

Evaluating Management Strategies in Paraguacu River Basin by Analytic Hierarchy Process

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Abstract: An approach is proposed for evaluating water management strategies in river basins. Reasonably large sets of criteria and objectives are manipulated during a three-phase process by appropriate shrinking and enlarging related decision hierarchies. In the first phase an unrestricted set of management interests are grouped into (1) long-term, and (2) middle- and short-term decision context by creating decision hierarchies and evaluating them by the Analytic Hierarchy Process (AHP). After refining the hierarchies by deleting dominated elements, management plans are introduced at their fingertips and so enlarged hierarchies are repeatedly evaluated by AHP in the second phase. Only two bottom levels of hierarchies is necessary to consider by this break-in evaluating procedure. Size of decision hierarchies is rationally preserved in both phases considering limited human abilities in handling numerous decision elements while comparing them, and difficulties in attaining desired decision consistency. The last phase aggregates weights of management plans derived in the second phase for two hierarchies and performs a final ranking of the management alternatives. The Paraguacu river basin in Brazil is used as a case study. This is the most important alluvium in the state of Bahia, which spreads out over 55 thousand square kilometres. Within the basin there are 84 municipalities with nearly 2 million inhabitants. Prevailing water management conditions are semi-arid and major water uses are human and animal supply, irrigation and low river flow augmentation for ecological purposes. Three management plans for a 40-year time horizon were evaluated and ranked.

Keywords: river basin, water management, Analytic Hierarchy Process

1. INTRODUCTION

Effective water management assumes assessment of both amounts of water needed to meet diverse demands, and quality of water that enables its proper multiple and cyclical use [Azevedo et al., 2000]. On a river basin level it is strongly related to legislation, multiple and conflicting interests of water users and social entities, inadequate space and time distribution of demands and water availability. As an activity itself, water management is imbedded into global, regional and local development and may be considered as a part of larger multiple objective decision frameworks. This means that evaluating alternative management strategies is usually based on criteria and objectives taken from a broader socio-economic environment.

Two important decision making principles must be followed in water management. The first relates to the integration of environmental, economic and social objectives in decision-making. It is based on

the notion that narrowly focused decisions lead to poor outcomes. The second principle relates to the importance of community involvement in decision-making and implies active participation of multiple interest groups. Both principles create a complex decision environment that involves various tradeoffs between conflicting objectives, input from interest groups and synthesis of large and complex data sets.

Hierarchically structured decision-making is particularly well suited for management and engineering decisions that involve multiple conflicting objectives and human judgments. To preserve consistency of decision process and trustiness in decisions made, the whole issue must be kept at a reasonable level of complexity. During the problem statement phase, a reasonably large set of options should be specified. Otherwise, the decision maker may be overburdened by too many objectives and alternatives, and exhausted by long lasting judgments. The ultimate consequence could be inconsistency and erroneous decision. The

problem solving should be organized as straightforward decision-making process that enables the decision maker to feel comfortable.

In this paper, a particular decision making procedure in river basin water management is proposed. It enables efficient manipulation of large sets of criteria, objectives and alternatives in water management, typical for undeveloped semi-arid regions where long-term (strategic) and short and middle-term (tactical) interests of river basin community are hard to articulate in an organized and consistent fashion. To integrate all decision elements into single and valuable decision-making framework, an iterative method of shrinking and enlarging decision hierarchies is suggested. In the first phase it is assumed that two hierarchies exist consisting only of goals, criteria and objectives, which can be broken-down to sub-criteria and sub-objectives. Hierarchies should relate to strategic and tactical management goals of the river basin community that can roughly be defined as 'benefit for all' and 'human well being', respectively. Initial hierarchies are supposed to be shrunk to acceptable size by applying Analytic Hierarchy Process (AHP) [Saaty, 1980], i.e. by deleting their most inferior elements. In the second phase, shrunk hierarchies expand by inclusion of management alternative plans. AHP performs assessment of new hierarchies, and management plans' weights are recomputed. The third phase aggregates weights derived in second phase to come up to a final ranking of plans. This way it is preserved that both long-term and short and middle-term aspects of basin water management are consistently considered.

2. DECISION MAKING BY AHP

A variety of algorithms and techniques can be employed in the completion of multi-objective decision-making (MODM) process. Nijkamp [1989] identified around 40 to 50 such methods, which in different ways weight the objectives, rank the alternatives and standardize the data. One of the best-known MODM tools in the field is AHP. In the last two decades AHP has gained significant popularity, and there are many reported real-life applications in business, engineering and management. AHP owes its popularity primarily to methodological and mathematical simplicity, ability to handle qualitative and/or quantitative data, and availability of good software support [EC, 2000]. On methodological level it enables activities typical in decision-making: (1) weighting the objectives, and (2) ranking the alternatives. On implementation level, it enables the decision maker to get involved in weighting the objectives and given an opportunity to observe and

understand the weighting process. Examples of AHP applications in water resources are reported in Jandric and Srdjevic [2000] and Srdjevic et al. [2000].

The AHP decomposes a complex multi-factor problem into a hierarchy and uses matrices and linear algebra to formalize the decision process. The overriding goal is specified first and is then progressively linked down with criteria, sub-criteria, sub-sub-criteria and so on, down to the fingertips of the hierarchy where lie the alternatives. The AHP determines the priority of each alternative by analysing the judgmental matrices and their eigenvalues and eigenvectors. Both subjective and objective judgments are combined in an integrated framework based on ratio scales from simple pair wise comparisons. Original AHP requires the decision maker to use the 9-point scale with 1 designating equal importance and 9 indicating absolutely more important. The use of that scale is controversial because there is no substantive reason why it is any superior to, for example, a 7-point or 10-point scale. Generally speaking, decision analyst can adopt any scale that maximizes his understanding of the comparison process. Similar flexibility exists in inserting weights directly to elements at certain hierarchy level (assuming they sum up to 1), and after that in continuing pair wise evaluating process downward. Such a break-in strategy is exploited in this study.

The simplicity and intuitive logic of AHP facilitate the participation of various decision makers and even stimulate their involvement in brainstorming sessions, which ultimately may improve collective thinking, reasoning, and the efficiency of group decision. In most cases, the stakeholders will apply weights to the criteria, while placing weights on alternatives tends to be a more scientific/technical task that is undertaken by experts or decision analysts [Hajkowicz and Prato, 1998]. The same is valid for management situations, where political bodies, delegates or stakeholders, or all, take part in stating the most general goal (objective), such as sustainable development or good quality of life, and then in defining criteria (sub-objectives) that have economic, social and environmental aspects. Scientific and technical staff generally takes part in providing alternatives at the bottom level of the hierarchy as possible solution to a problem. In all cases it must be ensured that the alternatives are appropriately related to upper level elements of the hierarchy and to overall goal at the top.

3. METHODOLOGY

A three-phase procedure is proposed for evaluating water management strategies (plans) on river basin scale. It articulates related multiobjective decision-making environment and stems from possible real-life situations typical for developing countries where water management is frequently faced with problems such as unavailability or unreliability of data, improper legislation, or difficulties in motivating society to participate in management. In the first phase extensive set of long-term (strategic) interests of community is assessed by manipulating properly defined management criteria and sub-criteria related to social, economical, environmental and other interests within a river basin. The point is that only mutual importance of criteria and sub-criteria is evaluated with relation to overall management goal, stated for example as 'benefit for all'. It is supposed that various interest groups at basin, sub-basin and local level may formulate such a set of criteria and sub-criteria. With the help of AHP this set should be shrunk so that the decision makers may afterwards concentrate only on dominant issues.

In this phase, a parallel evaluation process should be performed by considering 'human well being' as the management goal along with the set of objectives and sub-objectives such as employment, income, balance of expenses, health care, or scenic beauty. In this way it is possible to articulate short and middle-term ('tactical') human interests that are naturally related to present rather than to future life conditions. This set of objectives and sub-objectives should also be identified by interest groups within the basin and shrunk after the application of AHP.

The result of the first stage is two hierarchies with adjusted sets of criteria and objectives (and their subs). They are used in the second phase for evaluating possible management scenarios and strategies specified as 'management plans'. Until the second phase there is no notion of management plans, and by their inclusion from now on, two shrunk hierarchies are actually enlarged to final size to enable evaluation of plans with respect to dominant basin-wide interests. Such an integration provides consistent consideration of both dominant criteria and objectives and management strategies, and the result of this phase is two sets of weights for management plans, one with regard to long-term, and other to short and middle-term community interests and preferences.

The last, third, phase considers corresponding plans' weights computed by AHP in the second phase. Aggregating weights can be performed by

simple averaging or by additional weighting of strategic and tactical interests in the basin. Furthermore, an aggregation may be considered as two-objective optimisation problem with objectives being: (1) long-term and (2) short and middle-term benefits, and variables being plans' weights. The last could be an interesting subject of further research.

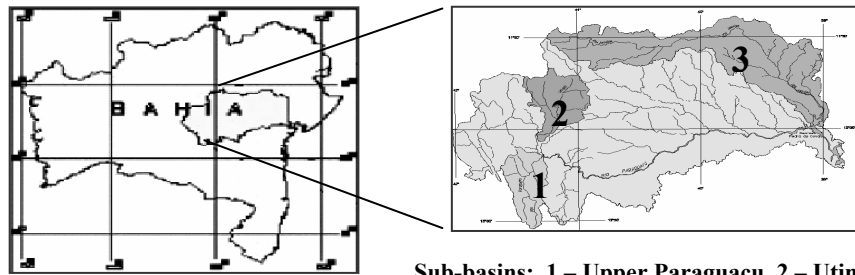
4. PARAGUACU RIVER BASIN

The Paraguaçu River Basin (PRB) is located in central part of the Bahia state in Brazil, Figure 1. It spreads out over 55 thousand km², which is about 10% of total Bahia's territory. Within the basin there are 84 municipalities with nearly 2 million inhabitants. In upper basin parts climate ranges from semi-arid to semi-arid and semi-humid; in medium and lower parts the climate is semi-humid and humid; finally, in estuary zone by seashore of the Atlantic Ocean the climate is dominantly humid. Prevailing conditions in the basin are semi-arid.

The available waters of acceptable quality are dominantly superficial; groundwater is generally salinized due to the existence of huge crystalline structures throughout the basin [GRH, 2001]. There are more than 15 reservoirs in the basin, but only three are of great importance: 1. Pedra do Cavalo (5x10⁹m³), 2. Sao Jose de Jacuibe (355x10⁶m³), and 3. Franca (24x10⁶m³). Major water uses within the basin are: drinking water for humans and animals, industrial supply, agricultural irrigation, and to a lesser extent tourism, recreation and various ecological uses. Conflicts in water uses are evidenced as follows:

- Upper zone: mechanized irrigation vs. mineral research vs. agricultural activities;
- Medium and lower zone: irrigation vs. water supply vs. wastewater disposal and treatment;
- Sao Jose de Jacuibe Dam: salinisation vs. human water supply (drinking water) vs. irrigation;
- Pedra do Cavalo Dam: human water supply (drinking water) vs. hydropower production (after electric power facilities are installed).

Indicated conflicts are under increased attention of local and regional private and public subjects within the Paraguaçu basin. Responsible state and federal agencies recognize these conflicts as well, and by many means try to improve the situation. An important course of joint action at federal and state level is radical focusing on intensive use of advanced database management systems and decision support systems [GRH, 2001].



Sub-basins: 1 – Upper Paraguaçu, 2 – Utinga, 3 – Jacuípe

Figure 1. Paraguaçu River Basin

5. ASSESSMENT OF MANAGEMENT STRATEGIES

5.1 Phase One

Strategic long-term management goal is defined as ‘Well-balanced inter-basin development for benefit of all’. The Hierarchy 1 was created consisting of 5 criteria (A–E) and 24 sub-criteria (A1–E4) as listed below, and AHP was used to simulate participative decision-making process. Computed weights are given in parentheses; note that respective weights sum up to 1.

A. POLITICAL IMPACTS (.251)

- A1: State and basin agencies and bodies (.188)
- A2: In-basin water committees (.100)
- A3: Human population in cities/villages (.071)
- A4: Stakeholders (.308)
- A5: Producers (agriculture and industry) (.233)
- A6: Local leaders (city majors and others) (.100)

B. ECONOMICAL ISSUES (.409)

- B1: Implementing economical process (.478)
- B2: Reliability of economical parameters (.256)
- B3: Costs (investment, oper. and maint.) (.128)
- B4: Benefits (direct, indirect) (.138)

C. SOCIAL ISSUES (.149)

- C1: Infrastructure (.465)
- C2: Demographic changes and migration (.063)
- C3: Health care issues (.293)
- C4: Working conditions (.179)

D. ENVIRONMENT & AMBIENT (.138)

- D1: Distribution of pleasant resorts (.198)
- D2: Preserving cultural values (.080)
- D3: Conditions for water conservation (.180)
- D4: Accessing objects and facilities (.090)
- D5: Protecting waters (water quality) (.264)
- D6: Sanitary conditions (.188)

E. TECHNICAL CRITERION (.054)

- E1: Spatial distribution of projects (.510)
- E2: Technical conditions of projects (.221)
- E3: Technologies involved (clean/dirty) (.188)
- E4: Eligibility for technical improvements (.081)

The Hierarchy 1 has three levels and comprises 30 elements. A total of 58 pair wise comparisons are performed by AHP, which is considered as edge-acceptable. Inconsistency of decision process was 5%.

Tactical short and middle-term goal is defined as ‘Basin-wide improved human well being’. The Hierarchy 2 was created comprising three typical objectives (a–c) broken-down into 13 sub-objectives (a1–c4). This hierarchy has 18 elements and 21 pair wise comparisons were made by AHP with global inconsistency index of 8%.

a. ECONOMICAL OBJECTIVES (.627)

- a1: Balanced payments (.335)
- a2: Increased salaries (.364)
- a3: Gains in trading (.071)
- a4: Better loan opportunities (.143)
- a5: New sources of family income (.087)

b. SOCIAL OBJECTIVES (.280)

- b1: Higher employment rate (.391)
- b2: Infrastructure development (.146)
- b3: Better public services/health (.305)
- b4: Better housing and living conditions (.158)

c. ENVIRONMENTAL OBJECTIVES (.094)

- c1: Resource conservation (.519)
- c2: Preserving cultural values (.228)
- c3: Preserving natural ecosystems (.152)
- c4: Preserving scenic beauty (.101)

There are different ways to shrink the hierarchies. A rational approach is to leave active, at a particular hierarchical level, all elements whose weights sum up to at least .70 after all elements are being ordered in descending manner. In this way dominant set of elements can be extracted and saved for further analysis, as indicated in Table 1 and Table 2.

Table 1. Shrunk Hierarchy 1

Criterion / Sub-criterion	Computed Weights	Normalized Weights
B	0.409	0.506
B1	0.478	0.651
B2	0.256	0.349
A	0.251	0.310
A4	0.308	0.422

A5	0.233	0.319
A1	0.188	0.258
C	0.149	0.184
C1	0.465	0.613
C3	0.293	0.387

Table 2. Shrunk Hierarchy 2

Objective / Sub-objective	Computed Weights	Normalized Weights
a	0.627	0.691
a2	0.364	0.432
a1	0.335	0.398
a4	0.143	0.170
b	0.280	0.309
b1	0.391	0.458
b3	0.305	0.357
b4	0.158	0.185

5.2 Phase Two

Three management plans were preliminary defined by anticipating present (year 2002) and future (year 2040) water supplies and demands in three representative sub-basins: Upper Paraguacu, Utinga and Jacuipe (cf. shaded areas in Figure 1). Available water quantities were estimated according to two distinct aspects: (a) the 90% guarantee discharge in Upper Paraguacu and Utinga sub-basins, and (b) according to stored water in reservoirs (Franca and Sao Jose do Jacuipe) in Jacuipe sub-basin. Main water uses

identified within the region are human supply, animal thirst quenching (animal supply) and irrigation. In addition and as established by law, 20% of the available water should be maintained in the riverbed to attend ecological finalities.

All relevant water quantities were calculated and summarized in Table 3. Alternative management plans were elaborated as follows:

PLAN 1: Demands related to human supply and animal thirst quenching should be fully satisfied in future at present level needs. Remaining waters should be used with priority given to irrigation according to future needs. In case of any surplus waters, ecological demands should be satisfied.

PLAN 2: Priority should be given to attending human supply and animal thirst quenching demands, followed by irrigation demands -- all according to future needs. Again, in case of available water surplus, the ecological demands should be satisfied.

PLAN 3: This alternative considers attending human supply and animal thirst quenching necessities as priority, according to future necessity values, followed by the ecological demands. Only in case of available water surplus, irrigation demands should be satisfied.

Table 3. Water availability, projected demands and management plans in Paraguacu river basin

SUB-BASINS INCLUDED	AVAILABLE WATER (10 ⁶ m ³ /yr)	WATER USES	PRESENT NEEDS (2002) (10 ⁶ m ³ /yr)	FUTURE NEEDS (2040) (10 ⁶ m ³ /yr)	PLAN 1	PLAN 2	PLAN 3
					DEMANDS (10 ⁶ m ³ /yr)	DEMANDS (10 ⁶ m ³ /yr)	DEMANDS (10 ⁶ m ³ /yr)
UPPER PARAGUACU	444,15	HUMAN SUPPLY	8,22	18,33	8,22	18,33	18,33
		ANIMAL SUPPLY	3,45	4,67	3,45	4,67	4,67
UTINGA		IRRIGATION	102,39	426,37	389,36	379,28	332,33
JACUIPE		ECOLOGY	88,82	88,82	43,12	41,87	88,82
		TOTAL	202,88	538,19	444,15	444,15	444,15

After including management plans, final hierarchies are created as shown in Figure 2 and Figure 3. AHP was applied only to evaluate plans with regard to upper level sub-criteria

(Hierarchy 1) and sub-objectives (Hierarchy 2). Final plans' weights are derived with overall inconsistency less than 10% and presented in Table 4.

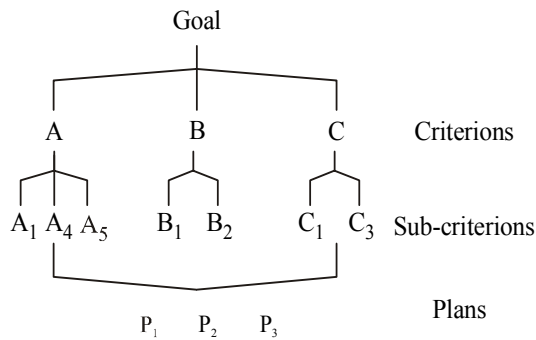


Figure 2. Final Hierarchy 1

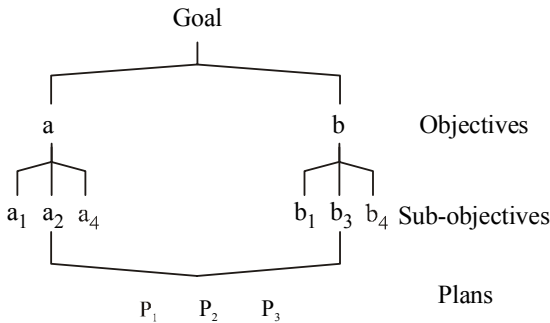


Figure 3. Final Hierarchy 2

Table 4. Management Plans Weights

Hierarchy/Plan	Plan 1	Plan 2	Plan 3
Hierarchy 1 (Strategic)	0.376	0.498	0.126
Hierarchy 2 (Tactical)	0.452	0.519	0.029
Average	0.414	0.508	0.078

5.3 Phase Three

Results of the second phase are here interpreted and aggregated to derive final management plans' ranks. Weights in Table 4 indicate that from both long-term and short and middle-term basin wide interests, the PLAN 2 could be the first choice ('best plan'), the PLAN 1 could be the second choice ('second best'), while PLAN 3 is obviously so inferior that could be rejected.

Finally, since all three plans are ranked the same way for both management frameworks, there is no need for applying particular aggregation procedure. Plans' weights for two hierarchies are averaged and global ranking of plans is preserved.

6. CONCLUSIONS

Water management in semi-arid river basins is an intriguingly complex task. It is frequently faced with the problem of how to identify various interest groups and articulate their preferences. Reported researches indicate that even it was successfully accomplished, decision framework may perform as ill-structured architecture not

suitable for deriving proper management decisions.

In this paper it is suggested how to act in such situation, how to identify dominant preferences of the community within river basin, and finally how to consistently evaluate management strategies afterwards. Proposed phasing of the decision process within water management framework is general enough from the methodological standpoint. Recent research indicates it as promising to resolve at least some of existing problems within the Paraguacu river basin in Brazil.

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