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# An Objective Multi-Criteria Evaluation of Water Management Scenarios

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**Abstract.** Advanced computer models are commonly used to simulate reservoir system's performance. If the number of possible management scenarios is large, it can be extremely difficult to follow related system's operation and get a valuable picture on its spatial and temporal behavior. The decision maker or analyst can be overburdened by quantity and complexity of information generated by model, particularly if system operation is repeatedly simulated for multiyear periods. Related problem is how to select the scenario with most desired long-term consequences. Possible approach is to use selected parts of model's output and re-interpret system behavior by means of certain performance indicators, create appropriate decision matrix and perform multi-criteria analysis to rank decision alternatives (scenarios). The paper proposes a methodology that includes: (1) multiyear simulations of system operation; (2) computing spatially and temporally distributed system performance indices such as supply reliability, resiliency and vulnerability; (3) unbiased entropy-based weighting the importance of performance indices; and (4) final ranking of scenarios by means of multi-criteria analysis. The number of scenarios and number of performance indices is not restricted, and to account for possibly large sets of scenarios, an ideal-point-distance multi-criteria method TOPSIS is suggested. Proposed methodology appeared to be confident and robust in proof-of-concept application in Brazil.

**Key words:** entropy, multi-criteria analysis, performance, reservoir system, scenario

## 1. Introduction

An important issue in river basin water management is how to evaluate effects of possible management scenarios. Simulation of even small-scale reservoir system over 20 or 30 yr may, for given scenario, generate comprehensive output which commonly includes reservoirs' storage levels, delivery patterns, flows in rivers and channels and other relevant data. While analyzing several scenarios in search for the best one, the analyst is in fact the decision maker (DM) interested to get clear information on system's performance. The problem is that he/she may easily be disorientated by numerical and graphical output generated by computer model. For example, it might be difficult to compare simultaneously storage level diagrams for reservoirs that are far from each other and/or are of different sizes and importance for the system, or if applied operational strategy is inferred by tradeoffs in water distribution. Part of a problem can also be a need for triggering menus and searching for locations of interest, which after some time may go into obscurity. Finally, although the DM may fully understand the effects of applied management strategy, even minor scenario's modification may have as a consequence effects that cannot be satisfactorily managed. Obviously, there is a need for merging this multi-dimensional problem into properly structured decision-making framework and for applying some consistent solving methodology.

Recent applications of decision support systems and river basin simulation models indicate that frameworks for monitoring system's performance under different operating scenarios are commonly problem oriented, and that there is not established methodology for multi-criteria analysis of scenarios in straightforward and objective manner (e.g. USDI, 2000; Azevedo *et al*., 2000; Raju and Pillai, 1999; Silva *et al*., 2001). In particular, there are not reported methodologies that enable an integrated explicit treatment of 'technical system's performance' in so-called hazard operating circumstances when issues such as water allocation reliability, or system's resiliency and vulnerability become important. In this regard we propose an approach that combines river basin simulation and multi-criteria analysis. Firstly we recall to 6 commonly used measures and indicators of long-term system performance and adopt them as criteria set for evaluating management scenarios. The decision matrix is then created with columns corresponding to performance criteria and rows corresponding to alternative scenarios. Scoring of scenarios across criteria is accomplished by running the model and post-processing it's output. Computed performance indicators, i.e. scenario scores, become key constitutes of the decision matrix, and represent cardinal information for deriving the weights of importance of criteria. This task is efficiently achieved by applying Shannon's entropy concept, which basically considers decision matrix contents as a specific source of information emitted through criteria to the DM. Entropy based method in turn computes unbiased relative criteria weights, and enable the final step – an application of the TOPSIS multi-criteria method to rank scenarios appropriately. Obtained ranking is considered the final result of proposed methodology.

The paper is organized as follows. In Section 2 we give relevant literature review relating to the topics contained in proposed approach. In Section 3 we present underlying assumptions and justifications for proposed methodology, followed by description of system performance indices defined as twofold entities: (1) scoring mechanism for scenarios, and (2) criteria in multi-criteria analysis. The section ends with multi-criteria part of the methodology: brief description of the entropy method for deriving criteria weights, and the TOPSIS method for ranking the scenarios. A case study application for selected reservoir system in Brazil is described in Section 4; 12 management scenarios are simulated and ranked in proposed way, and brief discussion is provided with regard to the results obtained by some other multi-criteria methods. The conclusions in Section 5 close the paper.

## 2. Literature Review

### 2.1. RIVER BASIN SIMULATION MODELS

Water resources management supported by computerized river basin simulation models has gained an increased attention in last few decades. Various approaches and techniques have been applied to manage conflicts in water uses, plan river basins development, or evaluate socio-economic consequences and environmental impacts of management strategies. Almost all existing single-criterion and multi-criteria optimization methods have been employed in this area, and it is hardly to say which direction in research has had more proponents. Obviously, there is not unique framework in which all-relevant information on water management topics could fit. This is mostly because management belongs or is closely related to economy, administration, law, business and other non-technical disciplines, as well to systems theory, hydrology, mathematics, operations research, all engineering etc. Therefore, only literature sources that closely relate to the problem will be referenced here; for more specific topics, pertinent literature will be given in succeeding sections.

Large scale water resources systems with surface reservoirs has been simulated since early 70-ties by various models (Loucks and Sigvaldason, 1982; Yeh, 1985; Simonovic, 1992; Wurbs, 1993). Worthily to mention are two important schools of modeling. The one established by Hydrologic Engineering Center, U.S. Army Corps. of Engineers, is well represented by models HEC-3 (HEC, 1972) and HEC-5 (HEC, 1979). Basically, both models simulate system operation in long-term period and use reservoirs' zoning to force withdrawals for downstream users. Priority schemes in water allocation are modeled indirectly, and overall system operation control is governed by balancing reservoirs with regard to their local zoning and associated downstream control points with specified demands. The other school has origins in Texas Water Development Board's projects in early 70-ties. It is characterized by modeling a reservoir system operation as the network LP problem, i.e. optimization and mixed simulation-optimization procedures for emulating system operation. Several models have been developed such as AL-IV, AL-V and SIM-IV, but most famous became SIMYLD-II (TWDB, 1972). This model simulates system operation on monthly basis. In each month original system's description (configuration and capacities, storage and non-storage characteristics), complete hydrology and preference structure of imposed demands are transformed into artificial capacitated closed network and solved as LP problem. Obtained optimal solution and other necessary data are used to define initial conditions for the next month and solving the new LP problem. This way, a SIMYLD-II run is a chain of successive monthly optimizations. Because the original multi-year problem of system operation is decomposed into isolated monthly problems, the model is generally considered as mixed simulation-optimization model.

A direct follower of SIMYLD-II model is the MODSIM model (Labadie, 1995), developed in Colorado State University in middle 80-ties. The later is established as powerful software system with friendly interface and additions for easy handling, connections with GIS and various database systems.

### 2.2. PERFORMANCE INDICES OF RESERVOIR SYSTEMS

In describing long-term behavior of water resources systems, most commonly used performance indices are reliability, resiliency and vulnerability. Although for some of these indices there is a variety of definitions (Askew, 1974; Fiering, 1982; Moy *et al.*, 1986; Srdjevic, 1987; Burn *et al.*, 1991; Azevedo *et al.*, 2000), those presented by Hashimoto *et al.* (1982) are most complete and commonly referenced in a literature; they will be briefly presented in next section. A risk as performance index is most often defined as opposite to reliability; however, it can also be defined in more specific way to indicate hazard in reservoir real-time operation (Burn *et al.*, 1991). As far guaranteed water as performance index is considered, an implicit stochastic model introduced by Simonovic (1987) performs the reservoir yield optimization when demand is not known. More traditional definition of firm yield has been used by Srdjevic (1987) in developing control strategies for reservoir systems. It was also shown that firm yield concept can be extended to enable determining a degree of firm yield risk; simplified approach in computing this indicator of system's performance is presented in the next section.

### 2.3. MULTI-CRITERIA TECHNIQUES

The central issue in ranking management scenarios by technical system's performance is how to preserve objectivity of the process, i.e. to reduce or eliminate influence of the DM. Possible means for accomplishing this are to apply a method for direct deriving the weights of importance of criteria based on only performance scores of scenarios, and then to perform multi-criteria analysis of the performance matrix to extract ordinal preference information – the final ranks of scenarios. In other words, if evaluation of scenarios pretends to be technically objective, weights of importance of criteria is necessary to obtain in some unbiased way before multi-criteria analysis is applied.

It was shown that criteria weights might be determined by only analyzing the data contained in decision matrix. Several methods based on Shannon's entropy (Shannon and Weaver, 1947) have been recently used to achieve the task (Cheng, 1996; Deng *et al.*, 2000), as well as several DEA models based on LP (Salminen *et al.*, 1998; Sarkis, 2000). Worthy to mention is also statistical method CRITIC (Diakoulaki *et al.*, 1995) that uses correlation analysis to detect contrast between criteria. Most of reported applications point necessity of managing sufficiently large discrete sets of alternatives in order to prevent violating statistical requirements on sample size. However, there is not consensus on how large the alternatives set should be.

A multi-criteria decision-making method TOPSIS (Hwang and Yoon, 1981) is proposed here for ranking scenarios after criteria weights has been derived by entropy method. For comparison purposes, two other methods were also used, namely modified TOPSIS (Deng *et al.*, 2000), and CP (Zeleny, 1982). All three are considered as 'ideal-point' methods that directly perform over the decision matrix by measuring scenarios' distances from ideal and negative ideal points (original and modified TOPSIS), or from utopia-point (CP). Other methods, however, might be used such as various additive and product methods (Faria *et al.*, 2002), AHP (Saaty, 1980), or outranking methods ELECTRE (Roy, 1968) and PROMETHEE (Brans and Vincke, 1985).

## 3. Methodology

### 3.1. STRUCTURE AND JUSTIFICATION

Simulation of system performance for given management scenario usually means prescribing a set of priorities in achieving system targets, preparing historical and/or generating hydrological series of data, and running proper river basin simulation model. Model may be instructed to record desired information on system states during simulation and in turn compute values of certain performance indicators. If direct computation is not possible, and this is the case in most existing models, post-processing of model's output may provide such information. However, repeated simulations for different management scenarios may significantly enlarge the set of indicators' values thus creating complicate analysis framework and imposing difficulties to recognize best or most desired scenario.

To resolve the problem, a methodology is proposed which enables evaluation of given set of scenarios in straightforward and consistent manner. It is structured as follows:

1. Adopt representative indices of system performance as instruments for scoring simulated scenarios. Consider indices as members of criteria set for multi-criteria analysis.
2. Describe and parameterize each management scenario as required by river basin simulation model.
3. Simulate system operation for each scenario, record performance indices (scenario scores) and keep track on other performance data. If necessary, compute indices by post-processing selected models' output.
4. Create decision matrix with columns corresponding to criteria (performance indices), rows corresponding to alternatives (scenarios), and entries being scores from step 3 for all scenarios across all criteria.
5. Apply entropy concept to recognize the emitting intensity of each criterion, and derive unbiased weights of relative importance of criteria.
6. Evaluate cardinal preference structure of the decision matrix by TOPSIS method, rank scenarios and adopt the top ranked as the optimal one in multi-criteria sense.

To tackle real long-term management situations, the following assumptions are adopted: (a) each management scenario represents a strategy in water allocation and is defined by consumptive and no-consumptive demands (specified by reservoirs' operating rules) and by prescribed demand priorities scheme; (b) water allocation is evaluated at local, sub system and/or system level on month-by-month basis; and (c) tolerant shortages are defined to distinguish favorable and unfavorable ('failure') system performance.

Performance indices have twofold role: (1) they measure effects of scenarios, and (2) they serve as criteria for ranking scenarios in multi-criteria environment. Measuring role encapsulates both spatial and temporal component of system operation. Spatial means that, in general, various and distant control points are selected where system performance will be monitored and checked if failures occur. Temporal component relates to division of criteria set into two subsets. The first consists of reliability, resiliency and vulnerability indices that are computed on monthly basis, and the second consists of shortage index, firm yield and degree of risk that are computed on annual basis.

An important task in evaluating the scenarios is to perform unbiased weighting of performance indices. Water management context itself highlights the notion of criteria weights related to some commonly accepted decision framework, which is not easy to achieve because of complexity and conflicts of social, economic, environmental and technical interests, as well as unpredictable parameters related to water availability and demands. The DMs involved in decision process usually have different attitudes and rarely may reach an agreement on the relative importance of system performance measures via a subjective weighting process. Another difficulty is that sometimes they are not available when needed, or their subjective weights are unreliable. Therefore, it is justified to undertake the weighting process independently of subjective preferences of the DMs. Logic behind is that each scenario is objectively described by its performance scores, and that scores in a decision matrix represent the source of information emitted to the DM. Any method capable to measure that information can be used to determine relative importance of each performance criterion afterwards. In other words, it is possible to recognize the relative weights of criteria by quantifying the intrinsic information emitted by each criterion through related scores contained in the matrix (Zeleny, 1982). Two fundamental notions are the contrast intensity, and the conflicting character of criteria; the latter is essential because certain performance indices are often highly correlated.

Due to verified success and robustness in different decision situations (Cheng, 1996; Deng *et al.*, 2000), the entropy method is suggested for accomplishing the task. Assuming context-dependent concept of information importance defined by Shannon and Weaver (1947), it is relatively easy to measure the 'information message' emitted by each scenario through generated output of simulation model and scenarios' scores across selected performance criteria, and finally determine desired relative criteria weights.

### 3.2. CRITERIA SET (SYSTEM PERFORMANCE INDICES)

It was shown that system's performance might efficiently be measured with respect to specified targets and preferences, whatever point of view is selected – local, regional or global. By defining tolerant shortages in supply, or acceptable deviations from prescribed reservoir storage targets, it is possible to identify so-called favorable and unfavorable system statuses and compute various indices of system performance (Hashimoto *et al.*, 1982).

In evaluating long-term operation of reservoir systems, several performance measures are in common use such as reliability, resiliency and vulnerability. In addition, we suggest three more traditional measures, namely shortage index, firm yield (guaranteed water), and degree of firm yield risk. Formal descriptions of performance indices are mostly problem dependent (e.g. Azevedo *et al.*, 2000; Burn *et al.*, 1991), each representing an attempt to capture certain part of complex information on system performance in a long time period. Definitions given below are in common use; therefore only brief overview will be presented for better understanding of the results obtained in the case study application described in Section 4. Notice that definitions of reliability, resiliency and vulnerability have been introduced in (Hashimoto *et al.*, 1982).

#### 3.2.1. *Reliability ($\alpha$)*

Reliability is a probability of not failing to achieve some target. For example, in water supply reservoir operation, it is probability that reservoir will not fail to deliver targeted water to specified customer. Here we define reliability of water supply as probability that system performance at given demand point is satisfactory if supply is within tolerant shortage (e.g. 10%). The higher value of $\alpha$, more reliable is the system.

#### 3.2.2. *Resiliency ($\gamma$)*

This performance index describes how quickly a system is likely to recover from failure, once failure has occurred. It relates to situations such as the following: the users of a water system that experience, say, five periods of failure within 12 months, with each shortfall followed by a period of no shortage, are likely to feel different impacts when compared to a situation of a shortage in five consecutive periods. The higher value of $\gamma$ indicates more resilient system. In cases there are not supply deficits, by definition system is considered fully resilient ($\gamma = 1$).

#### 3.2.3. *Vulnerability ($\nu$)*

In water management failures are very unlikely to be of the same magnitude and importance. A failure with a deficit of $0.5 \times 10^6$ m$^3$ day$^{-1}$ from a $10 \times 10^6$ m$^3$ day$^{-1}$ target does not present the same consequences as deficit of $5 \times 10^6$ m$^3$ day$^{-1}$ from the same target. We define vulnerability as a measure of how much deep is the system in unacceptable status once it went into that status. Vulnerable separation measure is defined as sufficiently high ratio of monthly shortage (e.g. 0.7 or 0.8) beyond which system is considered vulnerable. Higher is the value of $\nu$, more vulnerable is the system.

#### 3.2.4. *Shortage Index (λ)*

This index serves as an indicator of both frequency and quantity of annual shortages over multiyear periods (Srdjevic, 1987). If water demand during year $i$ is $d_i$, and total annual shortages is $s_i$, then shortage index may be defined as:

$$\lambda = \frac{100}{N} \sum_{i=1}^{N} \left( \frac{s_i}{d_i} \right)^2 , \tag{1}$$

where $N$ is the number of years in simulated period. This index is quadratic dependent on shortage quantity for the same frequency of shortage occurrence; for the same shortage quantity, it is a linear function of shortage frequency. Obviously, a system performance is considered better for lower values of $\lambda$.

#### 3.2.5. *Firm Yield (y)*

Firm yield is commonly computed at system outlet, or at selected demand point; in later case this is most often a demand specified at some reservoir. Firm yield is a volume of water guaranteed with acceptable shortage, which means that fixed volume of water is to be delivered from year to year with given monthly distribution and permitted small deficit such as 5%.

#### 3.2.6. *Degree of Firm Yield Risk ($\rho_y$)*

This performance index is closely related to the firm yield. Since $y$ in fact represents attainable annual demand, $\rho_y$ is the associated indicator of a risk of not satisfying it. In computing $y$ and its risk of attendance $\rho_y$, all annual shortages (including zero shortages) recorded during simulation must be taken into account. While $y$ should be maximized, $\rho_y$ should be minimized.

### 3.3. MULTI-CRITERIA FRAMEWORK

Building blocks of this part of a methodology are decision matrix, entropy method for weighting criteria, and multi-criteria method for evaluating decision matrix and pointing the best scenario.

3.3.1. *Decision Matrix*

If number of scenarios is $n$ and number of indices of system performance is $m$, the decision matrix $R = \{r_{ij}\}$ can be constructed as:

$$R = \begin{array}{c} \\ \\ A_1 \\ A_2 \\ . \\ . \\ A_n \end{array} \begin{array}{c} (w_1 \;\; w_2 \;\; . \;\; . \;\; w_m) \\ C_1 \;\; C_2 \;\; . \;\; . \;\; C_m \\ \left[\begin{array}{ccccc} r_{11} & r_{12} & . & . & r_{1m} \\ r_{21} & r_{22} & . & . & r_{2m} \\ . & & & & . \\ . & & & & . \\ r_{n1} & r_{n2} & . & . & r_{nm} \end{array}\right] \end{array}. \tag{2}$$

In our case scenarios are alternatives ($A_1$, $A_2$, ..., $A_n$), and performance indices are criteria ($C_1$, $C_2$, ..., $C_m$). Values ($w_1$, $w_2$, ... ,$w_m$) written above the matrix are an importance weights of criteria defined by DM, or derived in another way; they usually (but not necessarily) sum to 1. Entries $r_{ij}$ in (2) represent scenarios' scores with respect to criteria set.

3.3.2. *Entropy Method*

Entropy is generally understood as a measure of uncertainty in the information. By considering scores of alternatives as specific emitters of information about importance of each criterion, entropy approach enables measuring that source and determining the relative weights of criteria ($w_1$,$w_2$,..., $w_m$) in rather simple and straightforward manner. By additive normalization (3) of each column in matrix (2), a new matrix (4) is derived containing relative scores of alternatives across criteria.

$$x_{ij} = r_{ij} \left[ \sum_{k=1}^{n} r_{kj} \right]^{-1}, i = 1, 2, ..., n \tag{3}$$

$$X = \begin{array}{c} \\ A_1 \\ A_2 \\ . \\ . \\ A_n \end{array} \begin{array}{c} C_1 \;\; C_2 \;\; . \;\; . \;\; C_m \\ \left[\begin{array}{ccccc} x_{11} & x_{12} & . & . & x_{1m} \\ x_{21} & x_{22} & . & . & x_{2m} \\ . & & & & . \\ . & & & & . \\ x_{n1} & x_{n2} & . & . & x_{nm} \end{array}\right] \end{array}. \tag{4}$$

The information contained in matrix $X$ can be considered as 'emission power' of each criterion $C_j$ ($j$ = 1, 2,..., $m$), and used to compute an entropy value $e_j$:

$$e_j = -k \sum_{i=1}^{n} x_{ij} \ln x_{ij}, \; j = 1, 2, ..., m \tag{5}$$

Constant $k = 1/\ln n$ is used to guarantee that $0 \leq e_j \leq 1$. Degree of divergence $f_j$ of average intrinsic information contained in each criterion is calculated as:

$$f_j = 1 - e_j, \qquad j = 1, 2, \ldots, m. \tag{6}$$

It means that if more divergent are initial scores $r_{ij}$ of alternatives $A_i (i = 1, 2, \ldots, n)$ for given criterion $C_j$, the higher is its $f_j$ and more important is criterion $C_j$ for the problem. Consequently, if all alternatives have similar scores for given criterion, this criterion is less important for specific problem, and if all scores against this criterion are the same, criterion can be eliminated because it transmits no information to the DM.

If $f_j$ is considered as specific measure of inherent contrast intensity of the criterion $C_j$, final relative weights for all criteria can be obtained by simple additive normalization:

$$w_j = f_j \left[ \sum_{k=1}^{m} f_k \right]^{-1}, \; j = 1, 2, \ldots, m. \tag{7}$$

Because the criteria weights are obtained directly from the decision matrix, which means independently of the DM, this qualifies the entropy method as unbiased ('objective') evaluation procedure and the same may be adopted as valid for the result obtained – criteria weights $(w_1, w_2, \ldots, w_m)$.

### 3.3.3. *TOPSIS Method*

This is a method based on order preference by similarity to ideal solution (Hwang and Yoon, 1981). The underlying concept is that most preferred alternative should not only have shortest distance from 'ideal' solution, but also longest distance from 'negative-ideal' solution. Notice that similar concept has been pointed out by Zeleny (1982); in his approach, however, multidimensional distances are measured from so-called an 'utopia point'.

TOPSIS is rational and relatively simple. It evaluates a decision matrix (2) in several steps (Triantaphyllou and Lin, 1996) starting by normalizing columns of a decision matrix and then multiplying values in columns is by corresponding criterion's weights. TOPSIS then identifies best and worst value in each column and create two sets of these values across all columns named 'ideal solution' and 'negative-ideal solution, respectively. In the next step so-called separation measures for all alternatives are computed based on their Euclidean distances from ideal and negative-ideal solutions (across all criteria). Finally, the relative closeness to ideal solution is calculated for each alternative and alternatives are appropriately ranked. Top-ranked alternative is with the shortest distance from ideal solution and TOPSIS guarantees that it also has the longest distance from negative-ideal solution.

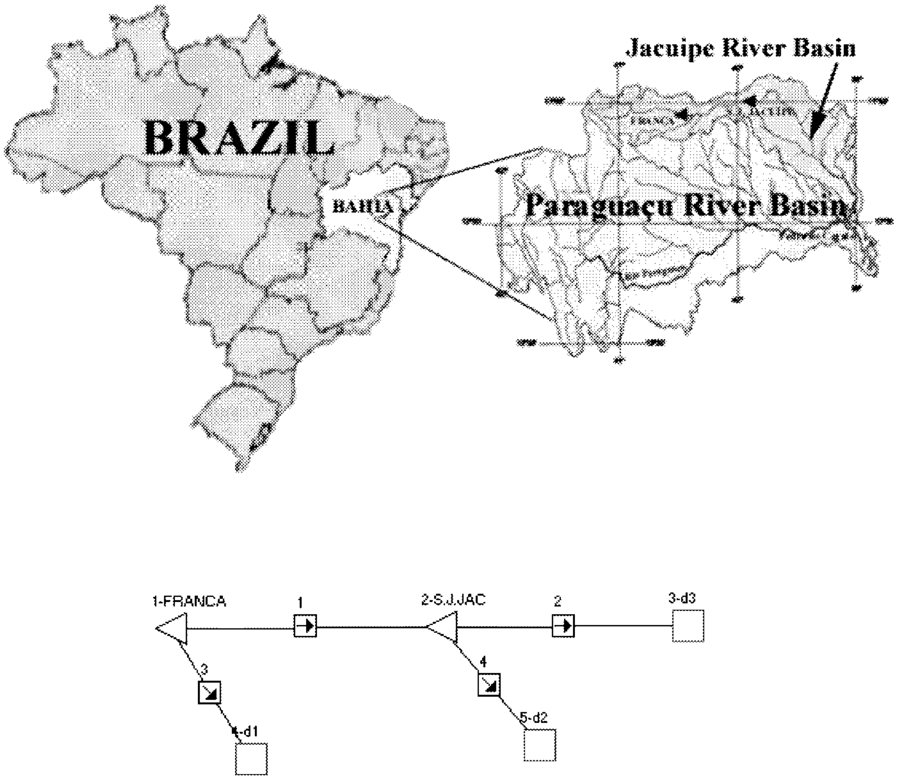


*Figure 1.* Reservoir system in Paraguacu River Basin.

## 4. Case Study Application

### 4.1. SYSTEM

A simplified water resources system is used to illustrate an approach. It consists of two reservoirs in cascade with two local demands and one control point at system outlet as shown in Figure 1. The reservoirs are built on the Jacuipe river in northern part of the Paraguacu river basin (the state of Bahia, Brazil) characterized by dominantly semi-arid hydro-climatic conditions. Both reservoirs are in operation for years, and there is an interest to improve their future use by investigating new long-term management scenarios.

Upstream reservoir Franca is of about 15 times smaller capacity then reservoir Sao Jose de Jacuipe (24 vs. 355 million $m^3$). Reservoirs have multiple purposes, however for illustrative purposes only municipal demands (d1 and d2) are considered. Demand at system outlet point (d3) is specified to assure downstream low flow augmentation.

*Table I.* Management scenarios

| Scenarios | Priorities | | | | | Demands [$10^6$ $m^3$] | | |
|---|---|---|---|---|---|---|---|---|
| | Demand points | | | Reservoirs | | Franca r. | S.J. de Jacuipe r. | System outlet |
| | d1 | d2 | d3 | r1 | r2 | d1 | d2 | d3 |
| 1 | 2 | 2 | 1 | 10 | 15 | 10.0 | 30.0 | 6.3 |
| 2 | 3 | 2 | 1 | 10 | 15 | 10.0 | 30.0 | 6.3 |
| 3 | 1 | 10 | 1 | 2 | 15 | 4.1($\gamma$)[a] | 30.0 | 6.3 |
| 4 | 2 | 2 | 1 | 10 | 15 | 10.0 | 6.8 ($\gamma$) | 6.3 |
| 5 | 3 | 2 | 1 | 10 | 15 | 10.0 | 6.9 ($\gamma$) | 6.3 |
| 6 | 3 | 2 | 1 | 10 | 5 | 10.0 | 12.0 ($\gamma$) | 6.3 |
| 7 | 2 | 2 | 1 | 10 | 15 | 4.1 | 6.9 | 12.6 ($\gamma$) |
| 8 | 2 | 2 | 1 | 15 | 15 | 4.1 | 12.0 | 6.3 |
| 9 | 3 | 2 | 1 | 15 | 15 | 4.1 | 12.0 | 12.6 |
| 10 | 2 | 3 | 1 | 15 | 15 | 4.1 | 12.0 | 9.5 |
| 11 | 2 | 2 | 1 | 2 | 3 | 4.1 | 12.0 | 9.5 |
| 12 | 2 | 2 | 1 | 10 | 15 | 5.0 | 15.0 | 6.3 |

[a] ($\gamma$) designates that at given demand point a firm yield was firstly computed and used as annual demand afterwards.

### 4.2. MANAGEMENT SCENARIOS

A set of 12 management scenarios is defined, Table I. Rows contain priority schemes and demand quantities which, together with physical characteristics of reservoirs and riverflows, determine water allocation preferences for different scenarios.

Priority numbers given in Table I have the following meaning: those associated with d1 and d2 are priorities of municipal demands supplied from reservoirs; a number associated with d3 is the priority of minimum flow requirement at system outlet; and numbers under r1 and r2 relate to reservoirs 1 (Franca) and 2 (S. J. Jacuipe) indicating priority in their refilling to maximum capacity. To establish complete priority scheme means to put together d1, d2, d3, r1 and r2 for each scenario and consider that the highest priority has the demand point with minimum integer number applied. For example, in Scenario 1 outlet demand has highest priority (d3 = 1), then municipal demands at both reservoirs should be satisfied with lower and equal priority (d1 = d2 = 2), and finally, reservoir 1 should be refilled before reservoir 2 (r1 = 10 > r2 = 15).

### 4.3. SIMULATING SCENARIOS AND CREATING THE DECISION MATRIX

The model MODSIM is used to simulate system operation for each scenario over period of 30 yr (2000–2030). Natural inflows into reservoirs and outlet point and unit net evaporations from reservoir surfaces were estimated based on historical data records for period 1930–1959. Annual demands for planning horizon 2030 are used during the whole simulation period, and uniform monthly distribution throughout the year was applied. In scenarios 3–7 some demands has been optimized as firm yield with prescribed 10% safe delivery probability.

All 6 criteria described in Subsection 3.2 are used to score the system performance. They are 'distributed' to local level so creating a set of 18 criteria, 6 for each control point (d1, d2, and d3). This way, detail monitoring of system behavior was enabled. By simulating scenarios with MODSIM, and by additional processing of some of its output files, performance scores are computed and transferred to the decision matrix shown in Table II. Notice that all scores are dimensionless except those representing a firm yield, which are given in millions of $m^3$ per year.

Local reliability and resiliency are computed with tolerant shortage of 10%. An extreme local shortage of 80% is specified to identify local vulnerability at demand points.

### 4.4. WEIGHTING THE CRITERIA

Relative importance weights for 18 local criteria are derived by using data in Table II and applying the entropy method (3–7). The results presented in Table III show that reliability criteria C5 and C6 do not emit any relevant information because there are no differences among scenarios; therefore, these two criteria could be deleted from further analysis. Aggregated weights' values by performance indices are presented in Table IV as indication of global system performance. Although this aggregation is not fully justified because it is performed a posteriori, it shows that entropy method preserve the same ordinal structure of global and local criteria.

Interesting to note is that shortage index received the highest relative weight at all demand points. At system level this value is 0.58, compared to second valued degree of firm yield risk with weight 0.18. The third important performance index is resiliency (0.13) and others are found to be meaningless in selecting the best scenario.

### 4.5. RANKING THE SCENARIOS

In the final stage TOPSIS method is used to evaluate scenarios. Entropy weights (EW) obtained for 18 local performance criteria are applied and the results are summarized in Table V. Scenario 8 is identified as the most preferred, followed by scenarios 7, 4 and 5. The worst three scenarios are 2, 1 and 11, which is easy to clarify by reviewing data and results contained in Tables I, II, and V.

In brief, best overall performance of the system may be achieved if it is operated under managing policy defined in scenario 8. It means safe total annual delivery of 22.4 million $m^3$ to demand points d1, d2 and d3. Quantities of 4.1 and 12 million $m^3$ per year can be delivered directly from reservoirs Franca and S. J. Jacuipe, respectively. Maximum degree of annual risk of such a supply is 9 and

*Table II.* Decision matrix

| sc. | Criteria | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Short index (Min) | | | Reliability (Max) | | | Resiliency (Max) | | | Vulnerability (Min) | | | F.Y. (demand) (Max) | | | Degree of risk (Min) | | |
| | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | C11 | C12 | C13 | C14 | C15 | C16 | C17 | C18 |
| | d1 | d2 | d3 | d1 | d2 | d3 | d1 | d2 | d3 | d1 | d2 | d3 | d1 | d2 | d3 | d1 | d2 | d3 |
| 1 | 7.93 | 8.81 | 5.77 | 0.87 | 0.87 | 0.90 | 0.23 | 0.15 | 0.30 | 0.94 | 0.93 | 0.73 | 10.0 | 30.0 | 6.3 | 0.84 | 0.93 | 0.76 |
| 2 | 10.21 | 8.06 | 5.77 | 0.84 | 0.87 | 0.90 | 0.16 | 0.15 | 0.30 | 0.96 | 0.87 | 0.73 | 10.0 | 30.0 | 6.3 | 1.00 | 0.88 | 0.76 |
| 3 | 0.03 | 9.71 | 0.09 | 0.99 | 0.86 | 0.99 | 1.00 | 0.08 | 1.00 | 0.50 | 0.82 | 1.00 | 4.1 | 30.0 | 6.3 | 0.10 | 0.95 | 0.16 |
| 4 | 4.36 | 0.03 | 0.04 | 0.93 | 0.99 | 1.00 | 0.19 | 0.50 | 1.00 | 0.81 | 0.50 | 1.00 | 10.0 | 6.8 | 6.3 | 0.79 | 0.10 | 0.08 |
| 5 | 4.53 | 0.03 | 0.02 | 0.93 | 0.99 | 1.00 | 0.19 | 0.50 | 1.00 | 0.85 | 0.50 | 1.00 | 10.0 | 6.9 | 6.3 | 0.79 | 0.09 | 0.08 |
| 6 | 37.44 | 0.03 | 0.02 | 0.33 | 1.00 | 1.00 | 0.19 | 0.50 | 1.00 | 0.65 | 0.50 | 1.00 | 10.0 | 12.0 | 6.3 | 0.65 | 0.09 | 0.08 |
| 7 | 0.21 | 0.21 | 0.03 | 0.99 | 0.99 | 0.99 | 0.67 | 0.67 | 0.67 | 1.00 | 1.00 | 1.00 | 4.1 | 6.9 | 12.6 | 0.25 | 0.25 | 0.10 |
| 8 | 0.03 | 0.10 | 0.02 | 1.00 | 0.99 | 1.00 | 1.00 | 0.67 | 1.00 | 1.00 | 0.33 | 1.00 | 4.1 | 12.0 | 6.3 | 0.09 | 0.18 | 0.08 |
| 9 | 2.41 | 2.36 | 1.74 | 0.97 | 0.97 | 0.97 | 0.17 | 0.17 | 0.18 | 1.00 | 0.92 | 0.82 | 4.1 | 12.0 | 12.6 | 0.83 | 0.83 | 0.72 |
| 10 | 1.08 | 1.13 | 0.56 | 0.98 | 0.98 | 0.99 | 0.29 | 0.29 | 0.40 | 1.00 | 1.00 | 1.00 | 4.1 | 12.0 | 9.5 | 0.57 | 0.58 | 0.41 |
| 11 | 47.65 | 2.55 | 0.00 | 0.32 | 0.96 | 1.00 | 0.15 | 0.15 | 1.00 | 0.89 | 0.77 | 0.00 | 4.1 | 12.0 | 9.5 | 1.00 | 0.87 | 0.00 |
| 12 | 1.88 | 1.88 | 1.15 | 0.98 | 0.97 | 0.98 | 0.22 | 0.30 | 0.25 | 1.00 | 0.90 | 0.88 | 5.0 | 15.0 | 6.3 | 0.75 | 0.75 | 0.59 |

*Table III.* Criteria weights derived by entropy method

| Weights | Criteria | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Shortage index | | | Reliability | | | Resiliency | | |
| | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 |
| EW | 0.193 | 0.156 | 0.234 | 0.010 | 0.000 | 0.000 | 0.062 | 0.039 | 0.031 |
| | Vulnerability | | | F.Y. (demand) | | | Degree of risk | | |
| | C10 | C11 | C12 | C13 | C14 | C15 | C16 | C17 | C18 |
| EW | 0.004 | 0.010 | 0.020 | 0.019 | 0.031 | 0.009 | 0.032 | 0.053 | 0.095 |

*Table IV.* Aggregated criteria weights

| Creteria | Aggregated EW |
|---|---|
| Shortage index | 0.583 |
| Reliability | 0.011 |
| Resiliency | 0.132 |
| Vulnerability | 0.034 |
| Firm yield (demand) | 0.059 |
| Degree of risk | 0.180 |

18%, respectively, which may be considered acceptable in semi-arid conditions of system operation. Uniformly distributed flow of 0.2 m$^3$ s$^{-1}$ (equivalent to 6.3 million m$^3$ yr$^{-1}$) at system outlet (d3) is guaranteed with maximum annual risk of 8%. Shortage index is near to zero for all three control points, which means that at annual level deficits of water are both minimal and seldom. Reliability of monthly deliveries with tolerant 10% shortage at control points is close to 100%, so real long-term risk is minimal. System is resilient with recovery time of one month at Franca reservoir and outlet, and 1.5 month at S. J. Jacuipe reservoir (clarify this by using reciprocals of related values contained in Table II).

In general, at all demand points high values for vulnerability index are obtained, which is a consequence of its rigorous definition. For example, in case of demand point d1 at Franca reservoir, only two deficits occurred in two consecutive months

*Table V.* Ranks of scenarios

| Scenario | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rank | 11 | 12 | 8 | 3 | 4 | 9 | 2 | 1 | 7 | 5 | 10 | 6 |

in 30 yr of simulation. The first was 5%, which is acceptable, and the second was 100%, which is considered failure performance at that point; consequently, vulnerability of 1 relates to this case. More relaxed formulation should decrease vulnerability values, but this was not intention in our study. Under scenario 8 reservoirs are simply ‘instructed’ to deliver all demanded waters with higher priority than to conserve it and refill, which is easy to clarify by examining priorities contained in Table I.

The scenario 7 is identified as second most preferred. Guaranteed deliveries are 4.1 and 6.9 million $m^3$ per year from two reservoirs in downstream order. However, guaranteed flow of 0.4 m3 $s^{-1}$ at system’s outlet is twice as big as minimum required flow. This means that system is able to provide safe additional downstream annual flow of about 6.3 million $m^3$ if direct deliveries from downstream reservoir S. J. Jacuipe are cut by 60% with respect to deliveries under scenario 8. Again, reservoirs are operated to deliver demanded waters with higher priority than to refill. However, after priority target deliveries at outlet and reservoirs are made, and there is still available water, conservation strategy is to store the water first in upstream reservoir Franca, and then in reservoir S. J. Jacuipe. In this way, Franca is considered to play a role of the reservoir in reserve. Since outlet point is controlled by both reservoirs with highest priority, performance indices for this point such as shortage index and degree of risk are expectedly the best.

There are a variety of possibilities in interpreting the results of multicriteria analysis. For example, scenario 4 is ranked as third the best. The only difference of this scenario and best scenario 8 is that demand at Franca reservoir is 2.5 times higher, and that system operation is forced to identify firm yield at downstream reservoir. Results contained in Table II indicate moderate increase of deficit indicators at upstream reservoir and minor changes in all other performance indices.

### 4.6. COMPARATIVE ANALYSIS

The results obtained by TOPSIS are compared with results obtained by two other multi-criteria methods: (1) modified TOPSIS, and (2) Compromise Programming (CP). All three belong to a class of ideal-point-distance methods and CP method is applied with adopted $p = 2$ metric.

By using standard and modified version of TOPSIS method it was possible to implicitly check sensitivity of the whole approach. Namely, standard version includes importance weights of criteria in early phase of analysis, while modified version does it later. In both cases ranking of scenarios is almost identical as shown in Table VI. CP method fully approved the results obtained by both TOPSIS methods.

Notice that scenario 8 is identified as the most preferred by all three methods, and that ordering for 6 top-ranked scenarios is the same. Small differences at lower orderings are meaningful.

*Table VI.* Ranking the scenarios by different methods

| Scenario | Method | | |
|---|---|---|---|
| | Topsis | ModTopsis | CP($p$ = 2) |
| 1 | 11 | 11 | 12 |
| 2 | 12 | 12 | 11 |
| 3 | 8 | 7 | 9 |
| 4 | 3 | 3 | 3 |
| 5 | 4 | 4 | 4 |
| 6 | 9 | 9 | 8 |
| 7 | 2 | 2 | 2 |
| 8 | 1 | 1 | 1 |
| 9 | 7 | 8 | 7 |
| 10 | 5 | 5 | 5 |
| 11 | 10 | 10 | 10 |
| 12 | 6 | 6 | 6 |

## 5. Summary and Conclusion

In a way, long-term managing the reservoir systems is a problem that may be analyzed and solved only if treated as multicomponent decision process. For given management scenario, which is commonly downscaled to related operating strategy, any forcing of the system to meet certain targets usually means system's failing to meet other targets. Hazard in system operation typically appears if misbalance of water availability and imposed water demands is significant. If several management scenarios should be evaluated, the requirement is to enable their comparison and ranking in consistent way, and provide means that identify best or most favorable one.

Simulation models, such as the MODSIM, which is used in our study, usually derive rich, but extensive information on system behavior, particularly if system is complex and simulation period is long. Cross-referencing information obtained for several scenarios is not easy because of inherent conflicts in reservoir control, which can be observed only after computing frequencies and magnitudes of water deficits, safe supplies, reliability, resiliency, or vulnerability at points of interest throughout the system. An improvement in one performance index at given point usually means deterioration of it or other indices at this or other points. Only multi-criteria approach can adequately manage such a complicate situations.

The purpose of this paper is to propose a framework for straightforward evaluation and ranking of a set of management scenarios. We show that various methods and techniques are possible to employ within unique multi-criteria environment. In its central part there is a decision matrix with management scenarios as decision alternatives and most common system performance indices as evaluating criteria. Values in a decision matrix are scenarios' scores obtained after comprehensive simulations are performed with river basin model and post-processing of its output is completed. A multi-criteria analysis then begins with deriving the weights of relative importance of evaluating criteria. This is accomplished by entropy method that measures an emission of information contained in the decision matrix. In particular way it corresponds to a situation when the decision maker is not available or his judgments are not reliable. Once criteria weights are derived, a multi-criteria method TOPSIS is used to rank scenarios. It belongs to a class of 'distance from ideal point' methods, and is particularly suitable for large decision matrices, i.e. large number of alternatives (scenarios). In principle, other methods might be used for this purpose.

For weighting criteria entropy method is proposed, which directly exploits information contained in scenarios' scores. Although there are other possibilities for achieving this, entropy approach has been proved as sufficiently reliable in identifying both contrast intensity and conflict of criteria and computing their weights appropriately. Its possible disadvantage is related to proper problem sizing, i.e. preserving that the decision matrix contains sufficiently large set of alternatives. In our study, for example, this requirement was satisfied because the number of scenarios was 12.

To conclude, this work represents an attempt to enable managing a large sets of scenarios for complex water management problems when the decision maker may easily be overburdened by amount and diversity of information generated by simulation model. The central issue is to preserve unbiased evaluation of scenarios by analysing system's performance as technical outcome of applied operating strategies. Case study application and presented results show that such an approach is comprehensive and confident in concept and relatively simple in computation.

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