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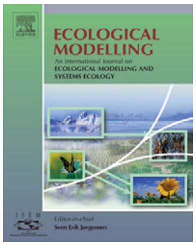

Design of a water quality monitoring network in a large river system using the genetic algorithm

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ABSTRACT

Despite several decades of operations and the increasing importance of water quality monitoring networks, the authorities still rely on experiential insights and subjective judgments in siting water quality monitoring stations. This study proposes an integrated technique which uses a genetic algorithm (GA) and a geographic information system (GIS) for the design of an effective water quality monitoring network in a large river system. In order to develop a design scheme, planning objectives were identified for water quality monitoring networks and corresponding fitness functions were defined using linear combinations of five selection criteria that are critical for developing a monitoring system. The criteria include the representativeness of a river system, compliance with water quality standards, supervision of water use, surveillance of pollution sources and examination of water quality changes. The fitness levels were obtained through a series of calculations of the fitness functions using GIS data. A sensitivity analysis was performed for major parameters such as the numbers of generations, population sizes and probability of crossover and mutation, in order to determine a good fitness level and convergence for optimum solutions. The proposed methodology was applied to the design of water quality monitoring networks in the Nakdong River system, in Korea. The results showed that only 35 out of 110 stations currently in operation coincide with those in the new network design, therefore indicating that the effectiveness of the current monitoring network should be carefully re-examined. From this study, it was concluded that the proposed methodology could be a useful decision support tool for the optimized design of water quality monitoring networks.

1. Introduction

Modernized management of water resources requires a large amount of temporal and spatial information on variations in water quality and quantity, in order to protect communities from floods or drought, to support various types of water use and to control pollution in water bodies. Recently, as urbanization and industrialization have increased and water pollution has become a threat for more areas, both the general public and policy makers have called for improvements in the design and operation of monitoring networks in river systems. However, water quality monitoring networks have traditionally been designed on the basis of experience and intuition in keeping with increased management needs related to preventing water quality deterioration, rather than being based on a systematic design and specified monitoring objectives. In many developing countries, most of the existing monitoring networks exhibit deficiencies in terms of providing information required for integrated watershed management. Furthermore, complicated monitoring system require-

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ments arising from new policies related to water management, such as the Total Maximum Daily Load (TMDL) program, integrated watershed management and information systems for water resources management, call for the development and operation of more systematic monitoring networks. The TMDL program, in particular, entails the quantitative estimation of pollution loads from each watershed unit and the use of results from appropriate water quality models. For this purpose, separately collected water quality and quantity parameters should be obtained simultaneously from an integrated monitoring system, and monitoring parameters and frequencies should also be rearranged to permit water quality modeling based on water and mass balance methods.

Water quality monitoring networks have been operated in Korea since the Environment Conservation Law was passed in 1977. Over the past several decades or so, water quality and/or quantity parameters have been measured regularly or irregularly through a variety of monitoring networks operated by a number of agencies, such as the Ministry of Environment, government public health and environment research institutes and the Korea Water Resources Corporation, to meet their own monitoring objectives. Lacking consistent principles, such diverse operations have created various challenges for the management of information on water quality parameters. Difficulties have also resulted from the ill-defined methodology used in siting monitoring stations in accordance with scientifically established planning objectives. The water quality monitoring networks are operated "in order to acquire fundamental information for understanding the current conditions and long- and short-term variations of water quality in nationwide rivers and lakes, for evaluating the effects of already enforced major policies for conservation of water quality and for establishing new policies" (Korea MOE, 2003). In order to meet the monitoring objectives, network planners select monitoring sites with a view to assessing water quality conditions for improvement, sustaining good water quality, tracking changes in water quality and pollution, studying inflowing pollutants and their effects on a water body and assessing pollution loading from freshwater flows in areas where mixing of freshwater and seawater occurs. However, the Korean DOE's approach to selecting monitoring sites is based solely on the basic objectives for water quality monitoring networks, and details of selection methodology are lacking.

The issues related to the optimal design of water quality monitoring networks and efficiency improvements have been the subject of research since 1970s (Ning and Chang, 2002). The basic principles of monitoring network design and site selection criteria for individual monitoring stations have been evaluated and applied (Skalski and Mackenzie, 1982; Lettenmaier et al., 1986; Smith and McBride, 1990; Loftis et al., 1991; Esterby et al., 1992). Later studies have focused greater attention on the effective design of water quality monitoring networks using various types of statistical and/or programming techniques, such as integer programming, multi-objective programming, kriging theory and optimization analysis (Hudak et al., 1995; Harmancioglu and Alpaslan, 1992; Cieniawski et al., 1995; Dixon and Chiswell, 1996; Timmerman et al., 1997; Dixon et al., 1999).

The aim of the present study was to develop a design framework for water quality monitoring networks in order to support newly introduced water management regulations and technologies as well as to satisfy the traditional network objectives of tracking water quality distribution and variations. A genetic algorithm was used in association with a GIS to derive an optimized design. The proposed framework was applied to the Nakdong River, the second largest river system in Korea, in order to devise an improved water quality monitoring scheme for the river.

2. Fundamentals of design methodology

2.1. *Planning objectives of water quality monitoring networks*

The design procedure for monitoring networks requires specific objectives for an efficient and effective monitoring system that will address sophisticated requirements related to water quality and quantity parameters. The monitoring objectives can be set based on operational and management requirements for monitoring programs and may include helping to establish water quality standards, determining water quality status and trends, identifying impaired waters, identifying the causes and sources of water quality problems, implementing water quality management programs and evaluating program effectiveness (U.S. EPA, 2003).

Both the traditional objectives of monitoring networks and the objectives required to support newly introduced water resource management programs have been considered in this study. Traditional objectives of water quality monitoring networks are listed below (Lettenmaier, 1979; Liebetrau, 1979):

Objective (1) To understand the long- and/or short-term trends of temporal variations in water quality parameters.
Objective (2) To monitor violations of the water quality standards specified for each watershed.
Objective (3) To identify external causes and sources affecting water quality changes.
Objective (4) To support utilization of water resources.
Objective (5) To examine short-term variations in water quality through a targeted investigation during a given period.

In addition, more recent policies and technologies such as TMDL and information systems for water resources management have created new management requirements, giving rise to additional objectives for monitoring networks, such as the following:

Objective (6) To estimate pollution loads from each watershed unit in order to perform TMDL analyses.
Objective (7) To use water quality modeling to support TMDL and scientific water quality management functions.
Objective (8) To establish information systems for water resources management.

The monitoring objectives listed above are for general use and can be supplemented or replaced with others according to each monitoring networks' own purposes.

2.2. Design criteria for macrolocations of monitoring stations

To accomplish the established objectives of monitoring networks, water quality and/or quantity samples should be collected at appropriate locations that have been carefully selected in keeping with criteria related to monitoring sites, parameters, frequency, etc. The selection criteria for station macrolocations are outlined in the section below.

2.2.1. Representativeness of a river basin

To meet objectives 1 and 8, water quality data should be collected at the monitoring stations representing each watershed unit in a river system. Drawing on earlier research into monitoring network design, Sanders and Adrian (1978) presented a general method for selecting macrolocations of monitoring stations to be used in examining long-term water quality changes. Sander's method is based on Sharp's method (Sharp, 1971), in which a stream network is divided into subdomains with a similar number of tributaries. The method was applied in designing a monitoring network to detect pollution sources implicated in water quality changes. In this method, a tributary is treated as a pollution source. A magnitude of one is assigned to any exterior tributary that has no inflowing connection, assuming a specified minimum mean discharge. The intersection of two exterior tributaries forms a new, second-order tributary that has the combined magnitude of the merging tributaries. Continuing downstream in the same manner, a river reach is formed by the intersection of two upstream tributaries and its magnitude increases, reaching maximum value at the river mouth, which represents the total number of tributaries. In this procedure, the number of selected links for monitoring stations increases exponentially until the target number of sampling stations in the design plan is reached. Sander's method offers the advantage that monitoring stations can be sited by taking available resources into account (Sanders, 1980).

2.2.2. Compliance with water quality standards

A major role of water quality monitoring networks is to find out whether water quality standards are being violated and, if so, where and how often the violations occur and how long they last. For such purposes (Objective 2), water quality samples should be collected in stream sections with degraded water quality. Since, in general, the spatial trend of water quality in a river system consists of increasing deterioration in a downstream direction, the designer of a monitoring network needs to divide the main stream between the influent and the effluent into a specified number of stream units with the same interval and to locate monitoring stations at the end of each stream unit. The length of a stream unit and, therefore, the total number of stream units can be determined in accordance with the available resources and the target number of monitoring stations in the network.

2.2.3. Surveillance of pollution sources

For monitoring stations established to track pollution sources (Objective 3), water quality samples should be collected in spots where identified point and non-point pollution sources can be regularly monitored. For careful observation of point pollution sources, such as industrial or treatment facilities and tributaries, monitoring stations should be located on the reaches below pollution discharging facilities and tributaries and on both upper and lower reaches at the point where the point sources flow into the stream. In cases where wastewater treatment facilities and other major point sources are required to report the quality and quantity of their effluent discharges, government-operated monitoring networks can exclude them from the list of candidate monitoring stations. For non-point sources, monitoring stations may be located at the starting and ending points of observation.

2.2.4. Supervision of water use

Water quality data should be sampled at water treatment facilities or other water intake facilities intended for municipal or industrial use, to support the utilization of water resources (Objective 4). Although these monitoring stations can be placed in specific locations to detect accidental pollution, they usually coincide with those dedicated to checking compliance with water quality standards. Because water quality standards are based on the assumption that there will be no adverse effects on water use and only native species in the water body, water use may not be affected by pollution sources unless water quality in the location already violated pre-established water quality standards. If there are tributaries or pollution sources between a monitoring site and a water intake, however, monitoring stations should be located at around the intake facilities in the upstream zone.

2.2.5. Examination of water quality changes

The quantitative evaluation of water quality changes begins with a mass balance study of pollutants flowing into a target water body together with a water balance analysis. Therefore, monitoring stations for Objectives 5 and 7 should be sited by taking topography, hydrology, relevant water chemistry and configurations of pollution sources and tributaries into consideration. Parameters for both water quality and quantity should be measured simultaneously at the monitoring stations. In addition, the monitoring network should be designed to permit easy application of the information for calibration and verification in water quality models.

2.2.6. Estimation of pollution loads

Analyses of mass balance and water balance and of TMDL performance in a watershed call for information on pollution loads and water quantity from each discharging basin. For this objective (Objective 6), it is appropriate to locate monitoring stations at the confluence of each discharging basin and to observe parameters for both water quality and water quantity. Monitoring stations for estimating pollution loads generally coincide with those for tracking water quality changes.

When macrolocations of monitoring stations are determined based on the above criteria, the physical accessibility of sampling points should also be taken into account, except when automated monitoring devices are installed. For exam-

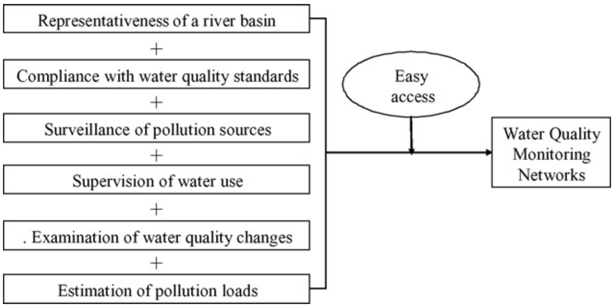


Fig. 1 – Selection of water quality monitoring stations.

ple, bridges over streams/rivers can provide easy access to water bodies. In addition, distance to laboratories and storage facilities can be considered in selecting monitoring sites. Fig. 1 shows criteria and factors that are considered in the selection of monitoring stations.

2.3. *Optimized network design using the genetic algorithm*

A genetic algorithm for designing water quality monitoring networks was developed in Visual C++ with GAlib, a library of genetic algorithm objects and tools for doing optimization using any representation and genetic operators (Fig. 2). The first step in the algorithm involves generating random numbers. These numbers are used to construct an initial chromosome consisting of a set of monitoring station locations in a water quality monitoring network. The size of the chromosome – the number of locations included in a chromosome – is determined by the dimensions of the monitoring network design. The next step involves spatial analysis of the locations, providing input data for the fitness evaluation. The initial chromosome, which now has fitness scores, undergoes different operations such as reproduction, crossover and mutation. The operation ends if the chromosome satisfies the conditions specified by its designers, or new generations are created until the station locations of the monitoring network are optimized.

Since the genetic algorithm is based on random searching for solutions, its final results cannot be identical since the starting points are randomly selected, although the other input parameters are unique. Therefore, iterative processes for determining appropriate parameters should be performed (Kuo et al., 2000). Previous research revealed that the optimal solution may be to search at a high rate of crossover, a low rate of mutation and proper population size (De Jong, 1975).

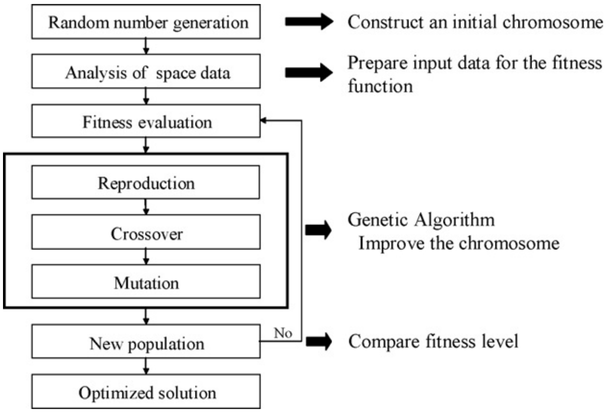


Fig. 2 – Solution searching scheme of the genetic algorithm.

3. Application of the proposed methodology

3.1. *Site description*

The Nakdong River, the second largest river in Korea, is located in the southeastern region of the Korean Peninsula (37°13′–35°2′N, 129°14′–127°30′E). The river drains an area of 23,817 km^2, which is approximately a quarter of Korea, and its main stream is 521.5 km long (Fig. 3). This region is affected by heavy rainfalls in the monsoon season from June through July along with several typhoon events with large amounts of precipitation. Mean annual precipitation is 1187 mm. However, about 60% of the precipitation falls during the monsoon season as is the case for all the river basins in Korea. The Nakdong River is, therefore, characterized by distinct annual patterns linked to its heavy rainfall. Water quality monitoring networks have been installed and operated since the 1960s to permit rigorous water resources management. By 2003, 110 monitoring stations were in operation, providing a variety of information on water quality (Korea MOE, 2003).

3.2. *Linking a geographic information system and a genetic algorithm*

A geographic information system was used in conjunction with the genetic algorithm for the effective analysis of information collected from an extensive river basin. By representing each geographic element as a “layer” through a

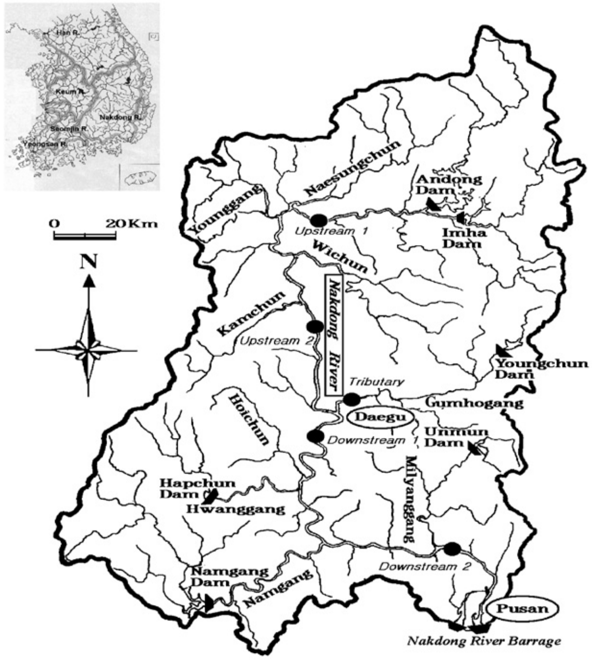
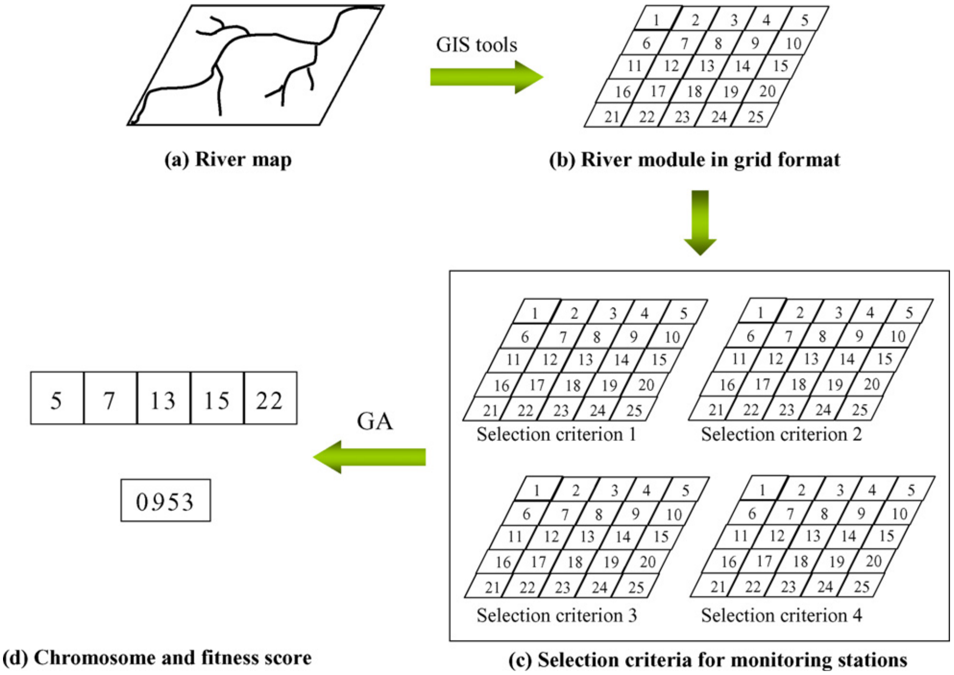


Fig. 3 – Map of study area—The Nakdong River, Korea.



(a) River map (b) River module in grid format (c) Selection criteria for monitoring stations (d) Chromosome and fitness score

Fig. 4 – Linking of GIS and GA.

systematic arrangement, ArcView (Version 3.2) GIS software was used to conduct various types of spatial analyses on massive amounts of geographic data. The constructed database was then linked to the genetic algorithm as input data for finding optimal solutions.

Fig. 4 delineates the conceptual scheme for linking the genetic algorithm and the geographic information system in designing a water quality monitoring network. A river map was constructed in grid format (Fig. 4a) using a GIS tool and a digitized map of the study site. Through a transformation process, the entire river basin was divided into homogeneous cells measuring 15,000 m × 15,000 m, and each cell was assigned a number representing a basic unit of geographic space (Fig. 4b). Each number is a gene making up a chromosome used by the genetic algorithm—a set of candidate locations for a monitoring network. Fig. 4c shows the selection criteria for the objectives of the water quality monitoring networks. As shown in Fig. 4d, each chromosome has a unique fitness score that is a key determinant of its evolution in the genetic algorithm.

3.3. *Fitness functions in the genetic algorithm*

The genetic algorithm determines which individuals should survive, which should reproduce and which should die. As a major determinant, a fitness score, F, is estimated from individual fitness functions and is used to calculate reproduction in the genetic algorithm. The final fitness score can be determined as:

$$F = \max\left[\sum_{i=1}^{n} w_i \bar{f}_i\right] \qquad (1)$$

where n is the number of individual fitness functions. w_i is the weighting function for the ith individual fitness function, which implies a weighting for each design criterion.

For the purpose of this study, all of the weighting functions were assigned a value of unity, which means no weighting for any specific criterion. Further studies on designer's preferences are needed to specify and apply weighting functions to the proposed genetic algorithm for designing water quality monitoring networks.

$\bar{f}_i$ is the normalized fitness score of the ith individual functions. In this study, six criteria were proposed for designing water quality monitoring networks and four fitness functions were defined from those criteria. For the criterion of representativeness of a river basin, instead of defining an individual fitness function, monitoring locations selected by Sander's method were used as the basis for candidate locations of water quality monitoring stations. The first criterion was expressed mathematically as a binary function in which each element at a location having a sufficient level of representativeness is defined to remain effective. The fitness function for compliance with water quality standards (f_1) was defined by the relative importance of candidate locations, as determined from the degree of violation of water quality standards using BOD as an indicator. The fitness function estimated the need for monitoring using an exceedance value relative to the dry season BOD. The need for monitoring for supervision of water use was estimated by the distance between the monitoring station and the nearest upstream water intake. The fitness function f_2 uses the reciprocal of this distance, so that the fitness score increases as the distance between the monitoring station and the water intake decreases. This means that the likelihood of being selected increases. The fitness function for the surveillance of pollution sources (f_3) was formulated based on the assumption that the concentrations of pollutants flow-

Table 1 – Fitness functions used to design a water quality monitoring network

Criteria	Fitness functions	
(A) Representativeness of a river basin	$Y_{ij} = \begin{cases} 1 : \text{where selected for the representativeness} \\ 0 : \text{otherwise} \end{cases}$	i: column number; j: row number
(B) Compliance with water quality standards	$f_1 = Y_{ij} \frac{C_{ij} - S_{ij}}{C_{ij}}$	C_{ij}: BOD measured in dry season (mg L^{-1}); S_{ij}: BOD for water quality standard (mg $L^{-}1$)
(C) Supervision of water use	$f_2 = Y_{ij}(E_{ij})^{-1}$	E_{ij}: distance to the nearest water intake in the upstream (km)
(D) Surveillance of pollution sources	$f_3 = Y_{ij} \sum_{k \in S} [(e^{x_{ij}})^{-1}]_k$	x_{ij}: distance to a pollution source (km); S: number of pollution sources in the upstream zone
(E) Examination of water quality changes/estimation of pollution loads	$f_4 = Y_{ij}(L_{ij})^{-1}$	L_{ij}: distance to the river outlet (km)

ing into a stream decrease exponentially as the flow moves downstream. Selection criteria for the examination of water quality changes and the estimation of pollution loads (f_4) were represented as a single fitness function using the concept of monitoring distance. It was assumed that the characteristics of water quality changes in a unit watershed are best represented closer to the corresponding outlet. In all, 191 unit watersheds in the Nakdong River system were included in this analysis, using the distance between the candidate locations and each outlet. The fitness functions proposed for selecting macrolocations of monitoring stations are listed in Table 1.

Owing to the differences in statistical meaning and range of values for each individual fitness score, the individual fitness scores had to be normalized by multiplying them by a weighting function, before summing them to obtain a final fitness score.

4. Results and discussion

4.1. *Sensitivity analysis*

In the process of evolution, the genetic algorithm makes use of three genetic operators, namely reproduction, crossover and mutation, for which occurrences are statistically determined. Genetic algorithms studies generally involve the analysis of various parameters that affect the operators; these parameters are usually determined on the basis of previous experience. However, in cases where little information is available and it is unclear what criteria should be used to design variables, the parameters should be empirically determined through a series of sensitivity analyses. The parameters that shape the evolutionary process and the rate of convergence toward the optimal solution include population size, number of generations, probability of crossover (P_c) and probability of mutation (P_m). In this study, a set of default values were initially assigned to the parameters, and the genetic algorithm was run for various cases.

Solutions generated using genetic algorithms generally show a rapid evolution and an immediate increase of fitness scores in early generations, followed by very small changes in later generations. It seems inefficient to pursue fully converged solutions by setting the generation number close to infinity. In this study, therefore, an approximate solution with reasonable precision was adopted as a final fitness score. Table 2 shows four sets of design parameters which stood out based on the sensitivity analyses for the parameters representing population size, number of generations, probability of crossover and probability of mutation. Applying these parameter sets to the genetic algorithm for obtaining final fitness scores, the optimal condition for designing parameters was determined.

Optimal design parameters for the genetic algorithm were determined for a monitoring network through a series of sensitivity analyses. Figs. 5 and 6 show how the average and maximum fitness scores vary as the number of generations is increased, for the four cases specified in Table 2. As mentioned above, the fitness scores have a high initial rate of change

Table 2 – Selected sets of design parameters for genetic algorithm

Case	Population size	Generation number	Probability of crossover (P_c)	Probability of mutation (P_m)
1	300	4000	0.8	0.005
2	300	4000	0.8	0.01
3	500	4000	0.8	0.005
4	500	4000	0.8	0.01

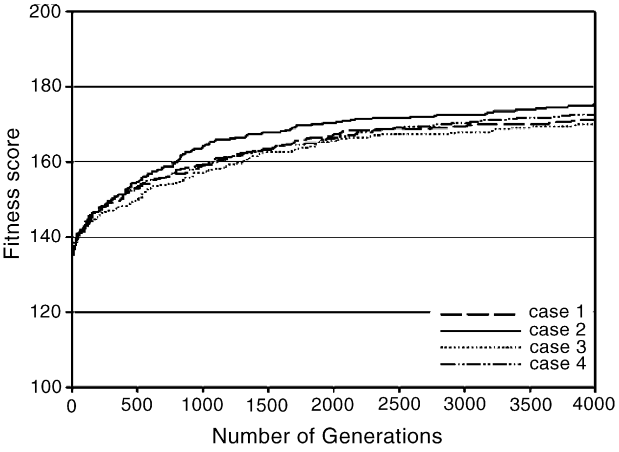


Fig. 5 – Comparison of fitness score in each case—average score.

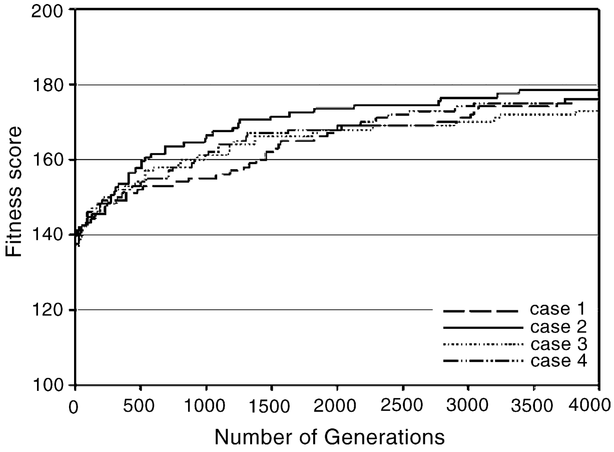


Fig. 6 – Comparison of fitness score in each case—maximum score.

but the rate of increase declines as the genetic algorithm proceeds. For both the average and maximum fitness scores, case 2 (Table 2) produced the highest values. Therefore, the parameter values used for case 2 were applied in the genetic algorithm to design the water quality monitoring network.

4.2. Proposed water quality monitoring network for the Nakdong River

The optimized combinations of design parameters were used to design the water quality monitoring network. Using the GIS, various types of information on the Nakdong River were transformed into specific data types suitable for the genetic algorithm. The results were proposed as candidate locations for water quality monitoring stations and were visualized using the geographic information system. The locations of the 110 proposed monitoring stations (same number as in the existing monitoring network for the Nakdong River) were compared with those in the existing network (Fig. 7). In all, 35 of the 110 proposed station locations coincided with existing stations; the rest of them represented new locations. This means that in order to improve the effectiveness of the Nakdong River monitoring network, some stations should be relocated and others added as part of a future expansion plan. Fig. 8 presents a detailed comparison of the existing and proposed sampling locations in the middle section of the Nakdong River.

Compared to countries with advanced water resources management programs, Korea still has a relatively small num-

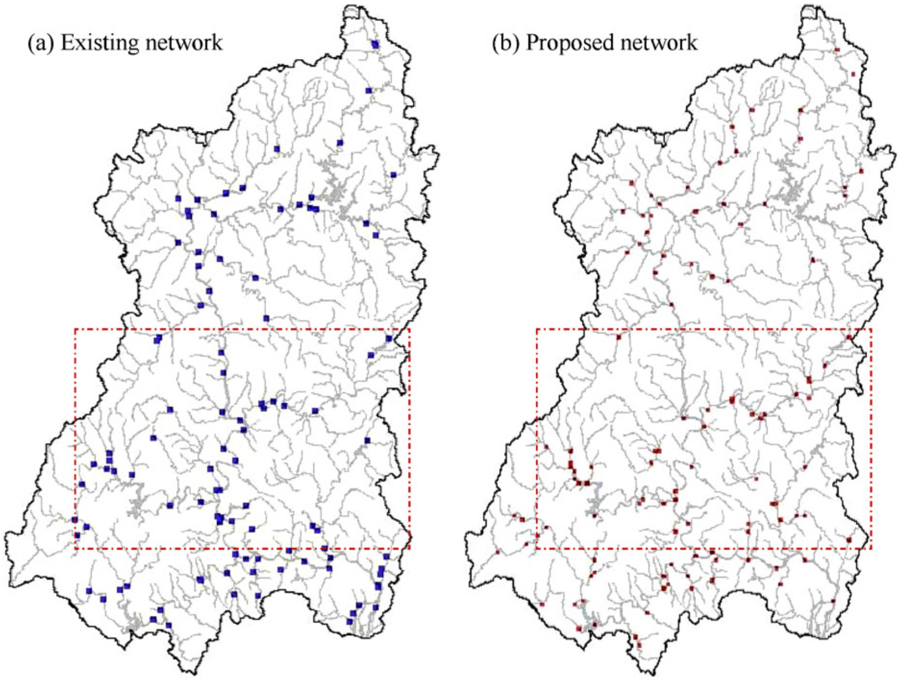


Fig. 7 – Comparison of proposed and existing water quality monitoring network in the Nakdong River—110 monitoring stations.

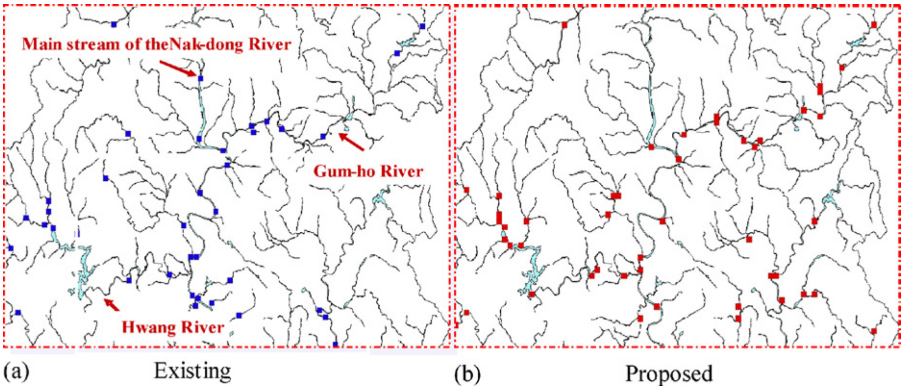


Fig. 8 – Detailed comparison of proposed to existing water quality monitoring stations in the Nakdong River.

ber of monitoring stations and these stations provide a limited amount of information. Although there have been serious discussions of these issues in recent decades, few studies have been conducted on the design criteria for water quality monitoring networks, and this has been an impediment to network expansion. Starting with the proposed water quality monitoring network, composed of 110 monitoring stations, this study also put forward a new stepwise expansion plan that adds 20 stations in each step. The expansion plan with the different number of stations can be seen in Fig. 9.

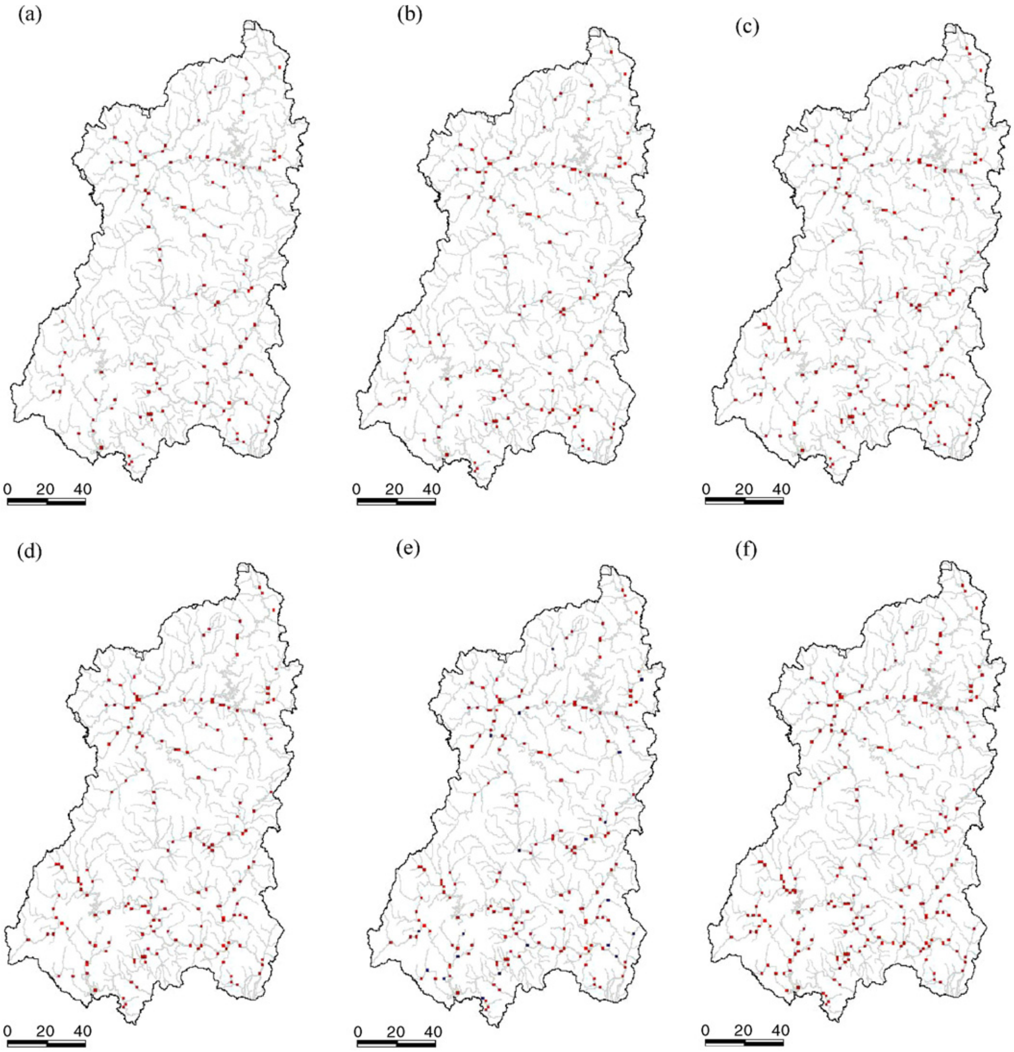


Fig. 9 – A proposed stepwise expansion plan for the water quality monitoring network in the Nakdong River. (a) 110 stations, (b) 130 stations, (c) 150 stations, (d) 170 stations, (e) 190 stations and (f) 210 stations.

5. Conclusion

In order to address critical issues related to the subjective or intuitive design of water quality monitoring networks, this study proposed a scientific design methodology using a genetic algorithm and a geographic information system. Through the identification of fitness functions for the genetic algorithm, a mathematical framework was developed with a view to meeting the objectives of monitoring networks and defining selection criteria for macrolocations of individual monitoring stations. A geographic information system was used to prepare input data for the genetic algorithm and to analyze and visualize a new monitoring network design for the entire Nakdong River system in Korea. The proposed methodology gave rise to a new water quality monitoring network consisting of 110 monitoring stations, and demonstrated its usefulness as a design tool for the stepwise redevelopment and/or expansion of water quality monitoring networks.

Although the optimized design for a monitoring network derived with the genetic algorithm may be superior to traditional, subjective designs, further studies are required to define fitness functions that can represent comprehensive relationships or priorities among selection criteria.

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