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SCREENING THE RELOCATION STRATEGIES OF WATER QUALITY MONITORING STATIONS BY COMPROMISE PROGRAMMING[1]

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ABSTRACT: Water quality monitoring network designs historically have tended to use experience, intuition, and subjective judgment in siting monitoring stations only sporadically. Better design procedures for optimizing monitoring systems with respect to multiple criteria decision analysis had rarely been put into practice up front when the needs for intensive monitoring became critical. This paper describes a systematic relocation strategy that is organized to identify several significant planning objectives and consider a series of inherent constraints simultaneously. The planning objectives considered in this analysis are designed to enhance the detection possibility for lower compliance areas, reflect the emphasis for different attainable water uses at different locations, promote the potential detection for the lower degradation areas of pollutants, increase the protection degree of those areas with higher population density in the proximity of the river system, and strengthen the pre-warning capability of water quality for water intakes. The constraint set contains the limitations of budget, the equity implication, and the detection sensitivity in the water environment. A case study in the Kao-Ping River Basin, South Taiwan, demonstrates the application potential of this methodology based on a seamless integration between the optimization and the simulation models. It enables identification of the optimal locational pattern stepwise using the embedded screening and sequencing capacity in a compromise programming model. However, a well calibrated and verified water quality model is an indispensable tool in support of this multiobjective evaluation. Extra sampling procedures become necessary for the sites with sparse environmental information. Comparison of planning outcomes of compromise programming is made against previously achieved analyses by using weighted programming and fuzzy programming.
(KEY TERMS: rivers/streams; monitoring network; water quality; watershed management; compromise programming; multicriteria decision making.)

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INTRODUCTION

To learn the processes, interactions, and impacts of environmental changes on livelihood, a water quality monitoring network is one of the vital environmental monitoring systems that are often installed to address regional water quality concerns at numerous time scales in an aquatic environment, such as river, estuary, reservoir/lake, wetland, or ground water system. The monitoring network was often designed to facilitate sustained monitoring of regular and emergency release attributes with regard to ecosystem features, environmental quality indices, human health factors, and economic impacts. The data from these sampling stations may help the decision makers identify problems, document improvements, and demonstrate overall trends in water quality. Thus, it is crucial to review the current network design procedures and develop basic guidelines to be followed in the design, expansion, and relocation of surface water quality monitoring networks. In recent years, the adequacy of collected water quality data and the performance of existing monitoring networks have been seriously evaluated for two basic reasons (Harmancioğlu *et al.,* 1998). First, an efficient information system is required to satisfy the needs of water quality management plans and to aid in the decision making process (Harmancioğlu *et al.,* 1998). Second, this system has to be realized under the constraints of limited financial resources, sampling and analysis facilities, and manpower (Harmancioğlu *et al.,* 1998). To ensure cost-effectiveness, an evaluation adopted for a water quality monitoring network should cover all relevant

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technical design features, including selection of sampling sites, sampling frequencies, variables to be monitored, sensors synergy, and sampling duration (Loftis and Ward, 1980).

The design issues relating to surface water quality monitoring networks have received wide attention since the 1970s (Moore, 1973; Beckers and Chamberlain, 1974; Lettenmaier, 1978; Ward, 1979). Various attempts were made in the 1980s to improve the monitoring efficiency with regard to the basic design criteria (Skalski and Mackenzie, 1982), optimization analysis (Groot and Schilperoot, 1983), comparisons of the features of fixed stations versus intensive surveys (Van Belle and Hughes, 1983), consolidation of the network design (Lettenmaier *et al.,* 1984), importance of data collection (Whitfeld, 1988), and interpretation of monitoring outcomes (Ellis, 1989). Earlier studies in the 1990s included the work done by Smith and McBride (1990), Loftis *et al.* (1991), and Esterby *et al.* (1992) that had covered the fundamental principles and applications in siting the water quality monitoring stations. Later, more advanced analyses utilized integer programming (Hudak *et al.,* 1995), multiobjective programming (Harmancioğlu and Alpaslan, 1992; Cieniawski *et al.,* 1995), Kriging theory (Lo *et al.,* 1996), goal programming (Ning and Chang, 2002), and fuzzy programming (Ning and Chang, 2004) for assessing complex issues of surface and ground water monitoring networks. The design principles, guidelines, strategies, and implementation for water quality monitoring and assessment that cover a broad sense of chemical and biological impact assessment were reviewed (Dixon and Chiswell, 1996; Timmerman *et al.,* 1997; Leeds *et al.,* 1997). Dixon and Gardner (1998) further described how the United Kingdom Acid Waters Monitoring Network (AWMN) worked collaboratively within a seven-year time frame. In particular, Harmancioğlu *et al.* (1998) summarized the technologies and solutions for planning and designing various water quality monitoring networks. Information retrieval from the monitoring networks has turned out to be critical, recently leading to develop a variety of visualization techniques that might be useful for demonstrating important aspects of a water quality monitoring network (Boyer *et al.,* 2000).

In the US, several state governments, such as Florida and Idaho, have implemented the water quality monitoring network program that is normally composed of four tiers (Idaho Department of Environmental Quality, 2002). Tier I monitoring is designed for meeting national goals under the Clean Water Act. Tier II is comprised of status and trend monitoring designed to answer province or state wide to regional questions. Tier III monitoring includes basin assessments and monitoring required for total maximum daily loads (TMDLs) development. Tier IV includes all monitoring tied to regulatory permits issued by the government and is associated with evaluating the effectiveness of best management practices (BMPs) or TMDLs. This paper presents a multiobjective evaluation that is equivalent to a basin-wide assessment for water quality monitoring (i.e., a Tier III analysis). It also uniquely shows a holistic approach of how to integrate an optimization scheme of compromise programming with QUAL2E simulation analysis for water quality monitoring network assessment (Ning *et al.,* 2001; Ning and Chang, 2002). Compromise programming is a relatively recent decision science methodology. It is based on the notion of distance from an ideal solution, which combines the best and most useful features of both linear multiobjective programming and goal programming and is not limited to the linear cases; it can be used for identifying nondominated solutions under the most general conditions. The model allows prespecified goals leading to provide an excellent base and a flexible tool for interactive programming (Zeleny, 1982).

The objective of this study was to search for the optimal relocation strategy of water quality monitoring stations to meet the goal of long term monitoring of water quality variations in the Kao-Ping River Basin, South Taiwan. As a companion study of Ning and Chang (2002), this analysis emphasized indirect tradeoffs between distance based scalable objective functions and direct tradeoffs using an earlier weighted method so as to enable one to pinpoint and entail easily the compensatory implications of decision making. For the indefinite characteristic of planning objectives, another previous study, using the fuzzy mathematical programming technique, accomplished the purpose of uncertainty analysis desired in decision making (Ning and Chang, 2004). Therefore, the needs for an updated systematic assessment to explore the possible relocation strategy and expansion sequence of a monitoring network in the Kao-Ping River Basin motivated the following analysis.

STUDY AREA

The Kao-Ping River in Taiwan flows approximately 140 kilometers and drains towards the south part of the Taiwan Strait. With an area of 3,256 square kilometers, including the major administrative regions of Kaohsiung and Pingtung counties, the main stream of the Kao-Ping River originates from four small tributaries: Chi-San River, Liao-Nung River, Cho-Kou River, and Ai-Liao River (see Figure 1). From the confluence to the union with those tributaries at the Li-Ling Bridge, the river carries the name Kao-Ping

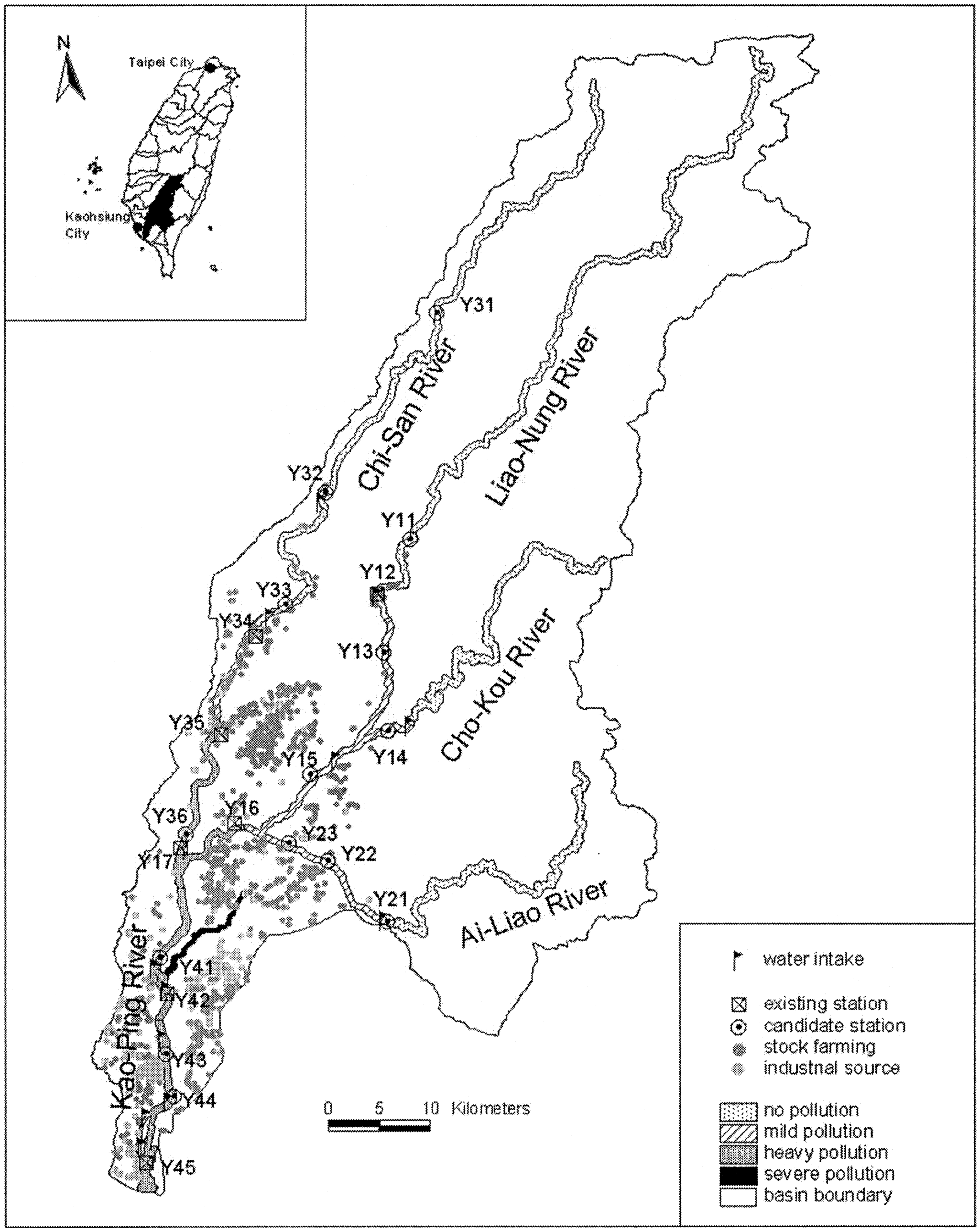

Figure 1. The Present Pollution Source Distribution in the Kao-Ping River Basin.

River. But Liao-Nung River and Kao-Ping River are generally regarded as the integrated main stream of the Kao-Ping River system in many governmental management practices.

The water year in a hydrological sense can be divided into two seasons. The wet season generally covers the time period from May to October, and the remaining time period is the dry season. Although the mean annual rainfall in this river basin is close to 3,000 mm, over 90 percent occurs in the wet season. Summer is hot, with the temperature often reaching 36°C. The period of high flow rate in the stream usually occurs in late spring and summer due to monsoons and typhoons. During the monsoon period, the Kao-Ping River flow increases to a level approximately 8 to 12 times higher than flow during the dry season. Uneven rainfall across seasons has resulted in issues of water resources redistribution in the winter and earlier spring that inevitably requires building more reservoirs for water storage.

The drainage area in the Kao-Ping River Basin is primarily used for agricultural production. Crops that are produced from the agricultural fields include: rice, sugar cane, pineapple, and a variety of vegetables.

Livestock farming is an active agricultural activity. In addition, a number of small scale and medium scale industries are also found in the downstream region. In addition to meeting the water demand for agricultural production and industrial manufacturing processes, water pumped from the river system is also essential for drinking and personal hygiene in this area of Taiwan. Concern and attention in water resources management have been directed primarily to the uneven distribution of rainfall and stream flows over the dry and wet seasons. While four reservoirs are in operation in the neighboring Tseng-Wen River Basin for water storage, none exists in the Kao-Ping River Basin. Yet the siting and building of an off-stream reservoir – Mei-Nung Reservoir – with its intake (i.e., Chiu-Chuang) located in the upper stream area of the Kao-Ping River system, have resulted in an intensive debate over its potential ecological impacts. At present, the transfer of water resources from the main stream of the Kao-Ping River to the Nan-Hua Reservoir, which is located in the Tseng-Wen River system, becomes an indispensable solution to improve the reliability of water supply for two big cities – Tainan and Kaohsiung – in the coastal region. Although the agriculture sector is always the largest user of water, the latest development of three large-scale industrial complexes in the Tseng-Wen River system requires more water transferred from the upper stream area of the Kao-Ping River in the wet season. Industrial water requirements will therefore increase substantially. For the Kao-Ping River system, which has a long history of higher biochemical oxygen demand (BOD) and ammonia-nitrogen (NH_3-N) due to inadequate disposal of manure from livestock farming, industrial effluents, and domestic wastewater discharges, proper utilization of river water as potable water has encountered a new challenge with regard to both technological and managerial requirements. Figures 2 and 3 describe the concentrations of BOD and NH_3-N in the Kaohsiung River Basin, where long term violation of water quality standards is salient. Continuous discharge of organic, degradable wastewaters into the middle and downstream areas of the Kao-Ping River system, where most water intakes are located in this region, has resulted in the need for a systematic policy for improving the water quality condition. Thus, a sound water quality monitoring system to support essential analyses has become an urgent demand.

SIMULATION ANALYSIS

Simulation analysis methods are an integral part of a complete monitoring program design, which should be considered in the initial planning stage. The simulation outputs that characterized the internal features of a river system will then largely dictate the later site selection process. The simulation model QUAL2E, which was used as a tool in this study, is a steady state model for tracing conventional pollutants in one-dimensional streams and well mixed ecosystems (Brown and Barnwell, 1987). It illustrates the important physical, biological, and chemical processes and their interactions for the particular water quality constituents of interest based on a set of partial differential equations. The governing equations of QUAL2E illustrate the effects of dispersion, advection, constituent reactions, and interactions among constituents. It allows multiple waste discharges, withdrawals, tributary flows, and incremental inflow and outflow. QUAL2E may consider up to 15 constituents, including a conservative mineral (C), algae (A), NH_3-N), nitrite-nitrogen (NO_2-N), nitrate-nitrogen (NO_3-N), organic-phosphorus (org-P), dissolved-phosphorus (dis-P), BOD, dissolved oxygen (DO), coliform, and radioactive material. This study is designed to be capable of predicting the variations of DO and the decay rate of BOD, total phosphorus, and NH_3-N along the river reaches.

To gain a deeper understanding of the water quality condition in river reaches, a large-scale sampling campaign was carried out during dry and wet seasons (Ning *et al.,* 2001). Each of the dry and wet sampling programs consisted of a 96-hour survey during August 1998 and February 1999. There was a total of 45 sampling sites covering the river system from its origin to the estuary. After accomplishing the field and laboratory measurements through a quality assurance and quality control procedure, environmental databases were integrated with a hydraulic database and applied for model (QUAL2E) calibration and verification (Ning *et al.,* 2001). In the simulation analysis, the total study length of 170 km in the Kao-Ping River system was discretized into nine river reaches that consisted of 85 computational elements. The calibrated QUAL2E model was applied directly for deriving a new parameter – the half-life distance, representing the distance required for the decay of half of the concentration for the constitutes of concern. The condition for calculation of half-life distance is set on the critical scenario of river discharge, which was the average flow rate in the dry season (i.e., October to March). The planning alternatives may vary over the design flow rate in the river, and an applicable water quality model is necessary for the projection of half-life distance. The assumption for dry season steady state condition has to be maintained during the whole modeling process. Once the decay versus distance associated with each designated constituent can be identified via the simulation analysis,

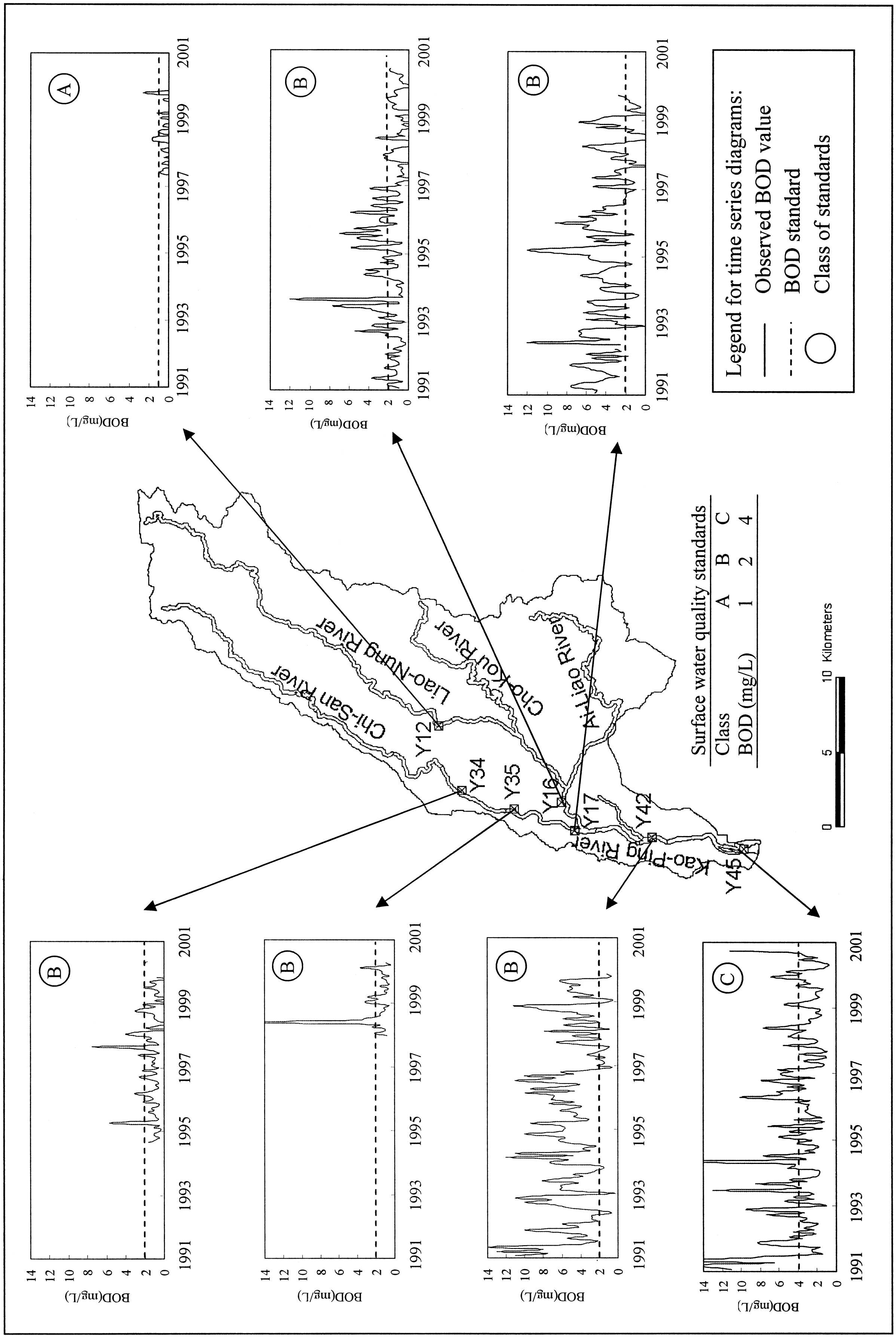

Figure 2. Water Quality Monitoring of BOD in the Kao-Ping River Basin.

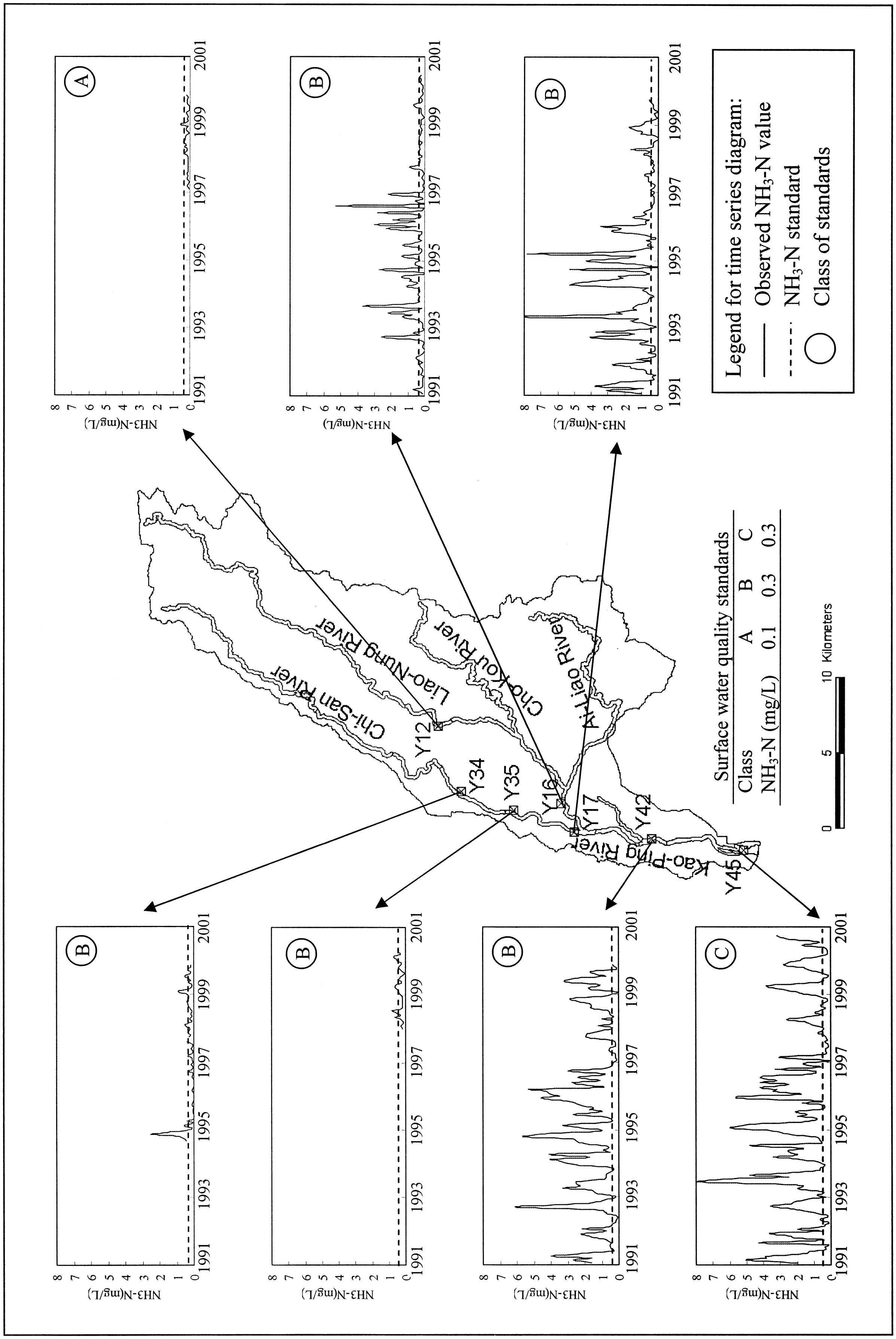

Figure 3. Water Quality Monitoring of Ammonia-Nitrogen in the Kao-Ping River Basin.

aggregate detection sensitivity of all constituents of concern in relation to each candidate site may become available for use in the subsequent optimization analysis. Moreover, the QUAL2E model is also responsible for simulating the water quality situation of concern in candidate monitoring stations that have no records. Figure 1 indicates the 21 candidate monitoring stations that were identified in the river system, in which seven of them are current. Obviously, most of the existing stations are located in the downstream area close to the higher populated region.

FORMULATION OF COMPROMISE PROGRAMMING MODEL

Kwiatkowski (1991) pointed out some essential objectives that are common to many large water-quality monitoring-networks. They were designed to: (1) provide information on the location, severity, regional or volumetric extent, frequency, and duration of non-compliance of variables of concern; (2) support information for measuring site specific or whole network responses to increase anthropogenic inputs or control measures, using trend analyses or cause and effect relationships and determine the presence of new or hitherto undetected problems, leading to proactive, rather than reactive pollution control measures; (3) supply information for development and application of predictive models for assessing the impact of new pollution sources and assessing various enforcement and management strategies; and (4) determine ecosystem health and identify significant changes from normal succession or expected sequential changes that occur naturally in aquatic ecosystems.

Five planning objectives were considered in this analysis. They were designed to protect: (1) the monitoring sites for lower compliance areas of water quality, (2) important locations with regard to attainable water uses, (3) lower degradation areas of specific pollutants, (4) regions of higher population density, and (5) upstream districts of potable water intakes. The constraint set contained the budget limitations, equity implications, and detection sensitivity in the water environment, eventually leading to a multiobjective, mixed integer programming model having five objectives to be compromised, subject to several inherent constraints. Since the difference in streamflow rate between the wet and dry seasons is substantial, only the dry season condition is a critical consideration in the design procedure. Sampling sites will be selected from a set of candidate sites for relocation and expansion. The following compromise programming looks for a set of compromise solutions instead of an optimal solution based on a multi objective evaluation framework.

Objective Function

The planning objectives are designed to increase the detection possibility for those lower compliance areas, to emphasize potential uses of the water body at different locations, to increase the potential detection sensitivity by applying better location strategy, to address the degree of protection of those areas with higher population density in the proximity of the river system, and to monitor the water quality in the areas upstream of all water intakes. The formulation of the objective functions is illustrated as follows.

- *Maximize the possibility of detecting sites violating water quality standards*. The proposed methodology for designing a water quality monitoring system first aims at compliance monitoring to detect violations of regulations. Thus, this objective indicates the monitoring network to be built or expanded should exhibit the highest potential capability to detect the severely polluted areas with respect to a set of pollutants of concern. It can be expressed as

$$Z_1 = \sum_{i=1}^{p} \sum_{j=1}^{q_i} Y_{ij} \sum_{k=1}^{r} \frac{C_{ijk} - S_{ijk}}{C_{ijk}}, \forall\, i, j, k \quad (1)$$

where C_{ijk} represents the mean concentration of the k^{th} pollutant of concern in the dry season at the j^{th} monitoring station in the i^{th} tributary (mg/L); S_{ijk} is the water quality standard of the k^{th} pollutant in the river reach of concern where the j^{th} monitoring station in the i^{th} tributary is located (mg/L); p is the total number of tributaries in the Kao-Ping River Basin; q_i is the total number of candidate stations in the i^{th} tributary; r is the total number of pollutants of concern; and Y_{ij} is the binary variable in which 1 represents that the candidate location is included in the alternative, 0 otherwise (dimensionless).

- *Maximize the possibility of detecting sites located on the important reaches of water quality protection*. This objective implies that the higher the degree of attainable water uses in the river reaches, the more the motivation for setting monitoring station(s) for the protection of water quality.

$$Z_2 = \sum_{i=1}^{p} \sum_{j=1}^{q_i} Y_{ij} R_{ij}, \ \forall\, i, j \quad (2)$$

where R_{ij} is the utilization category of a water body in the river reach where the j^{th} monitoring station in the i^{th} tributary is located. In Taiwan, water quality standards have been designated with respect to five surface water categories that are denoted from Class A to Class E and generally refer to various purposes of surface water utilization. Thus, the values of R_{ij} were assigned 10, 8, 6, 4, and 2 for each category in this study. The range of R_{ij} values is designed to be similar to the data range of other parameters to avoid the scaling problem in the mathematical programming.

• *Maximize the potential detection for the lower degradation areas of pollutants*. This objective shows that siting the monitoring stations in the river system must take the condition of pollutant transport and degradation capability into account at different locations. Such consideration may reflect the local condition of environmental assimilative capacity. The design criteria thus emphasize that an optimal monitoring network should be spatially located based on its overall detection sensitivity or warning potential with respect to a set of pollutants of concern in the river system. As a result, a new parameter – the half-life distance – should be defined in advance according to the output from the calibrated water quality simulation models, such as QUAL2E. This objective implies that the longer the half-life distance for a pollutant in the proximity of a specific candidate site, the less the chance for a neighboring candidate site to be selected as a monitoring station. Each half-life distance must be related to the flow velocity, river slope, depth, diffusivity, and particle settling at differing locations. The coordinate system used to define the half-life distance is a one-dimensional system along the river reaches starting from the estuary location to the origin of the river (i.e., denoted as $D_{i,j}$ in Figure 4). In Figure 4, $Y_{i,j}$ and $Y_{i,j+1}$ are the candidate sites and L_{ijk} is the half-life distance associated with candidate site $Y_{i,j}$, which can be estimated by a water quality simulation model. The integrated index covering all constitutes of concern through the summation of several half-life distances into a single value is thus designed to facilitate the comprehensive understanding of overall environmental assimilative capacity in the river system. The following formulation must be functioned along with the third constraint (i.e., Equation 6) to form the screening capability.

$$Z_3 = \sum_{i=1}^{p}\sum_{j=1}^{q_i} Y_{ij} \sum_{k=1}^{r} L_{ijk}, \forall\, i, j, k \quad (3)$$

where L_{ijk} is the half-life distance, that is, the geographical distance required for a decay of half the concentration of the k^{th} pollutant where the j^{th} monitoring station in the i^{th} tributary is located (km).

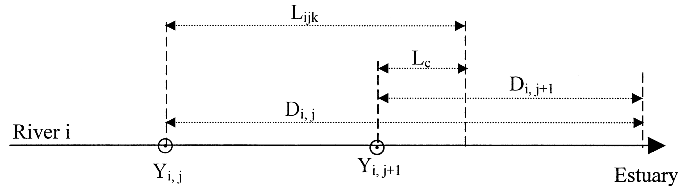

Figure 4. Coordinate System of Half-Life Distance as Defined in This Study.

• *Maximize the degree of protection of those areas with higher population density in the proximity of the river system*. This objective illustrates the purpose of monitoring stations being sited as close as possible to the locations where most people reside in the river basin.

$$Z_4 = \sum_{i=1}^{p}\sum_{j=1}^{q_i} Y_{ij}P_{ij},\ \forall\, i, j \quad (4)$$

where P_{ij} is the population within a 10 km radius of the j^{th} monitoring station in the i^{th} tributary (capita).

• *Maximize the monitoring potential for water quality at all upstream water intakes*. Monitoring stations should be sited as close as possible to the locations at which water intakes are sited. This is given by

$$Z_5 = \sum_{i=1}^{p}\sum_{j\in S} Y_{ij}\frac{1}{G_{ij}},\ \forall\, i,\ \ \forall\ j \in S \quad (5)$$

where G_{ij} is the distance between the j^{th} monitoring station in the i^{th} tributary and the nearest downstream water intake (km); and S is the subset of those candidate stations that are located in the stream above the water intake(s).

Constraint Set

The constraint set consists of the budget, detection sensitivity, equity, intake water quality, and the non-negativity constraints. The formulation of the constraint set is illustrated as follows.

• *Budget constraint*. This constraint implies that the total number of monitoring stations included in the alternative should be less than an upper bound with respect to the budget limitation.

$$\sum_{i=1}^{p}\sum_{j=1}^{q_i} Y_{ij} \le M, \ \forall\, i, j \qquad (6)$$

where M is the upper bound of the total number of monitoring stations (dimensionless). In this study, the cost of each monitoring station is assumed to be equal. Therefore, the monitoring equipment would be identical at each site.

• *Detection sensitivity constraint*. This constraint implies that the overlapped half-life distance between each pair of adjacent monitoring stations should be minimized to some extent. The information of the "effectiveness of coverage" from a spatial sense considered for each monitoring station must be addressed by a representative aggregate index in relation to the half-life distance for all constitutes of concern. Preference or emphasis can be assigned to a specific monitoring station or pollutant based on the weighting value (w_{ijk}) in the equation.

$$Y_{i,j+1}D_{i,j+1} - Y_{ij}\left[D_{ij} - \sum_{k=1}^{r}\left(w_{ijk}L_{ijk}\right)\right] < L_c, \ \forall\ i, j \qquad (7)$$

where D_{ij} is the geographical distance between the jth monitoring station located on the i^{th} tributary and the reference point at the estuary area (km); and L_c is the limitation of the overlapped half-life distance allowed in this systems analysis (km). Note that the subscript j is defined for each candidate site sequentially from the origin to the estuary region.

• *Equity constraint*. This constraint defines that each tributary in the river basin must at least have one monitoring station based on the equity sense.

$$\sum_{j=1}^{q_i} Y_{ij} \ge 1, \ \forall\, i \qquad (8)$$

• *Nonnegativity constraint*. All decision variables (i.e., Y_{ij}) must be defined as nonnegative and binary variables.

Overall, the decision variables Y_{ij} are binary variables that link all the requirements in the objective functions and the hydrological and environmental constraints to screen out a set of candidate sites for use as an integral part of the monitoring network.

Data Acquisition

The use of a geographic information system (GIS) to help determine the essential parameters for each site is viewed as an indispensable tool in this analysis. Spatial analysis, such as that in the ArcView® GIS software (ESRI, 1998), would be helpful to determine the population within a 10 km radius of each monitoring station. The GIS is also useful for measuring the geographical distance between each candidate monitoring station and a reference point, such as the estuary location or water intakes. Besides, with the aid of the QUAL2E simulation model, the half-life distance for each pollutant of concern around each candidate site may be obtained. Such information is used in the formulation of the third objective function (i.e., Equation 3) and the second constraint (i.e., Equation 7). In addition, attainment or nonattainment of water quality in the river system, needed for the first objective function, can be acquired from the previous sampling and simulation program. Table 1 shows the essential information acquired from the previous study (Ning and Chang, 2002).

Solution Techniques

Compromise programming, using the criteria of minimum distance from the ideal solution, is frequently used for solving various multiobjective decision analysis problems. Thus the noninferior solutions and tradeoffs among the objectives in this analysis are accordingly examined using compromise programming techniques. Due to the use of noncommensurable formats and units in those objectives, rescaling is needed before the optimization analysis is performed so that their values are all confined to a given range, such as [0,1]. Several scaling functions described in the literature can be applied. The recommended scaling function in this analysis is

$$Z = \frac{Z_k^*(x) - Z_k(x)}{Z_k^*(x) - Z_k^{**}(x)} \qquad (9)$$

where $Z_k(x)$ is the k^{th} objective function; and $Z_k^*(x)$ and $Z_k^{**}(x)$ are the maximum and minimum, respectively, value of each individual objective, which can be obtained from the payoff table (Zeleny, 1982). Hence, the compromise programming problem is equivalent to solving the following dimensionless function, which is just the relative measure of the decision maker's preference

TABLE 1. The Environmental Database of Candidate Stations.

Candidate Monitoring Stations	Objective 1 Degree of Violation of Water Quality Standard	Objective 2 Significance of Water Body	Objective 3 Half-Life Distance (km)	Objective 4 Population Covered Within a 10 km Radius (105 capita)	Objective 5 Distance to Nearest Downstream Water Intake (km)
Y_{11}	6.30	10	46.7	0.6189	0.6
*Y_{12}	3.20	10	34.0	1.1470	20.0
Y_{13}	3.16	10	26.0	1.4261	10.0
Y_{14}	0.00	8	22.0	0.9433	0.8
Y_{15}	0.00	8	16.0	1.9459	2.0
*Y_{16}	0.37	8	4.0	2.7363	2.0
*Y_{17}	5.64	8	2.0	2.3032	2.0
Y_{21}	2.38	10	14.0	0.5171	5.0
Y_{22}	0.00	8	6.0	2.4448	2.0
Y_{23}	0.00	8	2.0	2.7405	10.0
Y_{31}	2.80	10	34.0	0.1236	5.0
Y_{32}	4.40	10	26.7	0.5260	20.0
Y_{33}	0.00	8	10.0	1.3380	10.0
*Y_{34}	0.00	8	6.0	1.6424	20.0
*Y_{35}	9.98	8	2.0	4.0742	0.4
Y_{36}	14.61	8	6.0	2.2373	1.0
Y_{41}	4.22	8	9.3	10.2923	20.0
*Y_{42}	7.62	8	6.0	14.0617	2.2
Y_{43}	5.36	8	2.7	12.8035	1.8
Y_{44}	38.09	8	10.0	7.8133	10.0
*Y_{45}	23.05	6	2.0	4.6629	0.0

$$\text{Min } d_s = \left\{ \sum_{k=1}^{n} w_k^s \left(\frac{Z_k^*(x) - Z_k(x)}{Z_k^*(x) - Z_k^{**}(x)} \right)^s \right\}^{\frac{1}{s}} \tag{10}$$

where

$$1 \le s \le \infty, \ w_k^s > 0 \tag{11}$$

and

$$\sum_{k=1}^{n} w_k^s = 1 \tag{12}$$

The parameter n represents the total number of objectives, and w_k^s is the corresponding weight of each object (all w_k^s parameters were set at 1 in this study). In Equations (10) through (12) s is the distance parameter and $1 \le s \le \infty$. Observe that s = 1 corresponds to the cases of absolute compensation among the criteria, while $s = \infty$ indicates no compensation among the criteria. In particular, s = 1, s = 2, and $s = \infty$ are three cases of concern. For s = 1, the problem becomes a linear programming model and the objective function is defined as the Manhattan distance. While for s = 2, the solution will be the noninferior feasible solution which is closest to the ideal solution Z_k^* in terms of a weighted geometric distance and where the objective function is specifically denoted as the Euclidean distance. In this situation, the problem will be considered with a quadratic objective function, that is, objectives that contain the product of two variables. This problem can be converted to true linear form by writing the Karush/Kuhn/Tucker/LaGrange first-order conditions (Schrage, 1991). If $s = \infty$, the objective function is defined as the Tchebycheff distance and the model can be transformed into a linear programming model in which the largest weighted deviation determines the preferred solution and the situation among tradeoff mechanics turns out to be not only competitive but noncompensatory.

Overall, LINDO® software can be employed in this analysis (Schrage, 1991).

DECISION WEIGHT ANALYSIS

Considering multiple objectives requires further decision analysis to determine the preference weights so as to aid in the tradeoff procedure in the multi-objective, decision making process. It may require an optimization study to extract such information and evaluate the overall effectiveness of the locating strategy. In a previous study, Ning and Chang (2002) had proposed a new method for evaluating the preference weights via questionnaire investigation and goal programming analysis. Five main river basins in Taiwan were selected as candidates for assessment of how well those monitoring stations were sited in each river basin with respect to the five designated planning objectives. With a questionnaire designed explicitly to elicit the performance of existing networks, 15 experts in the field of environmental management were invited to form an evaluation committee and, sequentially, grade the monitoring system situated in each river basin. The possible range of the grade was defined in advance to have a set of more consistent outputs. Until all similar monitoring systems can be evaluated and graded in terms of a series of criteria, all experts on the evaluation committee may proceed with an overall ranking with regard to the integrated performance of each system. Then, using a preemptive goal programming analysis may derive final weighting factors. This approach may provide more meaningful outputs rather than taking a straightforward mean value over all individual grades subject to the constraint that confirms the normalization of weighting factors directly (Ning and Chang, 2002).

RESULTS AND DISCUSSIONS

The optimal relocation strategy of water quality monitoring networks based on the compromise programming analysis that can be realized as the optimization model was developed by the software LINDO®. The outputs of planning scenarios are divided into three cases, depending on the value of the distance parameter s, as shown in Table 2. It is observed that conflict and compromise between these five planning objectives are obvious since the second objective tries to emphasize the importance of conserving the higher water quality regions in the upper stream area but the first and fourth objectives focus on the protection of those nonattainment areas close to the estuary region where the population density is higher. Besides, the first and second objectives exhibit higher impacts in the tradeoff process since the severe pollution areas are located downstream, with the source of potable water usually situated upstream. Equity concerns make the final selection of candidate sites those that are uniformly distributed in all tributaries.

No matter which value is selected for the distance parameter s, five candidate sites are always favored in the Liao-Nung River system when tradeoffs exist among objectives (Table 2). On the other hand, both existing monitoring stations (i.e., Y_{16} and Y_{17}) that are located at the downstream area of this tributary were excluded in all runs due to lower detection sensitivity and potential for different attainable water uses. Only one station (i.e., Y_{21}) that is located in the upstream area of the Ai-Liao River system was selected as a monitoring station due to the recognition of the importance of use attainability and the sensitivity for the lower compliance condition. Nevertheless, varying the parameter value of s would generate quite a different siting strategy in the Chi-San River system due to the actual tradeoffs among objectives. The tradeoff mechanisms among differing objectives turn out to be more influential when considering those monitoring stations in the Chi-San River and Kao-Ping River simultaneously. Both requirements of increasing the potential for different attainable water uses and improving the protection of higher populated regions would dominate the final choice. This is evident in Table 2 when comparing the output conditions of s = 1 and s = 2. In the Kao-Ping River system, higher population density and worse water quality would drive at least four out of the five candidate stations to be selected when the total number of candidate sites remains the same.

Comparative studies for the relocation of a water quality monitoring network using different multi-objective evaluation approaches, such as the weighted approach and fuzzy approach, seem appealing in systems analysis. Table 2 suggests that using the fuzzy approach may result in quite different planning alternatives in comparison to those generated by either the weighted approach or compromise approach (Ning and Chang, 2002, 2004). The main discrepancies arise from the siting patterns in the middle sections of the Ai-Liao River and the Chi-San River. Yet there is no obvious difference between the planning alternatives produced by the weighted and compromise approaches. This does imply that the inclusion of decision weights assigned by decision makers would not disturb the weak tradeoff between objectives no matter whether those alternatives are selected within the compromise set or not.

Overall, the parameter value s was not sensitive enough to alter the major siting patterns as evidenced

TABLE 2. The Optimal Planning Programs of Water Quality Monitoring Network.

Tributary	Candidate Monitoring Station[1]	Compromise Approach[2]			Weighted Approach[3]	Fuzzy Approach[4]
		s = 1	s = 2	s = ∞		
Laio-Nung River	Y_{11}	X	X	X	X	
	$^*Y_{12}$	X	X	X	X	X
	Y_{13}	X	X	X	X	X
	Y_{14}	X	X	X	X	X
	Y_{15}	X	X	X	X	X
	$^*Y_{16}$					X
	$^*Y_{17}$					
Ai-Laio River	Y_{21}	X	X	X	X	X
	Y_{22}					X
	Y_{23}					X
Chi-San River	Y_{31}	X	X	X	X	X
	Y_{32}	X	X	X	X	X
	Y_{33}	X	X	X	X	
	$^*Y_{34}$				X	
	$^*Y_{35}$	X		X		
	Y_{36}	X	X			
Kao-Ping River	Y_{41}	X	X	X	X	X
	$^*Y_{42}$	X	X	X	X	X
	Y_{43}	X	X	X	X	X
	Y_{44}	X	X	X	X	X
	$^*Y_{45}$		X	X	X	X

[1]"*" represents existing monitoring station.
[2]This study, "s" represents distance parameter.
[3]Ning and Chang (2002).
[4]Ning and Chang (2004).
Notes: "X" represents that the station is selected in the planning scenario.
Upper bound of total number of stations is 15.
Upper bound of overlapped distance is 30 km.

in these three planning scenarios. In the decision analysis, it appears that the effect of compensation between objectives is not so conspicuous in the optimization process. Finally, based on one of the planning scenarios in relation to the compromise programming framework (i.e., s = 1), the expansion sequence of selected monitoring stations could be derived by a step-wise procedure. The spatial priority analysis, as listed in Table 3, clearly provides a stepwise choice of expansion sequence in terms of the preference order of all candidate sties in the river system. It shows that Y_{11} and Y_{31}, which are close to the water intakes in the upstream and middle reaches of the river, or Y_{41}, located in the populous area, are the most important sites to be built in the water quality monitoring system. The information of expansion sequence would be useful once the governmental budget becomes critical.

CONCLUSIONS

Planning a sound water quality monitoring system in a river basin in response to the needs of a national or regional water quality monitoring goal is a complex and challenging task. This paper presents a multiobjective programming model with a view to optimizing the water quality monitoring network in a river basin. Extra sampling procedures become necessary for the sites with sparse environmental information. With the aid of the calibrated QUAL2E water quality simulation model, simulation analysis in the first stage is capable of determining the half-life distance along the river reaches for each candidate site based on the predicted environmental assimilative capacity. Such an application makes final assessment of the relocation alternatives achievable. To make successful simulation runs and formulate the representative

TABLE 3. Spatial Priority Analysis of All Candidate Sites.

Preference Order	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Candidate Site	Y_{11}	Y_{41}	Y_{31}	Y_{21}	Y_{32}	Y_{33}	Y_{15}
Preference Order	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Candidate Site	Y_{44}	Y_{12}	Y_{13}	Y_{42}	Y_{43}	Y_{36}	Y_{35}
Preference Order	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Candidate Site	Y_{14}	Y_{23}	Y_{34}	Y_{17}	Y_{16}	Y_{22}	Y_{45}

optimization model, GIS performs the data archival, data analysis, and essential spatial analysis to aid in the entire analytical framework. Compromise programming technique provides a useful means to fulfill the flexible design of a water quality monitoring network via an unbiased and trustworthy decision procedure. However, decision makers still can emphasize the specific intention via the adjustment of weighting factors associated with the planning objectives considered in this analysis. Such analytical framework eventually leads to a successful selection of the compromise relocation strategy of water quality monitoring systems in the Kao-ping River Basin, South Taiwan, where the water resources and water quality management systems have to be intimately linked together to meet the goals of regional economic development. It can be concluded that part of the existing monitoring stations that were not sited at those strategic locations should be removed in the long run. Once the governmental budget runs into a critical situation, spatial priority analysis may clearly provide a step-wise choice of expansion sequence based on the preference order of all candidate stations in the network.

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