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The Use of an Optimization Method in Assessment of Water Quality Sampling Sites

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Abstract: This paper examines the application of an optimization method that can be used to assess an existing water quality monitoring network with respect to its sampling sites. The method uses dynamic programming to evaluate the reduction of the number of sampling sites in a basin with respect to different monitoring objectives. The methodology is demonstrated in the case of the Gediz River basin in western Turkey.

Key words: water quality monitoring, network design, sampling sites, optimization, dynamic programming.

1. INTRODUCTION

Allocation of sampling sites is the initial and the most crucial step of the water quality monitoring network design and redesign process. Several different approaches have been used within the last 20-30 years in the selection of sampling sites. A review of these investigations and practices shows that the establishment of a multi-site monitoring network is still a controversial issue requiring further research.

The basic problem with multi-site monitoring is the realization of representative sampling. This means to select the sampling points in such a way that the river reach investigated is the best represented by these sites. If this approach can be realized, then the variability of water quality along the reach may be assessed for management and control purposes. Yet, there are no standard design procedures to accomplish such a network. Often, one has to refer to subjective judgments and assumptions in making his selection of sampling sites. Yet, there are some scientific methods which may help to minimize the subjective aspects of design, or which may, at least, provide guidelines for an effective design procedure. Currently, none of these methods seem to be widely accepted. They require further investigations to be justified for use in practice.

This paper examines the application of an optimization method that can be used to assess an existing water quality monitoring network with respect to its sampling sites. The method uses dynamic programming to evaluate the reduction of the number of sampling sites in a basin with respect to different monitoring objectives. The methodology is demonstrated in the case of the Gediz River basin in western Turkey.

2. ASSESSMENT OF SAMPLING SITES BY AN OPTIMIZATION METHOD

2.1 Background

The State Hydraulic Works (DSI), one of the major monitoring agencies in Turkey, has recently started to question the performance of its existing networks with respect to both efficiency and cost-effectiveness. Accordingly, DSI and DEU (Dokuz Eylul University, Turkey) have initiated cooperation in a research project towards assessment and the redesign of the monitoring network in the Gediz River basin. This project is essentially a pilot study where the efficiency of various network assessment procedures are tested. Icaga (1998) has carried out the preliminary studies for the above project, where he employed an optimization method to assess the locations of sampling stations in the Gediz River basin.

The optimization methodology employed here comprises the use of dynamic programming for systematic consolidation of a fixed station water quality monitoring network. The method has been used earlier by Lettenmaier et al. (1984) to consolidate the fixed trend detection baseline monitoring network of the Municipality of Metropolitan Seattle, USA, from 81 to 47 stations at annual savings of about $33,000. The case study presented here expands on this previous work by generating alternative monitoring scenarios with respect to different management objectives. As such, the methodology is used here as an assessment and redesign technique.

Water quality in the Gediz River has been observed by DSI at a number of sites since 1980. These observations started at 6 locations which still continue to operate. As of 1990, the number of surface water monitoring sites was increased to 33 to carry out specific surveys required by the protocol between the Ministry of Environment and DSI. The sampling sites were selected on the basis of Water Pollution Control Regulation issued in 1991 (DSI, 1993). Figure 1 shows the locations of the total 33 stations together with their drainage areas. After 1993, DSI reduced the number of sampling sites to 14. The application presented here covers an assessment of alternative combinations of monitoring sites when a total of 14 stations are to be retained in the network.

Monthly (or bimonthly for some variables) sampling frequencies are applied at all sampling locations. About 35 variables are observed at each station, including physical parameters as well as common ions, nutrients, Do, pH, alkalinity, and trace metals.

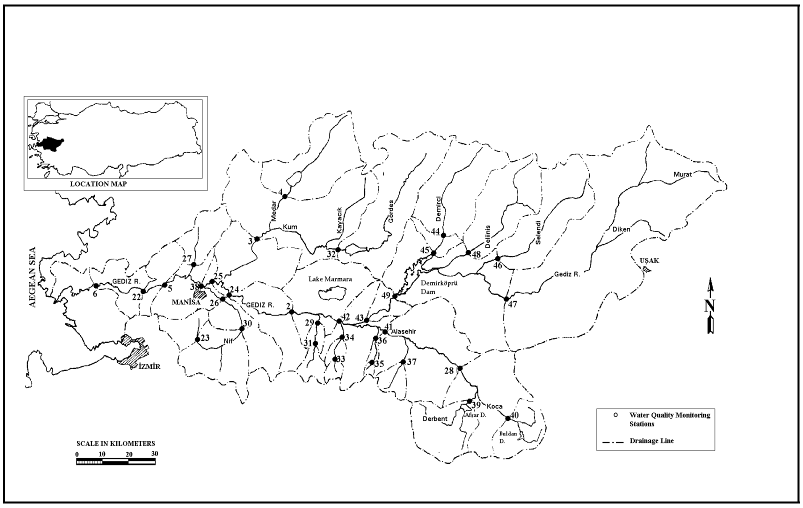

Figure 1. Locations of the 33 water quality monitoring stations in the Gediz River basin.

2.2 Applied Methodology

2.2.1 General Approach

Consolidation of a sampling network requires first the delineation of objective criteria for comparing the significance of stations. These criteria are used in priority listing of stations. Once this priority ordering is accomplished, selection of the n highest ranked stations to be retained in the reduced network can be realized. The major difficulty in this process is that the elimination of any one station may affect the attributes of the other stations.

The criteria to be used for ordering stations are essentially based on water quality management objectives in a basin. In the case investigated by Lettenmaier et al. (1984), the objectives of the

Municipality of Metropolitan Seattle had been to protect and enhance swimmability and fishability of the waters within the selected drainage basins. Thus, such criteria as swimmability and fishability indices, drainage area, number of jurisdictions within the accounting area of each station, and length of historic record as the total number of months in which samples had been collected were selected as quality attributes or indicators. The station retention algorithm described by Lettenmaier et al. (1984) uses a weighted sum of transformed values of the above criteria. The specific values of the criteria associated with the stations considered for retention are called station attributes and are denoted by "l" as the attribute index.

In the presented case study, the above methodology is modified in the sense that alternative basin water quality management objectives and criteria relevant to each objective are selected. The three objectives considered are the management of: (a) point source pollution in a basin stemming from domestic and industrial discharges; (b) nonpoint source pollution resulting basically from agricultural and irrigation practices; and (c) both point and nonpoint source pollution. The application of the methodology gives the optimum combination of stations in a reduced network for each management objective.

The basic steps to be covered in the optimization procedure are shown in Fig.2. The station allocation algorithm is employed in two steps. First, the basin is divided into subbasins or "primary basins", and for every primary basin, the algorithm determines the preferred sets of station combinations for each possible number of stations ranging from zero to the pre-existing number of stations. There may be very large numbers of station combinations; therefore, a method based on stream order numbers (Sharp, 1970) is used to limit the number of alternative station configurations within each primary basin. Thus, the preferred sets of station combinations are determined by maximizing the sum of the stream order numbers for each station retained and, for a fixed number of stations, by breaking ties through maximizing the score sums for weighted (transformed) attributes. In the second step, dynamic programming, using primary basins as stages, and stations within each primary basin as states, determines the combination of station allocations to the various primary basins, resulting in a total network of given size having maximum total score. The total score here is the sum of station scores within each primary basin for the selected station configurations determined in the first step.

The main difficulty in the above station selection process is that the elimination of any one station may affect some or all of the attributes of the other stations. Within this respect, stations reflect dependence, a factor which affects the rank of any one station in the priority listing since its attributes are affected. If one disregards this dependence in the station selection process, he may miss the most important stations and select the less important ones. The optimization algorithm used essentially determines the most significant stations by considering the dependence among stations.

The preliminary steps of the methodology cover two tasks:

a) basin identification, where primary basins are selected, dependence among stations is investigated and possible station combinations are determined according to the given reduced size of the network;
b) data preparation, where attributes (l) and their scores are determined. For each l, the score must be uniformly distributed so that the dominance of the score by any one attribute on the basis of its relative magnitude alone can be avoided. Thus, in this step, scores are normalized (if they are nonnormal) and further uniformized.

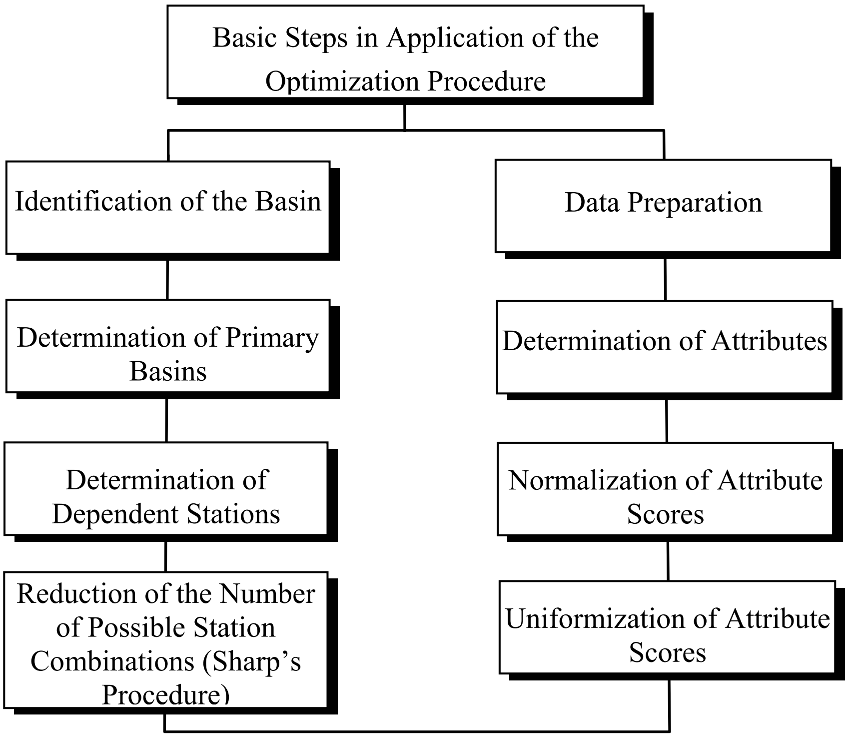

Figure 2. Basic steps in application of the dynamic programming procedure.

Once the above two steps are completed, Sharp's (1970) procedure is used to reduce the number of alternative combinations of stations. Finally, dynamic programming is used to select the most significant stations for the total network.

2.2.2 Identification of the Basin

The network reduction problem is approached first by dividing the river basin into N primary basins with k denoting the primary basin index as $k = 1, ..., N$. Basin properties such as topography, hydrology, geology, meteorology, land use, industry, population density, junctions of tributaries, etc., may be used as criteria for segregating the basin into primary basins. Such criteria assure that stations with similar properties are considered within the same primary basin. One criterion that must be satisfied is that each primary basin must have at least one monitoring station. Regarding each primary basin k, P_k denotes the pre-existing number of stations in the k^{th} primary basin and R_k, the number of stations to be retained in that primary basin.

Once the total basin is divided into primary basins, it is necessary to identify the dependence between stations in the same primary basin. Such a dependence is one of an upstream-downstream relationship.

2.2.3 Alternative Combinations of Stations

If the entire river basin is considered when determining the possible combinations of stations to be retained, the number of alternative combinations can be found as Binomial coefficients $C\,(TP_N;\,TR_N)$:

$$C\,(TP_N, TR_N) = \binom{TP_N}{TR_N} = \frac{TP_N!}{TR_N!(TP_N - TR_N)!} \tag{1}$$

where TP_N is number of the pre-existing number of stations in entire basin and TR_N , the number of stations to be retained in the total network. When Binomial expansion is used, the number of alternative station combinations increases significantly, depending on TP_N and TR_N (Icaga, 1998).

Once the basin is separated into N primary basins with $k=1,..., N$, each primary basin will have P_k number of stations which is a part of the total number (TP_N) of pre-existing stations in the entire basin:

$$TP_N = \sum_{k=1}^{N} P_k \tag{2}$$

When TR_N is defined as the resulting total number of stations, the number of stations to be retained in the k^{th} primary basin will be R_k.:

$$TR_N = \sum_{k=1}^{N} R_k \tag{3}$$

Then, the number of alternative combinations number will be:

$$C(P_k; R_k) = \frac{P_k\,!}{R_k\,!(P_k - R_k)!} \tag{4}$$

when P_k and R_k values are placed in Eq. (1). Since the number of stations to be retained in the k^{th} primary basin is not known at the beginning,

$$R_k = 0,\ 1,\ 2,\ ...\ P_k \tag{5}$$

so that the total alternative station combinations in primary basin k will be calculated, using Eqs. (4) and (5):

$$TASC_k = \sum_{R_k=0}^{P_k} C(P_k; R_k) = 2^{P_k} - 1 \tag{6}$$

where, $TASC_k$ is the total number of alternative station combinations in primary basin k. Since R_k in any one primary basin k is dependent upon R_k of other primary basins (Eq. (3)), the total number of alternative station combinations in the entire basin will be:

$$TASC = TASC_1 \text{ x } TASC_2 \text{ x ... x } TASC_N$$

or (7)

$$TASC = \prod_{k=1}^{N} TASC_k$$

It is quite evident that the *TASC* will assume a very high value depending on the $TASC_k$ values. Therefore, it is necessary to decrease the number of station combinations in each primary basin. Lettenmaier *et al.* (1984) suggest the use of a method based on stream order numbers (Sharp, 1970) to limit the number of alternative station combinations considered within each primary basin.

2.2.4 Preparation of Data

Determination of Attributes for Monitoring Stations

Each station in a monitoring network must be identified with its attributes (l) that comply with management objectives in the basin. Regarding the three management objectives hypothesized for Gediz basin, 6 basic attributes are defined as they relate to the above objectives:

a) *Drainage area (DrA):* drainage area acts as a surrogate for accountability of stations; they are also significant in terms of nonpoint pollution;
b) *Population (Pop):* This attribute is significant with respect to domestic point pollution.
c) *Irrigation area (IrA):* Irrigation areas that lie within the drainage area of a station contribute to nonpoint source pollution reaching that station;
d) *Number of observations (SNum):* Number of historic samples collected at a station is significant in terms of the information produced by that station; thus, stations with higher numbers of observations are preferred;
e) *Length of the observation period (OPer):* This refers to the total observational period of a station. Similar to (d) above, stations with longer periods of records are preferred;
f) *Quality variables (Qsum):* This attribute refers to the average values of the quality variables observed at a station: different variables may be selected as attributes with respect to different management objectives.

The above attributes are defined by their numerical values (or scores). These scores are represented by $SR_{j(i)kl}$ with k representing the primary basin index; l, the attribute index; i, the station index within primary basin k; and $j(i)$, index number of the i^{th} station in primary basin k. The determination of the numerical values for the first 5 attributes is straightforward. For the last attribute, appropriate water quality variables must be selected to comply with management objectives. The selection process is also complicated due to the presence of a large number of variables observed at each station.

Once water quality variables are selected and all attributes $SR_{j(i)kl}$ are identified, the significance of each attribute (or the preference to be given to each) must be specified. This is done by assigning weights w_l to each attribute. The selection of attribute weights is subjective and reflects different management concerns. Essentially, the stations to be allocated within each primary basin are a function of the weights; therefore, the sensitivity of station allocation to different weights may be tested (Lettenmaier *et al.*, 1984).

Selection of Water Quality Variables

There is basically no standard approach in selecting the quality variables to be considered in the station allocation procedure. Thus, for purposes of this study, possible alternative selection schemes are investigated, including water pollution control regulations in Turkey.

In a study by Lettenmaier *et al*. (1991) on determination of temporal trends in water quality, water quality variables are divided into a number of constituent groups where the relationship between these groups and the sources that lead to such pollutants, which they call explanatory variables, are also given. For purposes of this study, a similar classification of constituents is adopted as an appropriate means of selecting water quality variables that best represent the explanatory variables since the latter relate fairly well to management objectives. In addition, another classification is made, based upon the grouping of water quality variables with respect to their representativeness of point and nonpoint source pollution.

Normalization and Uniformization of Attribute Scores

According to Lettenmaier *et al*. (1984), it is desirable to specify the scores $SR_{j(i)kl}$ to have an approximately uniform distribution for each attribute (l). If this can be achieved, the dominance of the weighted score by any one attribute on the basis of its relative magnitude alone can be avoided.

The system adopted by Lettenmaier *et al*. (1984) had the property that the $SR_{j(i)kl}$ were approximately uniformly distributed on the interval (0, 100) and was achieved as follows: for a normally distributed random variable (e.g., attribute), a uniform distribution can easily be achieved by an inverse normal transformation, since the cumulative distribution function of a random variable is, by definition, uniform in the range (0,1). Alternately, if a variable can be made approximately normal by transformation (e.g., logarithm or power function), a two-step process can be followed to derive a score which is approximately uniform. Thus, tests for normality and normalization for nonnormal scores must be made first.

Next, the normalized $SR_{j(i)kl}$ values may be transformed once more to have a uniform distribution function for the interval (0, 100). For this purpose, the theorem of Probability-Integral Transformation may be used so that the cumulative distribution function $F(x)$ of attribute data ($x= SR_{j(i)kl}$), which is normal, becomes equal to the cumulative distribution function $F(y)$ of the line ($y = SU_{j(i)kl}$) that shows a uniform distribution function (Icaga, 1998). Here, $SU_{j(i)kl}$ represent the uniformized values of the attribute data $SR_{j(i)kl.}$

2.2.5 Optimization Procedure

Problem Definition

For the number of stations to be retained in the entire river basin (TR_N), it is necessary to determine the number of stations to be retained in each primary basin (R_k). Accordingly, the numbers of stations that will be retained in each primary basin should be determined such that the sum of the uniformized attribute data ($SU_{j(i)kl}$) at these stations becomes a maximum.

For each station combination in primary basin k, the sum of the uniformized attribute data ($SU_{j(i)kl}$) is shown as $TS_{j(i)k}$:

$$TS_{j(i)k} = \sum_{l=1}^{I_N} SU_{j(i)kl} \tag{8}$$

where $SU_{j(i)k}$ are the uniformized data at interval (0,100) for attribute l, at the primary basin k and for the i^{th} station; I_N is the number of attributes that will be used in the calculations. When weights are assigned to attribute data, Eq.(8) becomes:

$$TS_{j(i)k} = \sum_{l=1}^{I_N} (w_l \times SU_{j(i)kl}) \tag{9}$$

Equation (9) gives the total attribute value in primary basin k and for the $j(i)^{th}$ station combination. In each primary basin k, there will be different station combinations depending on R_k so that the $TS_{j(i)k}$ values of these station combinations will be different.

It is a general logical rule to select those combinations with the highest $TS_{j(i)k}$ values such that:

$$MTS_{j(i)k} = max \;\; TS_{j(i)k} \tag{10}$$

When determining the TR_N stations to be retained in the entire basin, the R_k combinations will be those that give the maximum $MTS_{j(i)k}$ attribute values:

$$SMTS = max \sum_{k=1}^{N} \sum_{i=1}^{R_k} MTS_{j(i)k} \tag{11}$$

where *SMTS* is the sum of the $MTS_{j(i)k}$, which give the maximum value for TR_N ; *N*, the number of primary basins; R_k,, the number of stations to be retained in primary basin *k*; $MTS_{j(i)k}$, maximum uniformized total attribute value for $j(i)^{th}$ station combination in primary basin *k*. Equation (11) indicates that the problem has two dimensions. Hence, it is not possible to determine the station combinations to be retained in the basin by ranking the $MTS_{j(i)k}$ values from the largest to the smallest and taking the first TR_N value reached. Dynamic programming method must be used to solve this problem as there several alternative combinations of maximum total scores $MTS_{j(i)k}$.

Application of Dynamic Programming to the Station Allocation Problem

The objective of the station allocation problem is to find the combination of stations that maximizes the $MTS_{j(i)k}$ corresponding to the determined TR_N so that the objective function of the problem can be determined as:

$$V = max \sum_{k=1}^{N} \sum_{i=1}^{R_k} MTS_{j(i)k} \tag{12}$$

The constraints of the problem are:

$$\sum_{k=1}^{N} R_k = TR_N \ ; \ 0 \le R_k \le TR_N \tag{13}$$

$$1 \le j(i) \le P_k \ ; \ j(i) \ne j(h), \ i \ne h \tag{14}$$

where *V* is the objective function; *N*, the total number of primary basins; R_k, the number of stations which will be retained in primary basin *k*; *k*, primary basin index; *i*, station index within primary basin *k*; *j(i)*, index number of i^{th} station in primary basin *k*; TR_N, the total number of stations to be retained in entire basin; and P_k, pre-existing number of stations in primary basin *k*.

3. APPLICATION TO GEDIZ RIVER BASIN

Basin properties such as topography, land use, industry, and junctions of tributaries are used to identify 6 primary basins in the Gediz River Basin. As noted earlier, the total number of pre-existing stations in the Gediz Basin is 33. For the current situation of 14 stations to be retained in the basin (TR_N=14), the number of possible alternative combinations of stations are calculated by Eq.(1) and further reduced by using Sharp's method (Sharp, 1970). To do this, stream order numbers are defined for each station in each primary basin. Next, it is necessary to determine the station combinations that have maximum sums of stream order numbers. Selection of station combinations that give the "maximum" sums reduces the number of combinations to 11, 4, 12, 6, 67 and 4 respectively for primary basins k = 1, ..., 6.

Considering the management objectives specified for the basin, 6 attributes were selected as: drainage area (DrA), population (Pop), irrigation area (IrA), number of samples (SNum), length of the observation period (Oper), and average values of observed water quality variables (QSum). The attribute QSum refers to the sum of the average observed values of selected water quality variables. 6 groups of attribute water quality variables were constituted. The first group, QSum1, covers common ions which are assumed to represent nonpoint pollution from irrigation. The second group, QSum2, includes nutrients and suspended sediment, characteristic of both domestic and irrigation wastewaters. The third group, QSum3, covers dissolved oxygen deficit and fecal bacteria to represent the quality of domestic waters. Group four, QSum4, includes only pH as a characteristic of industrial wastewaters. The fifth group, QSum5, covers trace metals to represent again the quality of industrial discharges. EC is considered as a separate group, QSum6, due to its significance with respect to nonpoint pollution from irrigation areas. The remaining quality variables are considered in the same group and a 7th group is defined as QSumT to represent general water quality conditions. The above groups are identified to represent different types of pollution. This identification is not strict; however, such an assumption had to be made to assign weight coefficients to attribute data.

Next, the raw values, $SR_{j(i)kl}$, of attributes QSum1 through QSumT are obtained by summing the average values of observed water quality variables in each group. Furthermore, since magnitudes of the variable values are not compatible, the observed series of each variable was transformed to a series with a mean of 100. As the last step of data preparation, the raw attribute scores $SR_{j(i)kl}$ were treated by two transformations. First, they were transformed into normally distributed scores using Box-Cox transformation; and second, the normalized scores were transformed into uniformized scores $SU_{j(i)kl}$.

Table 1. Allocated stations in each primary basin for N=6, TR_N = 14 (for each S, the numbers in the first line show the number of stations to be retained; the second line gives the station identity numbers)

	R_1	**R_2**	**R_3**	**R_4**	**R_5**	**R_6**
S1	5 (5-6-22-38-25)	2 (3-4)	1 (49)	1 (41)	2 (2-24)	3 (23-26-30)
S2(NP)	4 (5-6-22-38)	1 (3)	3 (43-47-49)	1 (41)	2 (2-24)	3 (23-26-30)
S3(P,NP)	4 (5-6-22-38)	2 (3-4)	1 (49)	1 (41)	3 (2-24-42)	3 (23-26-30)
S4(P)	5 (5-6-22-25-38)	2 (3-4)	1 (49)	1 (41)	2 (2-24)	3 (23-26-30)
S5(P)	5 (5-6-22-25-38)	2 (3-4)	1 (49)	1 (41)	2 (2-24)	3 (23-26-30)
S6(P)	4 (5-6-22-38)	2 (3-4)	1 (49)	1 (41)	3 (2-24-42)	3 (23-26-30)
S7(NP)	4 (5-6-22-38)	1 (3)	3 (43-47-49)	1 (41)	2 (2-24)	3 (23-26-30)
S8	4 (5-6-22--38)	1 (3)	3 (43-47-49)	1 (41)	2 (2-24)	3 (23-26-30)
S9(NP)	4 (5-6-22--38)	1 (3)	3 (43-47-49)	1 (41)	2 (2-24)	3 (26-30)
S10(P,NP)	4 (5-6-22-38)	2 (3-4)	2 (43-49)	1 (41)	2 (2-24)	3 (23-26-30)
S11(P)	4 (5-6-22-38)	1 (3)	3 (43-47-49)	1 (41)	2 (2-24)	3 (23-26-30)
S12(P)	4 (5-6-22-38)	1 (3)	3 (43--47-49)	1 (41)	2 (2-24)	3 (23-26-30)
S13(P)	4 (5-6-22-38)	2 (3-4)	3 (43-47-49)	1 (41)	2 (2-24)	2 (26-30)
S14(NP)	4 (5-6-22-38)	1 (3)	3 (43-47-49)	1 (41)	2 (2-24)	3 (23-26-30)
S15(P)	5 (5-6-22-25-38)	2 (3-4)	1 (49)	1 (41)	2 (2-24)	3 (23-26-30)
S16(P)	4 (5-6-22-38)	2 (3-4)	3 (43-47-49)	1 (41)	2 (2-24)	2 (26-30)
S17(P)	5 (5-6-22-25-38)	1 (3)	3 (43-47-49)	1 (41)	2 (2-24)	2 (26-30)
S18(NP)	5 (5-6-22-25-38)	1 (3)	3 (43-47-49)	1 (41)	2 (2-24)	2 (26-30)
S19(NP)	5 (5-6-22-25-38)	1 (3)	3 (43-47-49)	1 (41)	2 (2-24)	2 (26-30)
S20(NP)	5 (5-6-22-25-38)	1 (3)	3 (43-47-49)	1 (41)	2 (2-24)	2 (26-30)

S: alternative network schemes for different combinations of weighting coefficients,
N: Number of primary basins, R_k: Number of allocated stations in primary basin k, (k = 1, 2, ..., N),
TR_N : Total number of stations to be retained in Gediz river basin, P : Point pollution,
NP : Nonpoint pollution, G: General purpose.

In optimization of the network, weights were assigned to each attribute regarding basin management objectives. Accordingly, 20 different alternative schemes, S1 through S20, were developed on the basis of weight coefficients. Using all weight coefficient combinations, the total scores $TS_{j(i)k}$ were calculated. The maximum total scores $MTS_{j(i)k}$ are computed for each alternative combination of weight coefficients. These computations are realized for a total of 33 stations in the Gediz basin with R_k varying for each primary basin. The next step of the problem is to determine the locations of stations for a specified TR_N (total number of stations to be retained in the network) that give a maximum total value of $MTS_{j(i)k}$. This problem is solved by dynamic programming described in the previous section. For the case of Gediz, TR_N is selected as 14, which is the number of currently running stations. The problem is to find the locations of 14 stations that maximize the total $MTS_{j(i)k}$ value. Furthermore, the problem can be solved for alternative combinations of weighting factors, i.e., S1 through S20. Table 1 gives the results for TR_N = 14 and the number of primary basins being N = 6.

The above investigations may be detailed by varying the number of stations to be retained in the network (TR_N). The methodology is sufficiently flexible in analyzing a network development process such that one may add new stations to the system in an optimum manner (Icaga, 1998).

CONCLUSION

With respect to the application of the methodology to Gediz River basin, the following general considerations are made:

a. alternative stations are obtained for the case of 14 stations to be retained in the network. Selection of the most appropriate one requires two issues to be accomplished: (1) relevant costs of each alternative solution must be analyzed; (2) the monitoring agency has to delineate its own specific objectives for monitoring and then select the solution that best suits these objectives;
b. if the monitoring agency prefers to expand the existing network, the results of the study can be used to select the locations of new stations.

REFERENCES

DSI, 1993. Report on Water Pollution and Quality Classification in the Gediz and Yesilirmak Basins, General Directorate of DSI, October 1993.

Harmancioglu, N.B., and Alpaslan, N., 1992. Water quality monitoring network design: A problem of multi-objective decision making, AWRA, Water Resources Bulletin, Special Issue on "Multiple Objective Decision Making in Water Resources"; 28(1): 179-192.

Harmancioglu, N. B., Alpaslan, N., and Singh, V. P., 1994. Assessment of the entropy principle as applied to water quality monitoring network design. In: Hipel, K. W. et al. (eds.), Stochastic and Statistical Methods in Hydrology and Environmental Engineering, (Time Series Analysis in Hydrology and Environmental Engineering), Kluwer, Water Science and Technology Library; Vol.10/3: 135-148.

Husain, T., 1989. Hydrologic uncertainty measure and network design. AWRA, Water Resources Bulletin; 25(3): 527-534.

Icaga, Y., 1998. Spatial optimization of hydrometric data networks by systems analysis techniques. Ph.D. Thesis submitted to the Graduate School of Natural and Applied Sciences, Dokuz Eylul University, Hydraulics, Hydrology and Water Resources Program, Izmir, (February, 1998), 164p.

Lettenmaier, D. P., Anderson, D. E., and Brenner, R. N., 1984. Consolidation of a stream quality monitoring network, Water Resources Bulletin, AWRA; 20(4): 473-481.

Lettenmaier, D. P., Hooper, E. R., Wagoner, C., and Faris, K., 1991. Trends in stream quality in the continental United States, 1978-1987, Water Resources Research; 27(3): 327-339.

McMahon, T. A., and Mein, R. G., 1986. River and Reservoir Yield. Victoria: Water Resources Publications, Littleton, Colorado, 368 p.

Moss, M.E., 1997. On the proper selection of surrogate measures in the design of data collection networks. In: N.B. Harmancioglu, M.N. Alpaslan, S.D. Ozkul and V.P. Singh (eds.), Integrated Approach to Environmental Data Management Systems, Kluwer Academic Publishers, NATO ASI Series, 2. Environment; vol. 31: 79-88.

Sharp, W.E., 1970. Stream order as a measure of sample uncertainty, Water Resources Research; 6(3): 919-926.