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Revising river water quality monitoring networks using discrete entropy theory: the Jajrood River experience

Najmeh Mahjouri · Reza Kerachian

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Abstract This paper aims at evaluating and revising the spatial and temporal sampling frequencies of the water quality monitoring system of the Jajrood River in the Northern part of Tehran, Iran. This important river system supplies 23% of domestic water demand of the Tehran metropolitan area with population of more than 10 million people. In the proposed methodology, by developing a model for calculating a discrete version of pair-wise spatial information transfer indices (SITIs) for each pair of potential monitoring stations, the pair-wise SITI matrices for all water quality variables are formed. Also, using a similar model, the discrete temporal information transfer indices (TITIs) using the data of the existing monitoring stations are calculated. Then, the curves of the pair-wise SITI versus distance between monitoring stations and TITI versus time lags for all water quality variables are derived. Then, using a group pair-wise comparison matrix, the relative weights of the water quality variables are calculated. In this paper, a micro-genetic-algorithm-based optimization model with the objective of minimizing a weighted average spatial and temporal ITI is developed and for a pre-defined total number of stations, the best combination of monitoring stations is selected. The results show that the existing monitoring system of the Jajrood River should be partially strengthened and in some cases the sampling frequencies should be increased. Based on the results, the proposed approach can be used as an effective tool for evaluating, revising, or redesigning the existing river water quality monitoring systems.

Keywords River water quality monitoring · Discrete entropy theory · The Jajrood River · Spatial information transfer index (SITI) · Temporal information transfer index (TITI)

Introduction

Optimal management of surface water resources requires efficient and informative data and information which can be provided by an efficient water quality monitoring system. One of the promising theories used in the previous studies for designing or evaluating water quality monitoring systems is the entropy theory introduced by Shannon and Weaver (1949). So far, many researchers have worked on development of

N. Mahjouri
Department of Environmental Engineering,
University of Tehran, Tehran, Iran
e-mail: mahjouri@ut.ac.ir

R. Kerachian (✉)
Center of Excellence for Engineering and
Management of Infrastructures, School of Civil
Engineering, University of Tehran, Tehran, Iran
e-mail: kerachian@ut.ac.ir

entropy-based approaches for water quality monitoring systems design and assessment. In the following section, an overview of the past works in the mentioned context is given.

Uslu and Tanriover (1979) analyzed the information content and further the transfer of information between the observations of two stream gauging stations. They used the entropy concept for defining the optimum temporal and spatial sampling intervals in data collection systems.

Harmancioglu (1981) investigated the transfer of information between observations of two stream gauging stations. He showed the capability of the entropy concept in delineation of optimum sampling intervals in data collection systems. Later, Harmancioglu and Yevjevich (1987) extended the use of the method for the purposes of spatial design in case of stream flow gauging stations. They defined the concepts of transferred and transferable information. Afterwards, Harmancioglu and Baran (1989) used this theory to attain the maximum information about runoff at a point along a river. Their study involved the analysis of information transfer between runoff–runoff and precipitation–runoff processes in basins with different recharge systems located in Turkey.

Harmancioglu and Alpaslan (1992) proposed a statistical procedure based on the Entropy theory to assess the efficiency and cost effectiveness of a monitoring network. Also, Harmancioglu et al. (1999) suggested that major difficulty in design and evaluation of the monitoring systems is to assess the efficiency in terms of informativeness and also cost of monitoring.

Ozkul et al. (2000) presented a method using the entropy theory for assessing water quality monitoring networks. They extended the work of Harmancioglu and Alpaslan (1992) to better define the zones with high monitoring data uncertainties along a river. This model can only be used for reducing redundant stations or decreasing the sampling frequencies in an existing or a primary monitoring system.

Mogheir and Singh (2002) developed a methodology for designing an optimal groundwater monitoring network using the entropy theory. They applied this theory to describe the spatial variability of synthetic data that can represent spatially correlated groundwater quality data. The application involved calculating information measures such as transient information, the information transfer index (ITI) and the correlation coefficient.

Mogheir et al. (2004a) characterized the spatial variability of groundwater quality using discrete and analytical approaches. Also, Mogheir et al. (2004b) extended the previous work of Mogheir et al. (2004a) using the entropy theory to describe the spatial variability of groundwater quality data sets. They also illustrated the application of the entropy theory using the chloride observations obtained from a groundwater quality monitoring network in the Gaza Strip, Palestine.

Mogheir et al. (2005) evaluated the monitoring cycle in the Gaza Strip using the entropy theory. They prepared a questionnaire outlining the groundwater management and planning objectives, tasks and the data which had to be collected through monitoring activities in the Gaza Strip. They also proposed a flowchart to evaluate the relation between the objectives, the tasks, the data and the monitoring activities using the Entropy theory. The results of their study showed that more data should be collected and the existing monitoring network should be redesigned to improve the informativeness of the gathered data.

Karamouz et al. (2009) used the measure of transient information for selecting the best monitoring stations from a set of potential monitoring sites along a river. For each new potential monitoring station, the time series of the water quality data was generated using a water quality simulation model. They applied the model to the Karoon River in Iran for designing an on-line water quality monitoring system.

Masoumi and Kerachian (2008) developed an entropy-based approach for assessing the location of salinity monitoring stations in the Tehran Aquifer, Tehran, Iran. They used the measure of transinformation in the entropy theory to find the optimal distance among stations. Because of the large area of the Tehran aquifer and significant spatial variations of the electrical conductivity (EC) of the groundwater in the study area, they used the C-means clustering method to divide the area to some homogenous zones. The optimization model was then applied to each zone to find out the optimal location of monitoring stations.

Masoumi and Kerachian (2010) presented a new methodology for optimal redesign of groundwater quality monitoring networks. They used the measure of transinformation in discrete entropy theory and the transinformation–distance (T–D) curves to quantify the efficiency of sampling locations. Using the fuzzy set theory, the existing uncertainties in the T–D curves were taken into account and the fuzzy T–D curves of the zones were then used in a multi-objective hybrid genetic algorithm-based optimization model which could provide the optimal locations of monitoring stations.

In this paper, a new optimization model based on the discrete entropy theory is proposed for evaluating and revising the water quality monitoring network in a large scale case study in Tehran metropolitan area, Iran. In this methodology, the probability distribution functions of water quality variables are not required for quantifying the efficiency of the monitoring network. Evaluation of the gathered data from the existing monitoring stations is carried out using the discrete spatial and temporal information transfer indices (SITI and TITI). Then, using a group pair-wise comparison matrix, the relative weights of the water quality variables are estimated. Finally, using a micro-genetic algorithm (MGA), the optimization model with the objective of minimizing a weighted average spatial and temporal ITI is solved. The optimization model provides the best combination of monitoring stations and sampling frequencies for a pre-defined total number of stations.

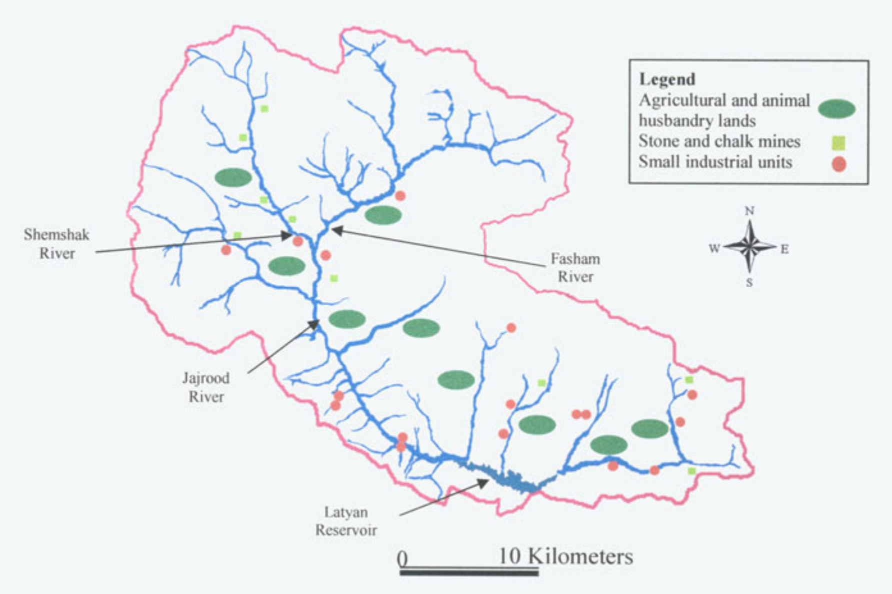
Case study

In this paper, the proposed methodology is applied to the Jajrood River system in the north eastern part of Tehran, Iran. This important river system supplies 23% of domestic water demand of the Tehran metropolitan area with population of more than 10 million people. The Jajrood River is originated from the Alborz mountain chains located in the north of Iran. The Fasham and Shemshak rivers are the main tributaries of the Jajrood River which join together in an area called Fasham and form the Jajrood River. As shown in Fig. 1, the study area consists of the Jajrood River and its tributaries from upstream of the Fasham and Shemshak rivers to the downstream of the Latyan reservoir.

The domestic wastewater with the average daily amount of 5,300 m^3 is directly or indirectly discharged into the river. Based on water quality data obtained from the existing water quality monitoring system in the study area, the concentrations of some water quality variables such as total and fecal coliform bacteria violate the water quality standards. According to the measurements, the highest concentrations of water quality variables such as total coliform, nitrate, and BOD take place during flood seasons and also in days with the heavy precipitations. For example, the maximum concentration of total coliform bacteria increases to 160,000 MPN/100 mL in flood seasons, which is mainly due to soil erosion in upstream basin and river banks. The Jajrood River basin is mostly a mountainous region; hence, it does not comprise considerable hectares of agricultural lands. The main agricultural lands in the study area consist of orchards with the total area of 8,000 ha. Hence, it can be concluded that agricultural pollutants do not significantly contribute to polluting the surface water resources. The laboratorial experiments show that the DO concentration along the river is usually around the saturation level due to the high self purification potential of the river. The previous studies also show that there are no traces of pesticides in the river water.

One of the main pollution sources in the study area is the municipal wastewaters. Due to the lack of supervision, sometimes the sludge of septic tanks and municipal effluents are directly discharged into the Jajrood River. Also, the contents of poorly designed septic tanks may leak into the aquifers and indirectly contaminate the Jajrood River. The disposal and accumulation of solid wastes along the river bank, especially in the vacation seasons is another pollution source of this river. According to the Water and Energy Research Center (1380), around 1,000 tonnes of municipal and industrial solid wastes are discharged into the Jajrood River annually. There are only a few important industrial pollution sources along the Jajrood River which mainly include five chalk and stone mines. The experimental analyses show

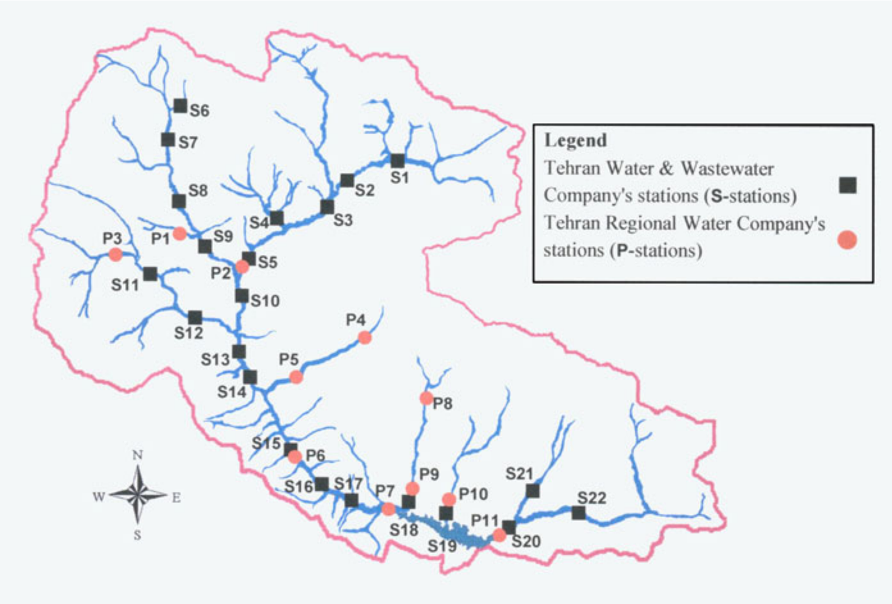
Fig. 1 The locations of the main pollution sources in the study area



that these industrial units do not adversely impact the river water quality. The location of the main pollution sources in the study area is also shown in Fig. 1. The Jajrood River is also polluted by wastewater discharge from some animal husbandries located near the river.

There are 33 monitoring stations on the Jajrood River and its main tributaries which have been measuring more than ten water quality variables during the past 40 years. These monitoring stations include 22 stations operated by Tehran Water and Wastewater Company (TWWC) and 11 stations operated by Tehran Regional Water Company (TRWC). The location of the monitoring stations in the study area is presented in Fig. 2.

Fig. 2 The locations of the existing monitoring stations in the study area



Model framework

In the proposed entropy-based methodology, optimal location of monitoring stations and temporal data sampling are determined based on maximizing the information contents of the gathered data and minimizing redundant information.

The framework of the methodology is presented in Fig. 3. As shown in this figure, firstly, water quality variables are selected based on the existing data and information gathered from the monitoring system of the Jajrood River. The methodology has three main parts namely spatial analysis, temporal analysis, and spatial–temporal analysis.

In almost all of the applications of analytical entropy theory, it is assumed that the probability distribution functions of the random variables are normal or log-normal. Since the water quality variables in the Jajrood River do not obey normal or log-normal distributions, the application of analytical entropy theory may cause considerable inaccuracy. In this paper, the concept of the discrete entropy theory is used to assess the efficiency of the Jajrood River monitoring network and revise both the location of existing monitoring stations and temporal frequencies of data gathering. In the section of spatial analysis, a module is developed for calculating the discrete version of pair-wise SITI for each pair of existing monitoring stations. Information transfer index, which indicates the standardized information transferred from one station to another, is computed as follows:

$$\mathrm{ITI} = \frac{T(X,Y)}{H(X,Y)} \tag{1}$$

In the above equation, $H(X{,}Y)$ is the total entropy of two independent random variables X and Y:

$$H(X,Y) = H(X) + H(Y) \tag{2}$$

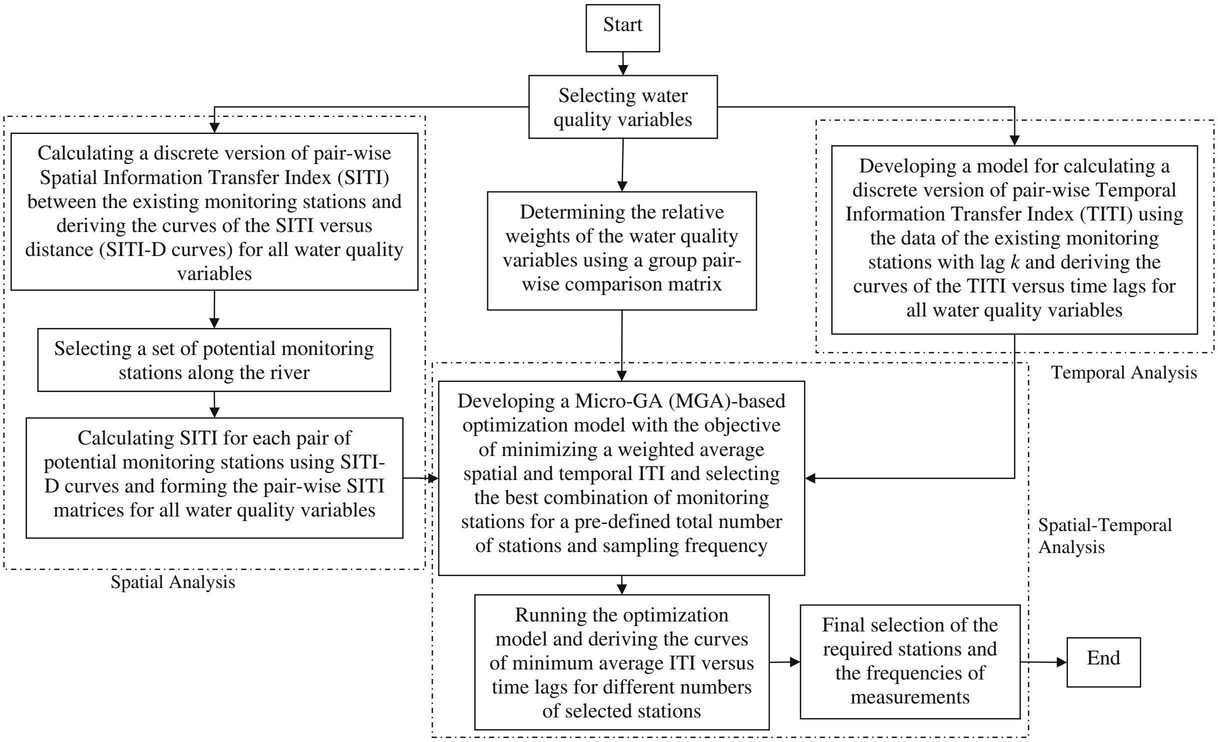


Fig. 3 The framework of the proposed methodology

where, $H(X)$ is calculated by the following equation proposed by Shannon and Weaver (1949):

$$E\left(I\left(X\right)\right) = H\left(X\right) = \sum_{i=1}^{N} p\left(x_i\right) \log p\left(x_i\right) \tag{3}$$

where, N represents the number of events x_i with probabilities $p(x_i)$ ($i = 1, \ldots, N$).

In Eq. 1, $T(X,Y)$ which measures the redundant or mutual information between X and Y (transinformation) can be calculated using the following equation (Mogheir et al. 2004a, b):

$$T\left(X, Y\right) = \sum_{i=1}^{n} \sum_{j=1}^{m} p\left(x_i, y_j\right) \ln\left[\frac{p\left(x_i, y_j\right)}{p\left(x_i\right) p\left(y_j\right)}\right] \tag{4}$$

where, $p(x_i)$ and $p(y_i)$ are respectively the probability of occurring X and Y, and $p(x_i, y_j)$ is the probability of accruing both random variables X and Y at the same time.

Using the above-mentioned equations, the values of the pair-wise SITI between the existing monitoring stations are calculated. Then, the curves of the SITI versus distance for all water quality variables are derived. A set of potential monitoring stations along the river are also chosen considering the spatial variations of the concentration of water quality variables and the location of pollution loads. In the last step of the spatial analysis, calculating SITIs regarding each pair of potential monitoring stations for each water quality variable, pair-wise SITI matrices for all water quality variables are derived.

In the temporal analysis section, to calculate the temporal sampling intervals of water quality variables, a discrete version of pair-wise TITI is used. For each station, the transinformation contents between the original time series and time series with different time lags are estimated. Then, the curves of the TITI versus time lags for all water quality variables are derived.

The spatial and temporal analyses are carried out based on only one water quality variable, while different water quality variables are usually sampled in a station at the same time. Therefore, to achieve a better judgment on the best sampling locations and also frequencies of data gathering for all variables, it is suggested to perform the analyses for a weighted water quality variable. For this purpose, the relative weights of the water quality variables are calculated using a group decision making method called analytical hierarchy process (AHP), developed by Saaty (1980, 1994). In this method, for weighting water quality variables, pair-wise comparison matrices proposed by experts and decision makers are incorporated. A decision maker should provide different values for the importance of water quality variables as a pair-wise comparison matrix. For example, consider $A = (a_{ij})$ is a k by k pair-wise comparison matrix for the water quality variables, where k is the number of basic criteria. The principal criterion for accepting a comparison matrix is to show that the comparisons are consistent. The difference between the dominant eigenvalue, $\lambda_{\max}$, and k is used for defining the inconsistency index, II (Karamouz et al. 2003):

$$\mathrm{II} = \frac{\lambda_{\max} - k}{k - 1} \tag{5}$$

The inconsistency ratio, IR is then defined as:

$$\mathrm{IR} = \mathrm{II} / \mathrm{IIR} \tag{6}$$

where, IIR is the inconsistency index of a random matrix obtained by calculating II for a randomly filled n by n matrix. If $\mathrm{IR} < 10\%$, then the consistency criterion is satisfied, otherwise the decision maker should be asked to revisit the pair-wise comparisons. This procedure continues until all pair-wise comparisons obtained from different matrices proposed by different experts satisfy the consistency criterion. Then, the geometric mean of each element of different proposed pair-wise comparison matrices is estimated. The eigenvector of the average pair-wise comparison matrix is then used for estimating the relative weights of different water quality variables. More details about weighting some indicators using pair-wise comparison matrices can be found in Karamouz et al. (2002, 2007).

The last step of the methodology comprises both spatial and temporal analyses. In this section, a new MGA-based optimization model with the objective of minimizing a weighted average spatial and temporal ITI is developed in order to select the best combination of monitoring stations for a pre-defined total number of stations and sampling frequencies:

$$\text{Minimize } Z = \left(\sum_{k_1=1}^{n} \sum_{k_2=k_1}^{n} \text{SITI}\,(k_1, k_2) + \sum_{k=1}^{n} \text{TITI}_L\,(k) \right) \Big/ \left(\sum_{k=1}^{n} k + n \right) \tag{7}$$

where, n is the total number of required monitoring stations. $\text{TITI}_L(k)$ shows the average TITI with time lag L in station k, $\text{SITI}(k_1, k_2)$ shows the average SITI between monitoring stations k_1 and k_2 and $\sum_{k=1}^{n} k$ represent the sum of the number of SITIs. The results of the optimization model suggest the optimum combination of potential monitoring stations for total number of required stations. For calculating $\text{TITI}_L(k)$ for potential monitoring station k, the TITI_L of the nearest existing monitoring station is used.

Results and discussion

Since, the most complete and reliable existing data are related to the water quality and quantity variables of EC, PH, sodium adsorption ratio (SAR), NO_3^-, NO_2^-, total coliform (TC) and river discharge, these variables are selected as the water quality and quantity indicators. The time series of the concentration of water quality and quantity variables are obtained from the existing monitoring stations for the period of 1968–2008. These data are gathered from 33 monitoring stations operated by TWWC and TRWC.

In this paper, using Eqs. 1 to 4, the SITI values between the existing monitoring stations are calculated and the SITI-D curves are derived. As an example, Fig. 4 shows the curve of SITI versus distance for water quality variable NO_3^-. This figure shows that the more the distance between the monitoring stations becomes, the less the SITI value or transinformation content of the data sets.

Considering the locations of the pollution sources and the spatial variations of the river water quality, 40 potential monitoring stations are selected. These stations are determined in a way that they comprise all the existing monitoring stations and also the whole study area can be sufficiently monitored. Then, using the SITI curves, the pairwise SITI matrices for all water quality variables are formed.

In the next step, the TITI values are calculated for the time series of data with 1 to 4 monthly time lags. The results of this step provide the curves of the TITI versus time lags for the water quality variables in different stations. For instance, Fig. 5 depicts the curve of TITI for station S15. As seen in this figure, the values of TITI are not considerable (they are less than 0.4) and the variation of the ITI versus the number of lags does not show any specific pattern. Therefore, it can be concluded that with a monthly sampling interval, there is no redundant information in the system. Also, the values of temporal transinformation in

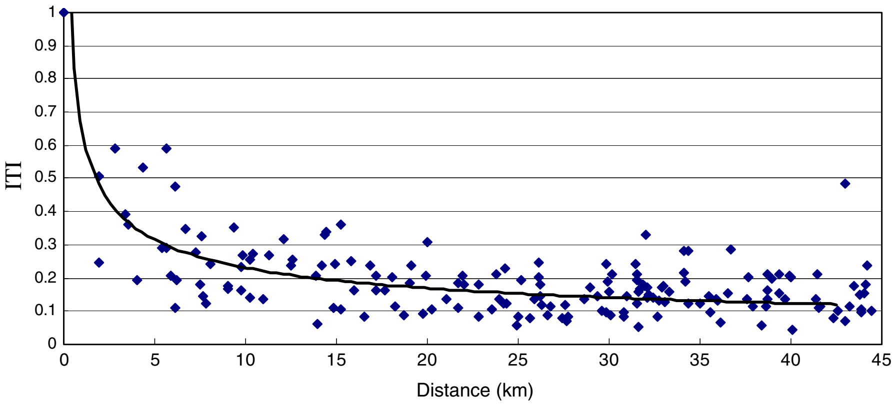
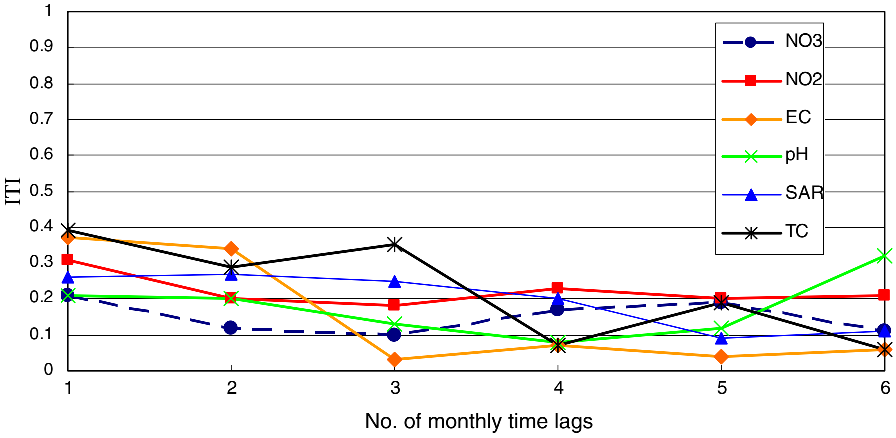


Fig. 4 Variation of SITI versus distance for the water quality variable NO_3^-

Fig. 5 Variations of the TITI versus monthly lags in Station S15



different stations show that based on the existing sampling frequencies, the data provides no redundant information and the sampling frequency should be at least once in a month. However, for determining the exact values of sampling frequencies, it is essential to monitor the water quality variables during a short period of time on a weekly or daily basis for at least one year and repeat the temporal entropy analysis.

In the proposed methodology, it is suggested to perform the spatial and temporal analyses for all water quality variables considering their relative weights. In this study, the relative weights of the water quality variables are calculated using AHP method. The following pair-wise comparison matrix, which has been provided by a group of experts, illustrates the relative importance of the selected water quality variables.

$$\begin{array}{l|ccccccc|}
 & \mathrm{EC} & Q & \mathrm{pH} & \mathrm{SAR} & \mathrm{NO_3} & \mathrm{NO_2} & \mathrm{TC} \\
\mathrm{EC} & 1.0 & 1.0 & 3.0 & 2.0 & 1.2 & 1.5 & 0.8 \\
Q & 1.0 & 1.0 & 3.0 & 2.0 & 1.2 & 1.5 & 0.8 \\
\mathrm{pH} & 0.3 & 0.3 & 1.0 & 0.7 & 0.4 & 0.5 & 0.3 \\
\mathrm{SAR} & 0.5 & 0.5 & 1.5 & 1.0 & 0.6 & 0.7 & 0.4 \\
\mathrm{NO_3} & 0.8 & 0.5 & 2.5 & 1.7 & 1.0 & 1.2 & 0.7 \\
\mathrm{NO_2} & 0.7 & 0.8 & 2.5 & 1.3 & 0.8 & 1.0 & 0.6 \\
\mathrm{TC} & 1.2 & 1.2 & 3.5 & 2.3 & 1.4 & 1.7 & 1.0
\end{array}$$

By estimating the eigenvector of this matrix, the relative weights of the water quality and quantity variables of EC, discharge, PH, SAR, NO_3, NO_2, and TC are calculated as 0.18, 0.18, 0.07, 0.1, 0.15, 0.12, and 0.2, respectively. The inconsistency ratio of the matrix is less than the maximum accepted level of 0.1.

The values of weighted TITIs for all stations with different time lags can be calculated using the calculated relative weights. As an example, the variations of the weighted ITI versus monthly time steps for four stations of S14, S16, S19, and S21 are illustrated in Fig. 6. Similar to the TITIs calculated for each water quality variable, the values of weighted TITI obtained for different monitoring stations do not follow any particular pattern; hence the sampling frequency of less than once in a month would be insufficient.

In the next step, using the developed MGA-based optimization model, the curves showing the minimum average ITI values versus the number of time lags for different numbers of stations are obtained. In the MGA, the population size and the probability of crossover are considered to be 200 and 0.7, respectively. For a pre-defined total number of monitoring stations and 0 to 3 monthly time lags, the optimization model provides a combination of stations which gives a minimum average ITI. Figure 7 is an example of the results of this process which illustrates the curve of minimum average ITI versus number of monthly time lags, having a pre-defined total number of stations equal to 28 to 33, for water quality variable EC. Also, the variation of minimum average weighted ITI with different monthly time lags is depicted in Fig. 8.

The results clearly show that there is a limited amount of redundant information in the existing

Fig. 6 Variation of weighted TITI versus monthly lags in four different stations (for a weighted water quality variable)

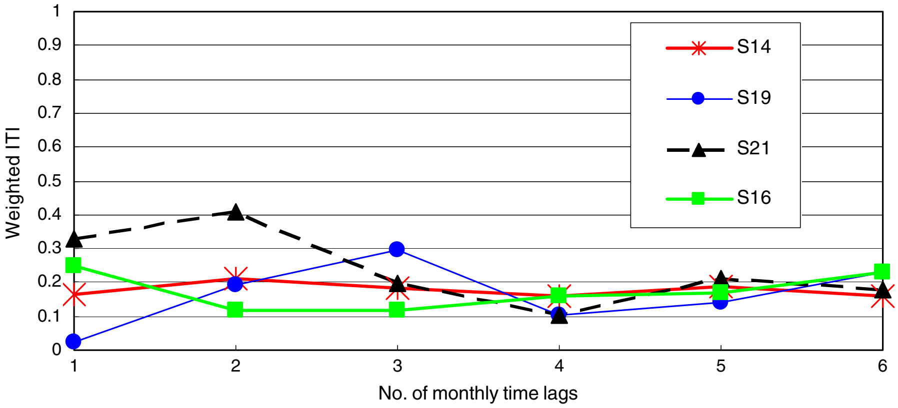


Fig. 7 Variation of minimum average ITI with different monthly time lags for water quality variable EC

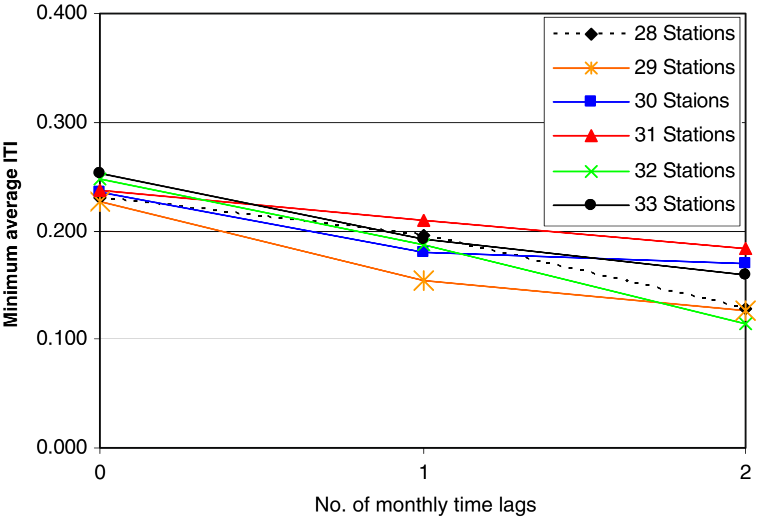
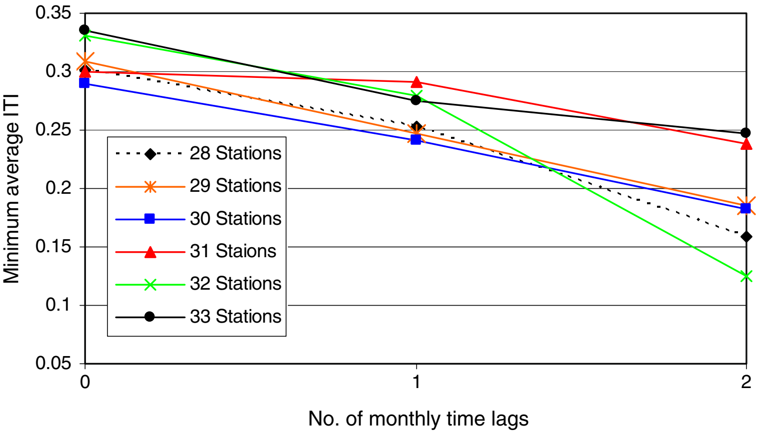


Fig. 8 Variation of minimum average weighted ITI with different monthly time lags for all water quality variables



monitoring system, spatially and temporally. Also, by increasing the total number of stations to 40 or more, the values of transinformation indices do not increase remarkably. Hence, it can be concluded that for having a complete and sufficient monitoring network, more than at least ten new monitoring stations should be added to the system. Estimating the cost of the new monitoring system shows that this would not be economically efficient.

Based on the water quality condition of the river and consulting with the decision makers and experts of the TRWC, 30 monitoring locations out of 40 potential locations are chosen. The proposed stations are selected using the proposed optimization model in a way that they can provide data and information efficiently and also comprise the existing monitoring stations as much as possible. Comparing the revised and the existing monitoring networks shows that monitoring stations P11 and S20, P10 and S19, P9 and S18, P6 and S15 and also P2 and S5 belonging to TWC and TWWC can be combined to form four stations and two more new monitoring stations should be added to the system. The locations of the revised monitoring stations are illustrated in Fig. 9. Also, Table 1 illustrates the proposed water quantity and quality variables along with the required temporal sampling frequencies which have been proposed based on the results of the optimization model as well as consulting with the experts and decision makers of the TRWC.

Table 1 Proposed water quality and quantity variables and their sampling frequencies

Variable	Sampling frequency
River discharge	Daily and hourly, in flood seasons Monthly, otherwise
Temperature	Monthly
EC	Monthly
pH	Monthly
Turbidity	Daily and hourly, in flood seasons Monthly, otherwise
DO	Monthly
BOD_5	Monthly
COD	Monthly
Phosphate	Monthly
Total phosphorus	Monthly
Sulfate	Monthly
Nitrate	Monthly
Nitrite	Monthly
Fe, Cd, As, Cr, Cu, Hg, Pb, Mn, Ba, Zn*	Seasonally
Heavy metals in river bed deposits	Every six months
NH_3 or NH_4^+	Monthly
Organic nitrogen	Monthly
Toxicants	Seasonally
FC,TC	Monthly

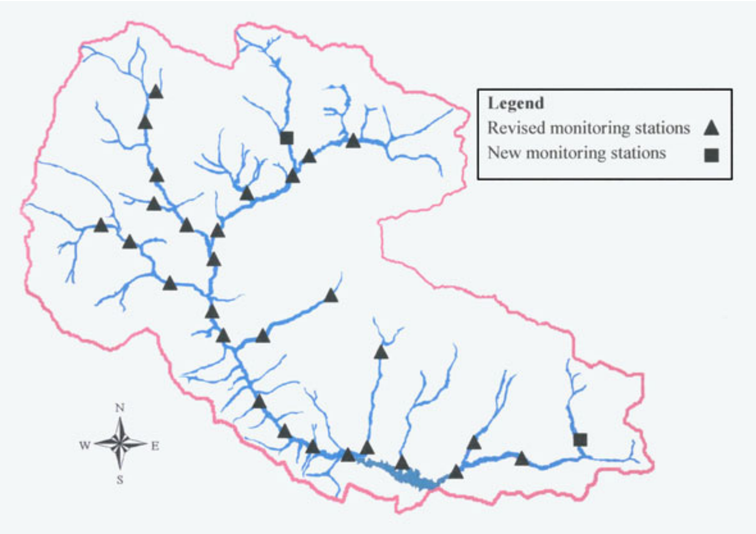


Fig. 9 The locations of the revised and new monitoring stations

Summary and conclusion

In this paper, a new optimization model based on the discrete entropy theory was applied to evaluate and revise spatial and temporal monitoring sampling frequencies in the case study of the Jajrood river system in Tehran, Iran. Evaluation of the gathered data from the existing monitoring stations was carried out using the discrete SITI and TITI for each pair of potential monitoring stations. Also, the discrete TITIs using the data of the existing monitoring stations with lag *k* were calculated. Then, the curves of the pair-wise SITI versus distance between monitoring stations and TITI versus time lags for all water quality variables were derived.

In this paper, using a group pair-wise comparison matrix, the relative weights of the water quality variables were estimated. Finally, using a MGA-based optimization model with the objective of minimizing a weighted average spatial and temporal ITI for a pre-defined total number of stations, the best combination of monitoring stations and sampling frequencies were selected.

In the previous works, by assuming that the probability distribution functions of the random variables, the analytical entropy theory has been frequently used. In this paper, the efficiency of the monitoring network was quantified using the measure of transient information in the discrete entropy theory. Therefore, the probability distribution functions of the random variables were not required for quantifying the efficiency of the monitoring network. Finally, the best locations for monitoring stations and the temporal sampling frequencies for several water quality variables were suggested using a new optimization model. The results showed that the proposed approach can be used as an effective tool for evaluating and revising the existing river water quality monitoring networks.

The methodology presented in this paper is deterministic. In future studies, this methodology can be extended to consider the existing uncertainties in SITI-D and TITI-time lag curves. These uncertainties can be incorporated using the fuzzy set theory.

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