

STATION RANKING BY ANALYTIC HIERARCHY PROCESS (AHP) IN A HYDROLOGIC MONITORING NETWORK REDUCTION PROBLEM

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ABSTRACT

Sustainable water resources management must take into account multiple users, multiple criteria, and multi objectives. Therefore, its success depends significantly on monitoring activities. Many countries have developed extensive water quality and quantity monitoring networks and expanded them to multi-site monitoring. Such a development eventually raises the question whether monitoring should be continued ever whereas it is constrained by increasing budgetary restrictions. These questions have led monitoring agencies to assess their current networks for efficiency and cost-effectiveness and to consolidate the networks while increasing their information productivity. The presented study is initiated in respect of the above questions to examine the Analytic Hierarchy Process (AHP) to assess existing networks for possible consolidation (reduction) of a monitoring network. The introduced method is applied to Gediz River Basin in Aegean Coast of Turkey. The results are evaluated with respect to the ten operational and three non-operational streamflow gauging stations and the answer to the question “which are those three stations to be closed?” is investigated.

1 INTRODUCTION AND BACKGROUND

Due to iterative complexity of recent water management problems, better analytical tools and methodologies are required to identify and evaluate alternative solutions for managing water resources systems. Accomplishment of this requirement depends essentially on information gathered on natural and environmental processes. Since data collection is the only way to retrieve such information, success of sustainable water resources management and exploitation depends on monitoring activities (Harmancioglu et.al., 1999). This need also forces policy and decision-makers to evaluate and review the existing monitoring networks to satisfy the enhanced data requirements on water quality and quantity in river basins.

Many countries have developed extensive water quality and quantity monitoring networks and expanded them to multi-site monitoring. Such a development eventually raises the questions whether they produce the expected information, and whether monitoring should be continued ever whereas it is constrained by increasing budgetary

restrictions. These questions have led monitoring agencies to assess their current networks for efficiency and cost-effectiveness and to consolidate the networks while increasing their information productivity.

The presented study is initiated in respect of the above questions to examine the Analytic Hierarchy Process (AHP) to assess existing networks for possible consolidation (reduction) of a monitoring network. The analytic hierarchy process uses a hierarchical value tree for decision aid, where the problems are decomposed into a hierarchical tree of alternatives and criteria. The approach enables an analytic design for the decision making problem through the ranking of decision alternatives with respect to their “performance” under various criteria and management targets. AHP may also be used to elicit weights of criteria through pair-wise comparisons by the principal eigenvector approach. The outcome of the application of AHP to a network reduction problem gives a hierarchical ranking of the operational and non-operational stations in a network in terms of defined monitoring objectives and station attributes. This situation provides a valid decision making ground for the planners (e.g., monitoring agencies) to assess the operational state of a monitoring station.

The study is particularly focused on the need expressed by the Electrical Works Authority (EIE) in Turkey towards assessment of the performance of their monitoring practices. The introduced method is applied to the streamflow monitoring network in Gediz River Basin in the Aegean Coast of Turkey. The results are evaluated with respect to the ten operational and three non-operational streamflow gauging stations and the answer to the question “which are those three stations to be closed?” is investigated.

2 ANALYTIC HIERARCHY PROCESS

The analytic hierarchy process is developed by Saaty (1980, 1994); it uses a hierarchical value tree for decision aid, where the problems are decomposed into a hierarchical tree of alternatives and criteria. In the “value tree” approach, the problem is presented in some connected levels constituted by objectives and criteria (Figure 1).

The basic features and levels of a decision value tree mentioned above are generally expressed in an iterative matrix format, which is called the “decision matrix”. A decision matrix is generally defined as an $(m \times n)$ matrix with a_{ij} elements that indicate the performances of each alternative (A_i , for $i = 1, 2, 3, \dots, m$) evaluated according to each criterion C_j (for $j = 1, 2, 3, \dots, n$) with the assigned weights of w_j .

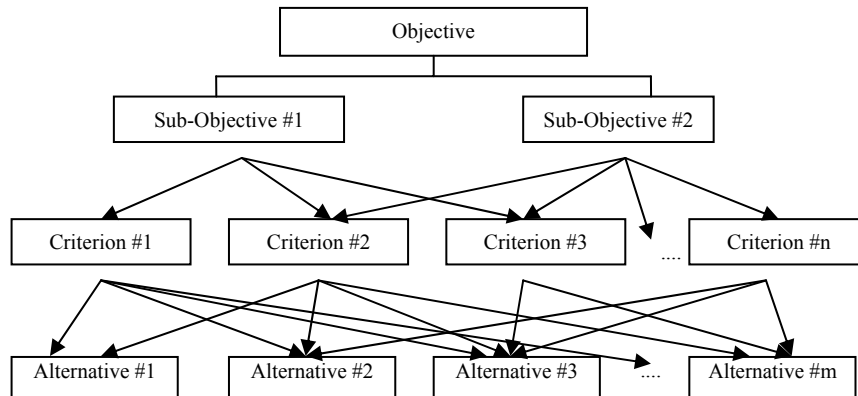


Figure 1- An example for a decision value tree.

AHP deals with these decision matrices where the matrix is constructed by using the relative importance of alternatives in terms of each criterion. The entry of a_{ij} , in an $(m \times n)$ decision matrix represents the relative value of alternative A_i in terms of the criterion C_j . The sum of a_{ij} for the j -th criterion is equal to 1, which is obtained through the division of each a_{ij} by the sum of a_{ij} for the j -th criterion. Then, in the case of maximization, the best alternative is determined by Eq. (1) (Triantaphyllou, 2000).

$$A_{(best)} = \max(or \min) \sum_{j=1}^n a_{ij} w_j \quad (1)$$

In order to deal with incommensurability issue in units of each different criterion, AHP uses relative a_{ij} values instead of actual ones; therefore, it can be used in multi-dimensional decision making problems as well. Generally, relative a_{ij} values are obtained through the division of every real a_{ij} value over the sum of the a_{ij} values indicated for any C_j criterion.

Weight elicitation through the Analytic Hierarchy Process (AHP) is based on paired comparisons and the use of ratio scales in preference judgements. The AHP uses a principal eigenvalue method to derive priority vectors (Saaty & Hu, 1998). The decision maker is asked to identify the ratio of attributes' weights through the use of a linear scale proposed by Saaty (1980) as shown in Table 1. The upper limit of the scale is set to 9, regarding the fact that most individuals cannot simultaneously compare more than seven (plus or minus two) objects (Miller, 1956; Triantaphyllou, 2000).

Table 1 Scale of relative importances according to Saaty (1980).

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective(s)
3	Weak importance of one over another	Experience and judgement slightly favour one activity over another
5	Essential or strong importance	Experience and judgement strongly favour one activity over another
7	Demonstrated importance	An activity is strongly favoured and its dominance demonstrated in practice
9	Absolute importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgements	When compromise is needed
Reciprocals of above nonzero	If activity i has one of the above nonzero numbers assigned to it when compared with activity j , then j has the reciprocal value when compared with i .	

In AHP, the decision maker is asked to define the r_{ij} ratio of attribute (objectives, alternatives) weights as:

$$r_{ij} = \frac{w_i}{w_j} \quad (2)$$

Fixed values of r_{ij} associated with verbal statements of Table 1 are used for purposes of comparison. Clearly, the selection of the comparison scale has an effect on the result; hence, the scale should be selected with careful attention. The AHP method presents the results of paired comparisons in the comparison matrix A as defined below:

$$\mathbf{A} = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nn} \end{bmatrix}$$

where the elements r_{ii} on the diagonal are assumed to be 1. Moreover, in the comparison process, only upper triangular matrix is demanded from the decision maker, and the lower triangular part is defined as

$$r_{ij} = \frac{1}{r_{ji}} \quad (3)$$

The weights w_i are estimated by normalising the elements of the eigenvector corresponding the largest eigenvalue of the matrix A. For n weights (values), the decision-maker makes n(n-1) estimates; and a consistent weighting procedure should possess the property that any r_{ij} is equal to the multiplication of r_{ik} and r_{kj} of the ratio of the k-th activity over the i-th and the j-th (Eq. 4):

$$r_{ij} = r_{ik} \times r_{kj} \quad \text{for } i, j, k = 1, 2, 3, \dots, n \quad (4)$$

Since the matrix A has rank 1 and $\lambda = n$ is its nonzero principal right eigenvalue, then the following equation can be written:

$$\mathbf{A} \times \mathbf{x} = n \times \mathbf{x} \quad (5)$$

where x is a principal right eigenvector. Considering Eq. 2; Eq. 5 takes the form of;

$$\sum_{j=1}^n r_{ij} w_j = \sum_{j=1}^n w_i \quad \text{or} \quad \mathbf{A} \mathbf{W} = n \mathbf{W} \quad \text{for } i = 1, 2, 3, \dots, n \quad (6)$$

where n is the number of elements to be compared.

In real life applications, the pairwise comparisons are not perfect, and the ratio r_{ij} may deviate from the real values; this situation leads Eq. (4) to an inequality. Considering the matrix A, it is now a “perturbation” of the consistent case, and the maximum eigenvalue is close to but greater than n with the slight change of r_{ij} ratios (Triantaphyllou, 2000). Saaty (1980) claims that one should find an eigenvector corresponding to the maximum right eigenvalue $\lambda_{\max}$ as in Eq. (7) to find the weights in such a non-consistent situation,

$$\mathbf{A} \mathbf{W} = \lambda_{\max} \mathbf{W}, \quad \text{where } \lambda_{\max} \geq n \quad (7)$$

Saaty proposed to estimate the reciprocal right eigenvector W by multiplying all

elements in each row of matrix A and taking the n-th root. An average perturbation value is then given by consistency index, CI as:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (8)$$

Then, the inconsistency of the weight estimates w_i given by the decision maker can be measured by the consistency ratio index, CR:

$$CR = \frac{CI}{RCI} \quad (9)$$

Here, RCI (Table 2) denotes the average random consistency index obtained from a sample of size 500 of randomly generated reciprocal matrices with entries derived from the scale $1/K, 1/(K+1), \dots, 1, \dots, K-1, K$, where K is a positive constant giving the bounds for the real weights. If this approach yields a CR value greater than 10 %, then a re-examination of the pairwise judgments is recommended until a CR less than or equal to 10 % is obtained (Triantaphyllou, 2000). Dietrich & Hämäläinen (2002) indicate this ratio as 20 %.

Table 2 RCI values of sets of different orders n (Triantaphyllou, 2000).

N	1	2	3	4	5	6	7	8	9
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Re-examination of the inconsistent matrix is realized through partial evaluation of pairwise judgments, i.e, the decision maker is initially forced to re-evaluate the highest preference comparison. If the decision maker does not change his value of relative importance, one considers the second highest inconsistent judgment and repeats the process until a near consistent matrix is reached (Saaty, 2003).

3 APPLICATION OF AHP TO A HYDROLOGIC MONITORING NETWORK REDUCTION PROBLEM: GEDIZ RIVER CASE

Streamflow gauging in Gediz basin was initiated in 1938 by EIE in order to obtain data for the planning and construction of the Demirkopru Dam. In 1941, EIE started to operate two more SGS and developed the network into 13 stations until 1978. At present, three of these stations are closed so that only 10 SGS of EIE have remained operational (EIE, 2003).

Figure 2 lists both the operational and the closed 13 EIE streamflow gauging stations (SGS) along the Gediz River. Reduction of the EIE network from 13 to 10 as presented in Figure 2 is the primary concern of the case study presented herein.

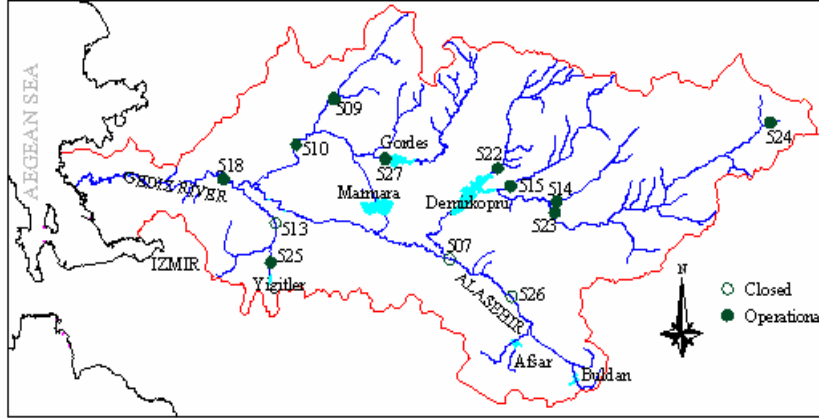


Figure 2. EIE monitoring stations evaluated in analyses.

The overall “objective” is set as the “reduction of the monitoring network” under criteria defined below. The stream gauging network in the basin includes different types of stations operated for varying purposes. Thus, there exists more than one management criteria for the network, the most important ones being: a) *Flood Management (FM)*; b) *Assessment of Water Potential (AWP)*; and c) *Modeling and Allocation Management (MAM)*. Those three criteria for the network reduction problem indicate the performance of stations in the network. Furthermore, such criteria are represented by station attributes identified below.

The set of attributes are chosen as; *Length of the observation period (Oper)*: This refers to the total observational period of a station in terms of years. *Continuity (Cont)*: The continuity of a station is defined as:

$$Cont = 1 - \frac{DWO}{TD} \quad (10)$$

where DWO is the “days without observation” and TD is the “total number of the days in observation period; *Technology (Tech)*: This attribute defines the monitoring technology used at the station such satellite remote sensing, limnigraph etc. The value is 0 for old-style conventional stations or 1 for stations with limnigraphs as in the Gediz case of the EIE network; *Project orientation (Pro)*: This attributes takes on the value 0 for stations which are not supposed to collect data for a specific project and 1 for vice versa; *Coefficient of variation of observed floods (Cv)*: This is the Cv value of the observed floods at the station; *Coefficient of skewness of observed floods (Cs)*: This is the Cs value of the observed floods at the station.

The set of attributes mentioned above are used in AHP, and their normalization is carried out by dividing their values by the total sum of the attribute values. For the Gediz case, the selected attributes are used to determine the values of the criteria for each station. In order to define the contribution of the SGS to a specific monitoring objective, the attributes are classified in terms of the criteria as shown in Fig. 3 below. Some attributes, such as “technology”, “length of observation period” etc., contribute to more than one criterion, whereas some others such as “project orientation” and “coefficient of skewness of observed floods” are unique for particular criteria. Next, the

stream gauging stations are interpreted as the “decision alternatives”, and the decision value tree for the network reduction problem is constructed as in Fig. 3. The decision weights for each attribute and criteria are set equal to each other.

The computations for each hierarchical level in the decision value tree are carried out following the sample given in Fig. 4. The resulting matrix indicates the total performance of stations within the network with respect to the defined criteria, attributes and their assigned weights. Accordingly, the station with the highest value has the first rank and the station with the lowest value has the least priority in the network. The ranking order of the stations is given in Table 3.

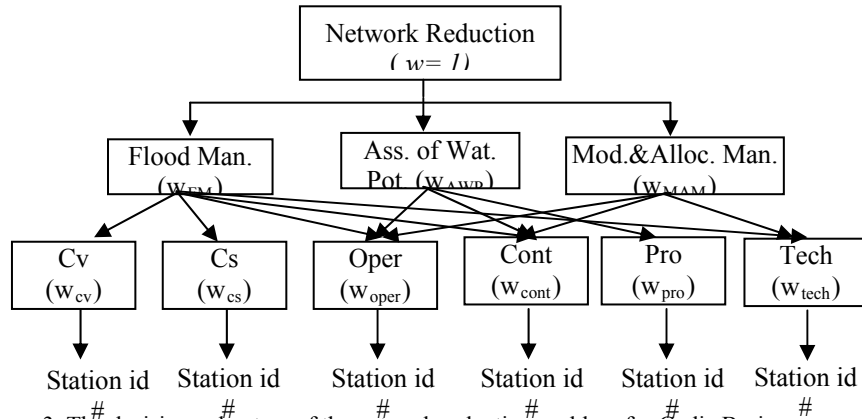


Figure 3. The decision value tree of the network reduction problem for Gediz Basin.

Station / Attr.	Cv	Cs	Tech	Oper	Cont			FM
507	0.076	0.087	0	0.027	0.046			507 0.047
509	0.071	0.056	0	0.115	0.074			509 0.063
510	0.085	0.070	0.111	0.115	0.069			510 0.090
513	0.050	0.015	0.111	0.014	0.088			513 0.056
514	0.077	0.051	0.111	0.101	0.085			514 0.085
515	0.065	0.032	0	0.099	0.085			515 0.056
518	0.054	0.028	0.111	0.107	0.088			518 0.078
522	0.071	0.068	0.111	0.082	0.077			522 0.082
523	0.072	0.091	0.111	0.085	0.087			523 0.089
524	0.087	0.130	0.111	0.077	0.088			524 0.099
525	0.106	0.151	0.111	0.068	0.086			525 0.104
526	0.088	0.079	0	0.052	0.060			526 0.056
527	0.099	0.141	0.111	0.058	0.066			527 0.095

Station / Attr.	Pro	Oper	Cont				AWP
507	0	0.027	0.046				507 0.024
509	0	0.115	0.074				509 0.063
510	0	0.115	0.069				510 0.061
513	0	0.014	0.088				513 0.034
514	0	0.101	0.085				514 0.062
515	0	0.099	0.085				515 0.061
518	0	0.107	0.088				518 0.065
522	0	0.082	0.077				522 0.053
523	0	0.085	0.087				523 0.057
524	0.333	0.077	0.088				524 0.166
525	0.333	0.068	0.086				525 0.162
526	0	0.052	0.060				526 0.037
527	0.333	0.058	0.066				527 0.152

Station / Attr.	Tech	Oper	Cont				MAM
507	0	0.027	0.046				507 0.024
509	0	0.115	0.074				509 0.063
510	0.111	0.115	0.069				510 0.098
513	0.111	0.014	0.088				513 0.071
514	0.111	0.101	0.085				514 0.099
515	0	0.099	0.085				515 0.061
518	0.111	0.107	0.088				518 0.102
522	0.111	0.082	0.077				522 0.090
523	0.111	0.085	0.087				523 0.094
524	0.111	0.077	0.088				524 0.092
525	0.111	0.068	0.086				525 0.088
526	0	0.052	0.060				526 0.037
527	0.111	0.058	0.066				527 0.078

Figure 4. Computation of station ranks for the network reduction process by AHP.

Station / Attr.	FM	AWP	MAM			Network Reduction		
507	0.047	0.024	0.024	×	$\begin{vmatrix} 0.3333 \\ 0.3333 \\ 0.3333 \end{vmatrix}$	=	507	0.032
509	0.063	0.063	0.063				509	0.063
510	0.090	0.061	0.098				510	0.083
513	0.056	0.034	0.071				513	0.054
514	0.085	0.062	0.099				514	0.082
515	0.056	0.061	0.061				515	0.060
518	0.078	0.065	0.102				518	0.082
522	0.082	0.053	0.090				522	0.075
523	0.089	0.057	0.094				523	0.080
524	0.099	0.166	0.092				524	0.119
525	0.104	0.162	0.088				525	0.118
526	0.056	0.037	0.037				526	0.043
527	0.095	0.152	0.078				527	0.109

Figure 4 (cont.). Computation of station ranks for the network reduction process by AHP.

The results show that stations 507, 513 and 526 have the lowest priorities so that, if the network is to be reduced to 10 stations, these three stations are the ones to be closed.

Table 3. Results of decision value tree approach by AHP.

Station No:	524	525	527	510	514	518	523
Score	0.119	0.118	0.109	0.083	0.082	0.082	0.080
Ri	1	2	3	4	5	6	7
Station No:	522	509	515	513	526	507	
Score	0.075	0.063	0.060	0.054	0.043	0.033	
Ri	8	9	10	11	12	13	

To demonstrate the use of ratio scales in preference judgements in AHP, three criteria, i.e., “flood management”, “assessment of water potential” and “modeling & allocation management”, are evaluated within a preference matrix through the use of Saaty’s scale explained in Table 1. Figure 5 demonstrates the computation of weights in a preference matrix. The values are obtained by the eigenvalue approach as explained in second section.

$$\begin{array}{c|ccc} & FM & AWP & MAM \\ \hline FM & 1 & 1/7 & 1/9 \\ AWP & 7 & 1 & 1/2 \\ MAM & 9 & 2 & 1 \end{array} = \begin{array}{c|ccc} & FM & AWP & MAM \\ \hline FM & 1 & 0.1429 & 0.1111 \\ AWP & 7 & 1 & 0.5 \\ MAM & 9 & 2 & 1 \end{array} \Rightarrow$$

$$\begin{array}{c|c} & w_{ij} \\ \hline FM & 0.057 \\ AWP & 0.346 \\ MAM & 0.597 \end{array} \Rightarrow$$

$$\lambda_{\max}=3.0217 \quad CI=0.011 \quad CR=0.018 \leq 0.10$$

Figure 5. Computation of weights derived from the preference matrix as defined by the AHP scale.

The preference matrix constituted has the maximum eigenvalue of 3.0127; the consistency index CI and the related consistency ratio index CR are computed through Eqs. 8 -9 with the help of Table 2. The CR value obtained is lower than 0.10; therefore the preference matrix is considered as a “consistent” one. Although there are slight changes in ranking of the stations, the lowest values are again encountered for the same three stations 507, 513 and 526.

4 CONCLUSIONS

The common criticism on multi-criteria decision making methods is that they focus on the adoption of a stance of a “given problem”. This criticism is also valid for the AHP methodology; yet, it provides some advantages to designers and decision makers. In particular, once the related attributes are defined and their weights are assigned, the assessment of the hierarchical priority order of the stations (alternatives) by the decision matrix approach simplifies the computations and enables rapid results. Similarly, despite its complex structure, the decision value tree approach enables a better understanding of the nature of the problem and the relevant criteria.

AHP obligates a close and interactive relation between the designer and the decision maker. This fact enables the acquisition of “desired” results rather than “forced” ones, which are perhaps the best solutions but do not reflect the tendencies and preferences of the decision makers. Moreover, the results obtained through the application of AHP are in order of priority; therefore, decision makers can be more confident in evaluating the results and can take the necessary steps to accomplish improvements towards their “desired” solution.

On the other hand, the AHP approach as applied for network assessment and reduction problem possesses the same disadvantages and deficiencies of the general methodology of AHP. The eigenvalue-eigenvector approach of the method is still controversial in literature and there is a certain degree of opposition to the approach.

Another issue to be stressed here is related to the difficulties in weight elicitation in AHP applications. In some cases, the inconsistent nature of human rationality is reflected in the preference matrix derived through the identified relative importance scale. In the case of an inconsistently elicited preference matrix, the designer should

enforce the decision maker to re-examine his/her preferences with respect to the same relative importance scale. Although this situation enforces the decision maker for more realistic statements, it may also lead to a dead end for the preference matrix. Another difficulty in weight elicitation emerges with an increase in the number of criteria considered, as this increase complicates the derivation of the preference matrix. Furthermore, in case of an inconsistent matrix, the re-examination of preferences becomes more difficult for the decision maker.

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