trends were identified in this systematic review: (1) a growing hybridization process of multi-criteria evaluation models, based on the combination of two or more MCDM methods, and, (2) an increasing fuzzification of these same models. The first trend seeks to add one or more supplementary methods to manage the inconsistencies of the nuclear method while, the second trend aims to adequately handle with subjective judgements and to effectively integrate uncertainty and imprecise or vague information into the evaluation models.

The multiple-actors involvement, the adjustment of the decision process to a group decision level and the methodological challenges implicated in the collection of stakeholders preferences within MCDA studies applied to dam management were not as consistently treated as in other areas (e.g. Transport and Environmental). From a holistic perspective of dam management, a multi-stakeholder and multi-criteria approach is strongly needed to assess not only the risks but also the benefits, costs and opportunities derived from repair, upgrade and removal measures applicable to aging-dam management.

However, our diagnosis is that further research is required to better understand what causes the difference between rational and intuitive decision processes by stakeholders involved in the management of dams, specially ageing dams during the operational phase; and to develop improved MCDA models that help decision-makers solidly learn about interactions and trade-offs between components of the evaluation problems, so that an effective decision-making process can be guaranteed. In the management of a strategic infrastructure asset, such as an ageing dam in operation is, several criteria are involved in complex decisions that are intimately interconnected (primarily socio-economic, environmental and technical), so making a decision implies making trade-offs between criteria.

ANP should play a key role in this aspect, as its approach to characterizing and quantifying loops and trade-offs between decisional components is its strongest capacity, which in turn has scarcely been explored in the area of dam management. Despite that, the few studies developed so far have showed promising results that point to ANP as an effective path to evaluate these interactions and dependencies within the MCDA model. Accordingly, we recommend further research on the combination of BOCR (Benefits-Opportunities-Cost-Risks) analysis and ANP as a potential framework, not explored yet in dam management, to effectively respond to complex problems related to the operation of ageing dams.

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Fig. 1. Total number of MCDA studies on dam management per year.

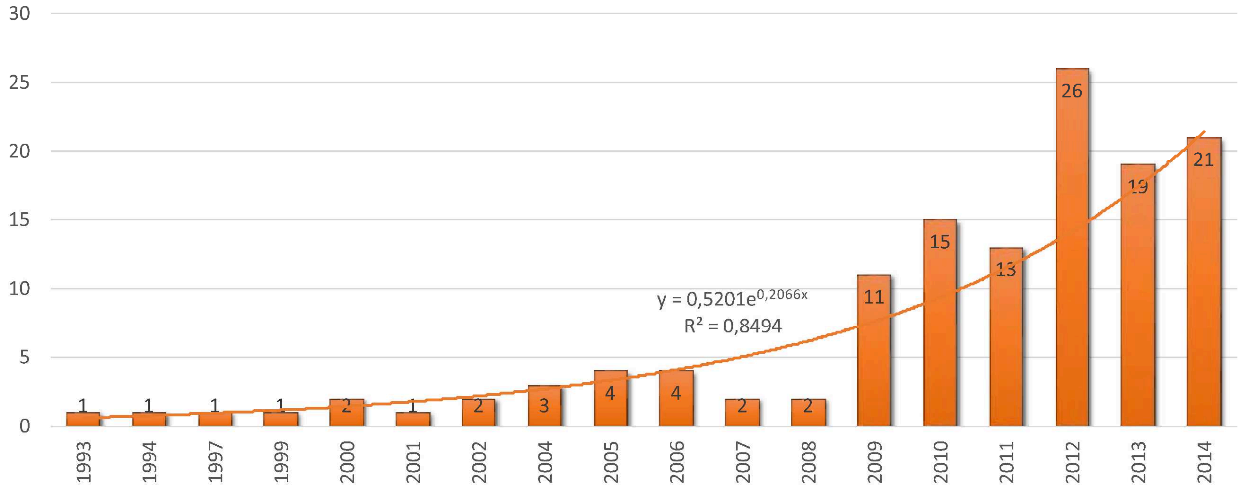
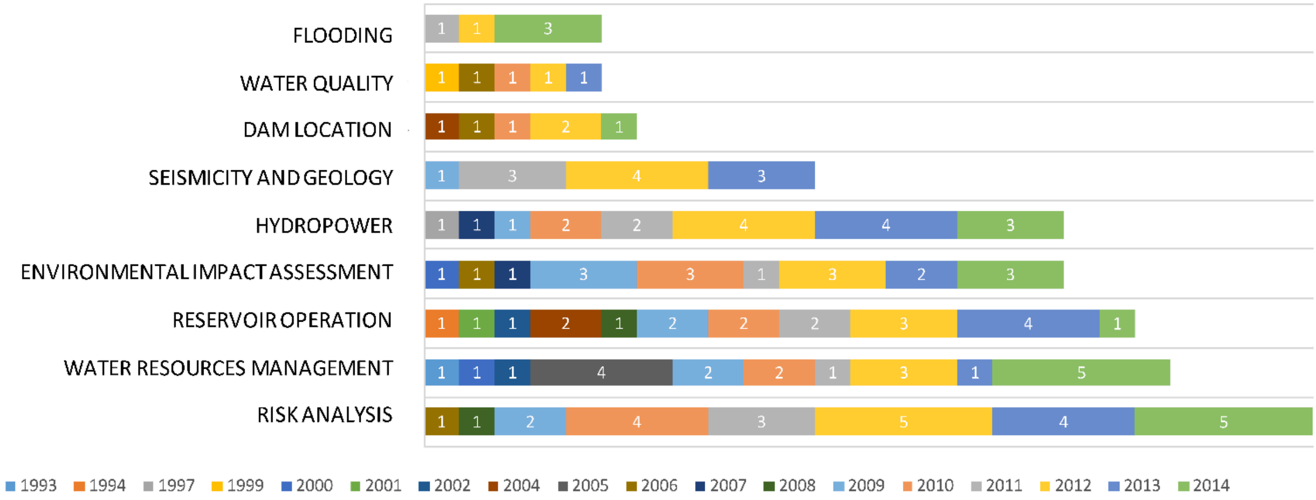


Fig. 2. Number of MCDA studies per year and application field.



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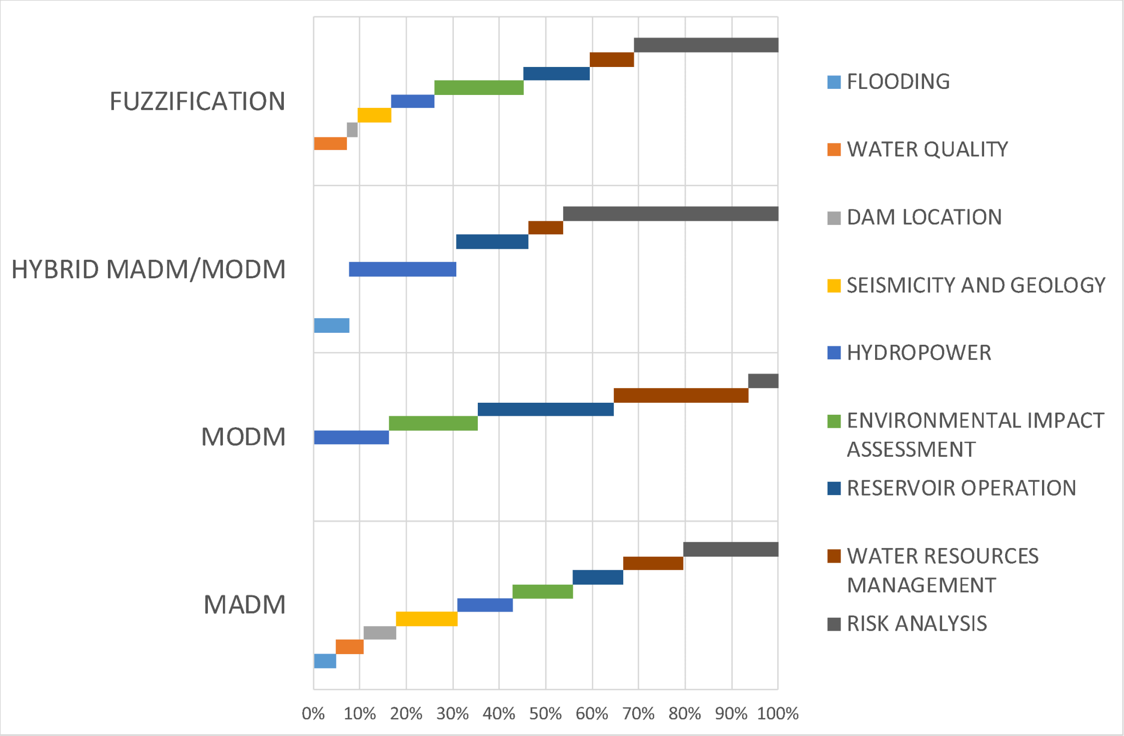

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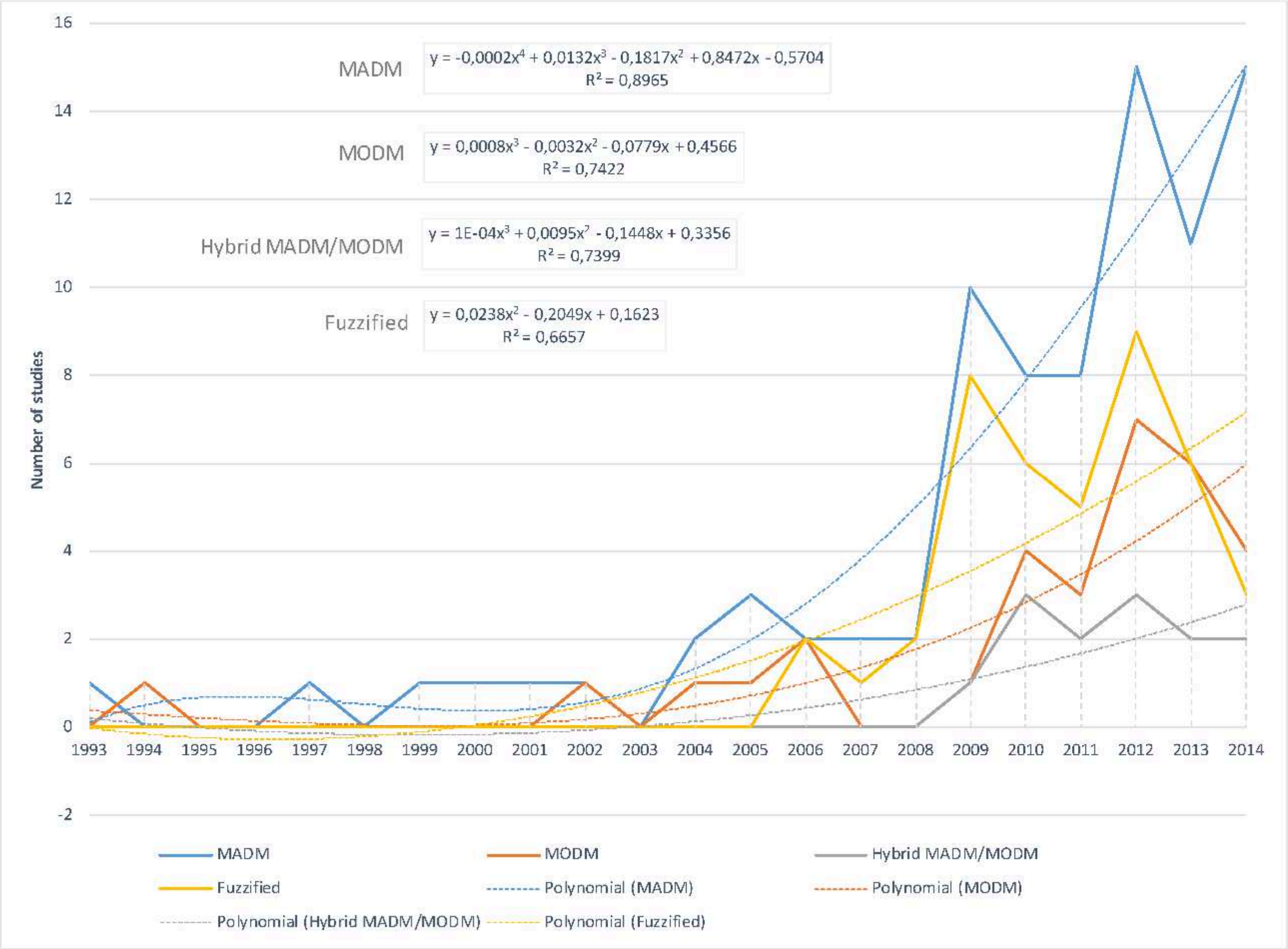

Fig. 5. Values spectrum limitation based on symmetrical normalization (standard deviation and correlation).

			Dimension # 3: Approaches and techniques			
		Dimension # 2: Application	Single -MADM-	Single -MODM-	Hybrid (MADM+MODM)	Fuzzified
Dimension #1: Type of decisional problem	ALFA	A	1	0	0	0
		B	0	0	0	0
		C	3	0	0	1
		D	0	0	0	0
		E	2	1	1	1
		F	3	2	0	1
		G	3	4	1	3
		H	2	0	0	0
		I	2	2	0	2
	BETA	A	0	0	0	0
		B	1	0	0	1
		C	0	0	0	0
		D	4	0	0	0
		E	0	0	0	0
		F	0	0	0	0
		G	0	0	0	0
		H	0	0	0	0
		I	2	0	0	2
	GAMMA	A	3	0	1	0
		B	3	0	0	1
		C	3	0	0	0
		D	5	0	0	2
		E	6	4	2	3
		F	8	3	0	7
		G	4	4	1	2
		H	9	9	1	4
		I	7	0	6	5
	DELTA	A	0	0	0	0
		B	1	0	0	1
		C	0	0	0	0
		D	2	0	0	1
		E	0	0	0	0
		F	0	0	0	0
		G	1	0	0	1
		H	0	0	0	0
		I	4	0	0	2
	KAPPA	A	0	0	0	0
		B	0	0	0	0
		C	0	0	0	0
		D	0	0	0	0
		E	2	0	0	0
		F	0	1	0	0
		G	1	1	0	0
		H	0	0	0	0
		I	2	0	0	2

Note: A: Flooding; B: Water Quality; C: Dam Location; D: Seismicity and Geology; E: Hydropower; F: Environmental Impact Assessment; G: Reservoir Operation; H: Water Resources Management; I: Risk Analysis.

Table 1. Categorization of studies according to three main dimensions

Table 2. Phi values between MCDA methods and applications.

Method - Application			**Phi's correlation coefficient**		
ID.	Method	Application	Value	Approx. Sig.	N of valid cases
1	ENTROPY	Water Quality	0,267	0,001	128
2	ELECTRE	Reservoir Operation	0,249	0,002	128