Multicriteria and Social Choice Methods in Assessing Water Management Plans

Bojan Srdjevic[1], Zorica Srdjevic[1], Yvonilde Dantas Pinto Medeiros[2]

[1] University of Novi Sad, Faculty of Agriculture, Department for Water Management, Trg D. Obradovica 8, 21000 Novi Sad, Serbia
[2]Escola Politécnica da Universidade Federal da Bahia
A. Novis 2, 40.210.630, Salvador, Brazil

Abstract. Selection of a good water management plan for the river basin is a complex decision-making problem because interests of stakeholders are usually confronted, rarely in complete agreement. If water committee has to emulate interest and power of key parties, decision-making process can be organized in many different ways, depending on adopted methodology for deriving decisions and formalizing setup to implement solutions. Group context brings individuals with different background, attitude and (in)consistencies they will demonstrate while evaluating and/or judging options. In this paper, we show how two methodologically distinct tools can efficiently support group decision making at a group and sub-group level within committee. We propose to firstly use analytic hierarchy process (AHP) to rank management plans, and secondly, to use voting method Borda Count (BC) for final ranking of plans selected by post analysis of the AHP results. Illustrative example from Brazil is used to show usefulness of combined approach.

Keywords: Decision-making; AHP; Borda Count; water management; long-term plan.

1 Introduction

The MCDM (multi-criteria decision-making) method known as Analytic Hierarchy Process (AHP) (Saaty 1980, 2003) and the SC (social choice) method known as Borda Count (BC) (d'Angelo et al., 1998; Srdjevic, 2007), are employed to manage a group decision-making process aimed at assessment of and selection of the best among five long-term water management plans across five criteria. During one of multiple workshops related to hierarchical decision-making processes held at the School of Polytechnic, Federal University of Bahia, Salvador, Brazil, a special session has been organized to analyze possibility of establishing decision-making framework related to water management at a catchment scale and within different group contexts. A group of 21 professionals took part in one of two sessions, which lasted in four hours, including two half-hour breaks.

AHP is used to support individuals' and sub-groups' cardinal assessments and prioritization of the decision elements and to rank management plans. Participants

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used evaluation sheets and judged decision elements within given hierarchy by strictly following standard AHP procedure. Once evaluation sheets are collected, prioritization of criteria and plans is followed by the final AHP synthesis. Values of weights for plans and decision makers are aggregated by weighted geometric mean (WGM) method to obtain the final weights and corresponding ranking of plans. Post analysis of the final AHP results is used to reduce set of five alternative plans to new set of 3 best ranked plans to be used in the second part of the session.

New set of plans was included in the appropriate evaluation sheet (voting ballot) according to requirements of the preferential method Borda Count. We selected SC method as the second part of the decision framework due to its simplicity, easiness to be explained to participants and as less time and effort consuming than AHP.

Sheets were distributed to individuals to set their preferences by simply ranking alternative plans considering all criteria as implicitly condensed into unique criterion; note that this is the case how voters usually do in real-life elections. Collected preferential opinions of participants, as fully ordinal information (differently from cardinal information obtained by AHP) are summarized to rank 3 alternative plans as final group decision.

Worthy to mention is that when applying AHP and BC, awareness is required because individuals' background and knowledge are generally very different, particularly if groups (and sub groups) are large. Also important is that in large river-basin water committees, a decision-making process related to planning and overall water management will expectedly be performed with participation of 'oriented committee members' bringing particular background and mostly narrowed interest from social, political or economic environment they are coming from. These facts have also been a part of our recent research, but are not discussed in details in this paper.

In strictly AHP context, reported approach recognizes importance of using equal weights of individuals, and, at the later stage, different weights of subgroups based on the number of members in the subgroups (larger a sub group – higher is its weight). At a committee level, sub groups actually act as a new (virtual single) individuals and the final preferences are determined by weighted geometric aggregation.

For the sake of completeness and to justify our methodological choices we consulted rich literature around group decision-making in agriculture, ecology, etc. that allow a multiple criteria and multiple participants, multiple evaluation tables setting, notably a lot of them applying the aggregation-disaggregation paradigm (e.g. Morais and de Almeida, 2012; Zendehdel et al., 2010; Jonoski and Seid, 2016; Jonoski and Seid, 2016). More methodological sources (Kadzinski et al., 2013; Cabrerizo et al., 2014) were consulted to check our ideas related to aggregation schemes.

Outline of the paper is as follows: after brief description of mathematical bases of both AHP and BC, illustrative example section contains statement of the decision problem, description of decision elements and final outcomes of AHP+BC application. Concluding remarks are given at the end of paper.

2 AHP and Borda Count Mathematics

2.1 Analytic Hierarchy Process (AHP) – Multicriteria Method

A philosophy of the Analytic hierarchy process (AHP) is easy to understand. Assume that hierarchy of the decision problem consists only of a goal (G), a set of criteria C_j (j=1, 2, M), and a set of alternatives A_i (i = 1, 2, N). This hierarchy may be called 3-level hierarchy, with levels counting from top to bottom (Fig. 1).

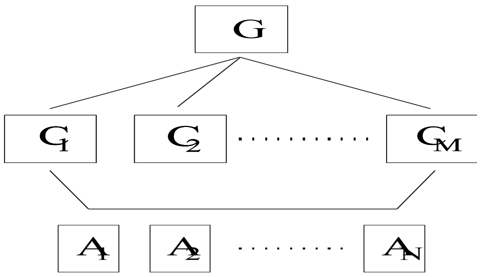

Fig. 1. Hierarchy of a decision-making problem

The AHP starts by performing a sequence of Mx(M-1)/2 pairwise comparisons of criteria with respect to a goal by using the 9-point Saaty's scale, Table 1 (Saaty, 1980).

Table 1. Original Saaty's scale for pairwise comparisons

Numerical values	Judgment Definition
1	Equal importance
3	Weak dominance
5	Strong dominance
7	Demonstrated dominance
9	Absolute dominance
2,4,6,8	Intermediate values

This way a judgment matrix (1) of size MxM is created

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1M} \\ a_{21} & a_{22} & \dots & a_{2M} \\ \dots & \dots & \dots & \dots \\ a_{M1} & a_{M2} & \dots & a_{MM} \end{bmatrix} \tag{1}$$

with entries a_{ij} $(i,j=1,2,\ldots,M)$ being numericals given in the first column of Table 1 as representation of preferences elicited from the individual as judgments defined in the righthand side of the same table. Reciprocal property of matrix A means that $a_{ij}=1$ for all $i=j$ $(i, j=1, 2, M)$, and $a_{ij}=1/a_{ji}$.

If we assume that entries of the vector $\boldsymbol{w}=(w_1,w_2,\ldots,w_M)^T$, commonly called priority vector, are weights of criteria, then it is desired to determine these values so that matrix (2) is best approximate of judgment matrix (1).

$$\tilde{A} = \begin{bmatrix} 1 & w_1/w_2 & \ldots & w_1/w_M \\ w_2/w_1 & 1 & \ldots & w_2/w_M \\ . & . & \ldots & . \\ . & . & \ldots & . \\ . & . & \ldots & . \\ w_M/w_1 & w_M/w_2 & \ldots & 1 \end{bmatrix} \quad (2)$$

In standard AHP, for matrix A the maximum eigenvalue $\lambda_{\max}$ is determined, and related eigenvector is adopted as vector **w**. This method is generally recognized as the eigenvector method (Saaty, 1980). There are, however, more than 20 other methods described in scientific articles for deriving vector **w**, for instance: additive normalization (Saaty, 1980), direct least squares (Chu et al., 1979), weighted least squares (Chu et al., 1979), logarithmic least squares (Crawford and Williams, 1985), fuzzy preference programming (Mikhailov, 2000), logarithmic goal programming (Bryson, 1995), evolution strategy prioritization (Srdjevic and Srdjevic, 2013), and most recently cosine maximization (Kou and Lin 2014). Useful information on these and many other methods can be found in rich scientific literature (e.g., Golany and Kress, 1993; Mikhailov and Singh, 1999; Srdjevic, 2005; Ishizaka and Labib, 2011; Blagojevic et al., 2016).

Next, Nx$(N$-1)/2 pairwise comparisons of alternatives are performed at level 3 with respect to each criterion at level 2. This way a set of M matrices of size NxN is created. Local eigenvectors (for each matrix one vector) are computed as before, and a new matrix (3) of size NxM is created. Computed local vectors represent columns of this new matrix X. Recall that elements of jth vector are partial ratings of alternatives with respect to the jth criterion and sum to 1.

$$\begin{matrix} & w_1 & w_1 & \ldots & w_M \end{matrix}$$

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1M} \\ x_{21} & x_{22} & \cdots & x_{2M} \\ \cdots & \cdots & \cdots & \cdots \\ x_{N1} & x_{N2} & \cdots & x_{NM} \end{bmatrix}. \quad (3)$$

Finally, local priority vectors are multiplied by the weights of related criterions to obtain matrix (4), which aggregates performance ratings of all alternatives with respect to all criteria.

$$Z = \begin{bmatrix} w_1x_{11} & w_2x_{12} & \dots & w_Mx_{1M} \\ w_1x_{21} & w_2x_{22} & \dots & w_Mx_{2M} \\ \dots & \dots & \dots & \dots \\ w_1x_{N1} & w_2x_{N2} & \dots & w_Mx_{NM} \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} & \dots & z_{1M} \\ z_{21} & z_{22} & \dots & z_{2M} \\ \dots & \dots & \dots & \dots \\ z_{N1} & z_{N2} & \dots & z_{NM} \end{bmatrix} \quad (4)$$

Summing the elements in each row of the matrix Z gives the final result (5): weights for alternatives at fingertips of the hierarchy with respect to the goal at the top of hierarchy.

$$w_i = \sum_{j=1}^{M} z_{ij}, i = 1,2,\dots,N \quad (5)$$

The alternative with the highest weight coefficient value w_i should be considered as 'the best alternative', i.e. the best choice in the multicriteria sense.

2.2 Borda Count – Social Choice Method

Preferential voting methods from the SC theory exclusively use ordinal preference information contained in the preference table (Table 2), created by collecting ballots (in real elections). A constructed preference table usually has the following properties. The size of the table is MxN, where M is the number of individuals and N is the number of possible alternatives (choices). Each row represents the ranking of alternatives performed by one individual. If j is the best alternative for individual i, then the rank number is $r_{ij} = 1$; if j is the second-best alternative, then $r_{ij} = 2$, and so on; if alternative j is the worst one, then $r_{ij} = N$.

Table 2. Preference table

	Alt. 1	Alt.2		Alt. j		Alt. N
Indiv. 1	r_{11}	r_{12}	...	r_{1j}	...	r_{1N}
Indiv. 2	r_{21}	r_{22}	...	r_{2j}	...	r_{2N}
...	...	...	...	...	...	...
Indiv. i	r_{i1}	r_{i2}	...	r_{ij}	...	r_{iN}
...	...	...	...	...	...	...
Indiv. M	r_{M1}	r_{M2}	...	r_{Mj}	...	r_{MN}

In Borda Count, each alternative gets 1 point for each last place vote received, 2 points for each next-to-last point vote, etc., all the way up to N points for each first-place vote. The alternative with the largest point total wins the election and is declared to be the social choice.

For each r_{ij} in the preference schedule, a number

$$q_{ij} = N - r_{ij} + 1 \quad \textbf{(6)}$$

is assigned by the above procedure, and the total score for alternative j is given as

$$Q_j = \sum_{i=1}^{M} q_{ij} = \sum_{i=1}^{M} (N - r_{ij} + 1) = M(N+1) - \sum_{i=1}^{M} r_{ij} \,. \quad \textbf{(7)}$$

The alternative j^* with the highest Q value can be selected as the winner, i.e. social choice:

$$Q_{j^*} = \max_{1 \le j \le N} Q_j \,. \quad \textbf{(8)}$$

3 Example Application of the AHP+Borda Methodology

3.1 Statement of the Decision Problem

The problem is stated as to select the most desired long-term water management plan for river basin by authorized institution such as the water committee (WC). The WC is considered to be a decision body (global group) and what is said hereafter to be 'the group choice' should be understood as 'the WC choice'. Assuming that individuals in sub groups will make certain decisions, the final decision should certainly be made at the WC level in a democratic manner with respect to the preferences derived by participating sub groups and/or their delegates.

3.2 Hierarchy

A decision problem is stated as a three-level hierarchy with: (1) a goal is at the top of hierarchy, (2) five evaluating criteria under goal, and (3) five alternative management plans under criteria level that is at the bottom of hierarchy Fig. 1.

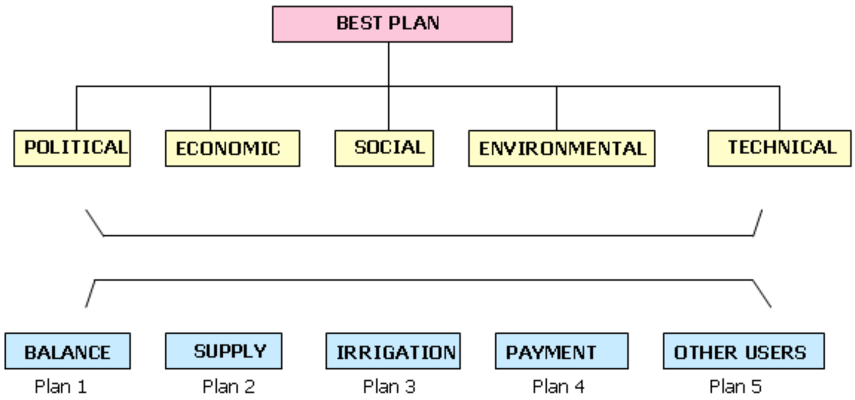

Fig. 2. Hierarchy of the problem

The hierarchy is adopted after each decision element is briefly described to all participants at a plenary part of a session. Main decision elements (goal, criteria set and alternatives) are as follows:

- *Goal*
  Select the best (most desired) plan using given set of criteria

- *Criteria set*
  Political influence criterion is considered as the gradually exposed impact of various state and in-basin agencies and bodies, representatives of cities/villages, stakeholders, producers and local leaders.
  Economic criterion relates to real possibilities to implement the economical process, reliability of economical parameters, estimated costs of investment, operation and maintenance, and expected direct and indirect benefits.
  Social issues criterion relates to issues such as infrastructure, demographic changes (migration), health care and working conditions.
  Environmental protection criterion relates to specific environmental and ambient conditions such as the distribution of pleasant resorts, preservation of historical sites and cultural values, accessing the objects and facilities, protecting water quality, and particularly preserving acceptable sanitary conditions.
  Technical criterion encapsulates interests in preserving proper spatial distribution of projects, technical conditions for project operations, technologies involved, and eligibility for technical improvements.

- *Decision alternatives (management plans)*
  Plan 1 (Balance). High industrial developments are foreseen as well as intensive irrigation. Electric power production will increase by 20% after certain reconstructions of the existing hydroelectric objects and facilities. All users, including big users such as irrigation and hydroelectric production, will have

approximately equal treatment. However, ecological and urban water requirements will receive top priority in water allocation.

Plan 2 (Supply). Water supply (municipal and rural, human and animal) will absolutely get an increased concern from the state agencies responsible for water management. It will be dominantly realized by means of reservoir management. Demographic movements from rural areas to cities and state capitals will continue with an actual increasing trend, but will be significantly decreased by the middle of the planning period. Irrigation will rise to only 50% of that amount estimated as maximum by the end of the period.

Plan 3 (Irrigation). Irrigation will have a dominant role with respect to the other water uses throughout the basin. Priority will be given to large irrigators (development at a level higher than 80% of the estimated maximum). No water payments are expected until 2020; only irrigation and industrial uses will be charged afterwards.

Plan 4 (Payment). Water payments will start progressively by 2020, with revisions of payment policy every 5 years (2025 and 2030). Pricing will be combined with an advanced system for obtaining the water rights. Other elements of the plan are the same as in Plan 3.

Plan 5 (Other users). This plan is a modification of Plan 1 in a way to emphasize importance of small irrigation users, tourism, eco-tourism and other small users (such as handmade manufacturers, ceramic industry). Intent is to enable that various users (other than large ones) will receive a higher priority by obtaining proper water rights and excluding payments; compensation for their uses of water will come from large consumers in irrigation, hydroelectric production and industry by proper pricing policy.

- *Decision makers, interest groups and water committee as a global group*
  Participants were divided to three main interest groups:
  (1) Public Authorities
  (2) Civil Society
  (3) Water Users.

Each participant is an individual decision-maker and fully autonomous. Note that within the water committee as a global group, sub groups may gather individuals in different ways for differently organized decision-making processes. In adopted context, a group is the entire body of a water committee where 'delegated' decisions, made in sub groups, have to be interpreted, justified, aggregated (by consensus or not) and put in power.

3.3 Remarks

Several main remarks can be given to better describe the decision-making framework:

Remark 1. WC decides by applying scientifically sound multicriteria (AHP) and election (Borda Count) methods, followed by common aggregating techniques.

Remark 2. WC recognizes panel meetings as principal mean of its work where mediating rules must be adopted by consensus, and where the final decisions are to be made. WC also recognizes 'decentralized part' of the decision process performed at separate meetings of each entity. Entities are by assumption authorized to make their own decisions and forward them to be aggregated at the WC level.
Remark 3. Each entity has 'its own point of view' while evaluating possible decision alternatives and ranking them appropriately. An outcome of the decision process conducted through each entity is forwarded to the WC level (for aggregation) as it is. That means that no any changes, interpretations or justifications are permitted.
Remark 4. As first part of the decision-framework, the method used by each entity in assessing criteria and management plans is AHP. Sub group consensus is assumed where logical and/or appropriate. Although AHP produces cardinal preferences of decision alternatives, represented by computed weights, only ordinal information is analyzed, i.e. ranking of the alternatives.
Remark 5. Each entity (individual or specific sub group) assesses the same set of management plans across the same criteria set.
Remark 6. By applying voting method Borda Count to the reduced set of best-ranked plans, it is possible to come-up to the final decision: the preferable management plan.

3.4 Procedure and Results

The WC as a global group is divided into three interest groups. After individual opinions were synthesized for each interest group, the sub-group decisions are forwarded to an upper level: the WC level is where the final aggregation and interpretation of result is performed. The decision procedure and obtained results were as given below.

A total of 21 participants split into three Interest Groups (IG), namely: Public Authorities (7 delegates); Civil Society (5 delegates); and Water Users (9 delegates).

- *First part of the session - AHP evaluation*

Delegates individually assessed hierarchy given in Fig. 1 by using AHP within each IG. Each delegate had to fill-in six pairwise comparison matrices with numbers from the Saaty's 9-points fundamental scale. Local weights of criteria vs goal and alternatives versus criteria are computed by the eigenvector method and standard AHP synthesis generated the final weights of alternative plans versus global goal (best plan) for each individual.

Based on the number of individuals in the sub-groups, participation weights of sub groups in the WC are defined as: 40% for interest sector of water users, 34% for public authorities and rest of 26% for civil society. By applying these weights, the final aggregation is performed to obtain the final group decision corresponding to the WC level, Table 3. The best plan, as the WC final choice, is Plan 1 (Balance), second ranked is Plan 2 (Supply), and third one is Plan 5 (Other Users). Least desired plan is Plan 3 (Irrigation). It is easy to see that Plan No. 1 (Balance) is selected as the best by two IGs: Public Authorities and Water Users. Top ranked by Civil Society is Plan 5 (Other Users), while Plan 1 is ranked as second. Worthy to notice is also that Plans 1, 2 and 5 are top-3 ranked by all IGs. Notice also that final ranking mostly reflects preferences of the third interest group (Water Users).

Table 3. Subgroups ranking and the final AHP aggregation at the WC level

IG		IG weight	Weights of Alternatives (Plans) 1	2	3	4	5
Public Authorities	(7)	α_1=0.34	0.258 (1)	0.249 (2)	0.117 (5)	0.145 (4)	0.231 (3)
Civil Society	(5)	α_2=0.26	0.314 (2)	0.178 (3)	0.037 (5)	0.056 (4)	0.415 (1)
Water Users	(9)	α_3=0.40	0.309 (1)	0.289 (2)	0.139 (4)	0.119 (5)	0.144 (3)
Aggregated (WGM)			0.306	0.254	0.098	0.110	0.232
Ranking			1	2	5	4	3

- *Second part of the session - Borda Count evaluation*

In the second part of decision-making process, the Borda Count is employed and within all three sub groups participants individually re-assess reduced set of alternatives. Result of the AHP application (Table 3) showed that plans 1, 2 and 5 are most prominent, having much higher weights then plans 3 (weight 0.098) and 4 (weight 0.110), so 21 participants re-assess only those three plans.

This time, however, they did not ranked criterions within criteria set like in AHP. Rather, all criteria are considered as unique criterion, which describes general desire and implicitly contains ‘a flavor’ of each criterion from the original criteria set. Keeping this in mind, each individual ranked by importance alternatives within new alternative set. Participants are asked to express their individual (ordinal) preferences by filling-in appropriate boxes with integers 1-3 in distributed evaluation sheet. BC computations were straightforward afterwards.

Individual and final ranking of alternative plans derived within each interest group by BC is summarized in Table 4.

Table 4. Final Borda Count assessment at the WC level

IG	IG weight	Ranks of Alternatives (Plans) 1	2	5
Public Authorities	α_1=0.33	2 (15)	3 (12)	3 (16)
Civil Society	α_2=0.33	1 (6)	3 (14)	2 (10)
Water Users	α_3=0.33	3 (21)	1(16)	2 (17)
Final aggregate		6	7	7
Final ranking		1	2-3	2-3

Assuming that obtained three rankings in interest groups are additionally aggregated at the WC level (by following the same Borda Count procedure and associating equal weight to each IGs’ ranking), the best alternative is Plan 1 (Balance), while Plan 2 (Supply) and Plan 5 (Other users) share second and third place.

4 Conclusions

The paper presents group decision-making framework that could be applicable as a part of paradigm decision-making in any water committee responsible for water management on the river basin scale. The problem is stated as to select the most desired long-term management plan among several offered plans by assessing plans across selected more or less conflict criteria. Presented approach illustrates how two different methodological options in decision-making can be combined for establishing common professional, social and political environment where people ought to make decisions by using advanced scientifically sound techniques. First part of session included more complex, more detailed and time and effort consuming evaluation of management plans. Thus, we believed that it is more convenient for participants to use simple voting method in second part of the session where final decision is to be made.

It should be noted that the final ranking does not necessarily depend on the number of voters, and on the size of the subgroups. So, in the SC process of voting a large subgroup has the same power as a small subgroup. This could yield to ranking that does not satisfy the conditions of social welfare functions, and especially the principle of majority decision. An issue of number of members in groups or sub-groups, importance of individuals (experts) within sub groups and across representatives on group level, and related problems of preserving fairness, competence and consistency - is always for discussion in practical applications. And of course, our approach is not immune of it.

In voting part of a methodology, we imply that only representatives of different subgroups (one person for one subgroup) within relatively large water committee should vote. This must not be a rule. A possible new direction of research could be how to effectively and consistently avoid any early confrontation of individuals and sub group within WC, i.e. how to define their different weights based on competences, i.e. expert knowledge, education, attitude, willingness, political impacts etc.

It is important to mention that involved decision makers found proposed methodology transparent, easy to understand and implement, and results trustful.

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