Multi-objective, decision-based assessment of a water quality monitoring network in a river system

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Water quality monitoring network design has historically tended to use experience, intuition and subjective judgement in locating monitoring stations. Better design procedures to optimize monitoring systems need to simultaneously identify significant planning objectives and consider a number of social, economic and
1 environmental constraints. The consideration of multiple objectives may require further decision analysis to determine the preference weights so as to aid in the trade-off procedure in the multi-objective decision-making process. This may require the application of an optimization study to extract such information from decision makers or experts and to evaluate the overall effectiveness of locating strategies. This paper assesses the optimal expansion and relocation strategies of a water quality monitoring network using a two-stage analysis. The first stage focuses on the information retrieval of preference weights with respect to the designated planning objectives. With the aid of a pre-emptive goal programming model, data analysis is applied to obtain the essential information from the questionnaire outputs. The second stage then utilizes a weighted multi-objective optimization approach to search for the optimal locating strategies of the monitoring stations in the river basin. Practical implementation is illustrated by a case study in the Kao-Ping River Basin, south Taiwan.

Introduction

River system monitoring networks need to collect both temporal and spatial information on variations relevant to an ideal or preferred utilization level of a water body. Water quality monitoring network design has historically tended to use experience, intuition and subjective judgement in locating monitoring stations. Many countries, after having run their monitoring networks for several decades, are still in the process of evaluating what they have achieved so far, and of expanding their existing monitoring networks for future development based on the shortcomings discovered. In addition, the need to perform total maximum daily load (TMDL) programs in many river basins has led designers to focus more critically on the design procedures of water quality monitoring networks. How they should proceed to improve the overall monitoring efficiency must be related to how to provide valuable initiatives towards a stepwise improvement of existing monitoring networks.

In many developing countries, water quality sampling or monitoring stations are located at sites of easy access or at stream flow gauging points. The total number of monitoring stations tends to increase over time to include sites located in highly populated regions, highly industrialized areas, point or non-point pollution source locations or intensive land use areas in both upstream and downstream river systems. Furthermore, the selection of sampling frequencies is not considered in terms of cost-effectiveness criteria, and the selection of the variables to be sampled depends frequently on project-oriented requirements. One of the major problems in many countries is the lack of coordination between monitoring agencies with respect to the purpose of the monitoring program and the activities involved in monitoring.[1] New developments proposed by various government agencies may lead to more sophisticated monitoring procedures. Consequently, an overall perspective of the total monitoring system, either to evaluate the existing system with a broader sense or to add new objectives and constraints in a future system, cannot be maintained. A new system-based approach is thus needed to achieve such goals.

The design issues relating to surface water quality monitoring networks have received wide attention since the 1970s.[2–5] Various attempts were made in the 1980s to improve monitoring efficiency with regard to basic design criteria,[6] optimization analysis,[7] comparison among features of fixed stations,[8] consolidation of the network design,[9] emphasis on data collection[10] and the interpretation of monitoring outcome.[11] Early studies in the 1990s covered the deeper principles and applications in locating water quality monitoring stations.[12–14] Kwiatkowski[15] pointed out some essential objectives that are common to many large-scale water quality monitoring networks. Later studies utilized integer programming,[16] multi-objective programming[17,18] and kriging theory[19] to assess some 2
complex issues. Advances in revised methodology, including biological or ecological factors or optimization analysis, can be found in other work.[20–22]

The determination of preference weights in a multi-objective evaluation framework has been emphasized in previous environmental studies.[23–25] The analytical hierarchy process (AHP),[26,27] which forms the basis of the expert choice decision support method, enhances decision making by providing a logical, easy to use approach to permit planners to derive relative, mathematically based weights for selected criteria instead of having to subjectively assign weights to planning objectives. Relevant work linking AHP with multi-objective evaluation includes: screening landfill sites,[23,24] evaluating factors deemed to be important for a sustainable pelagic fishery,[25] assessing overall environmental performance[28] and eliciting preference weights of stakeholder groups with respect to the objectives.[29] However, AHP was originally designed to assess issues in which the planners may foresee a hierarchical order in establishing planning objectives. Unfortunately, many real world applications are not consistent with such conditions as most

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multi-objective evaluation problems only contain a few objectives without having a hierarchical order. To overcome this problem, Wen and Lee[30] used a multilayer neural network algorithm to obtain the decision maker's preference in terms of the associated weights and to solve the optimization problems of water quality management planning in a river basin; but this approach still requires planners to consider many alternative preference weights in applications, as final decision making is still difficult to undertake given a set of non-inferior solutions.

This paper presents a two-stage analysis applied to the selection of both the locations and the numbers of monitoring stations in a river basin, with the emphasis on analyzing a trade-off between objectives by considering the preference weights. The first stage focuses on the investigation of the preference weights using an explicitly designed questionnaire and a pre-emptive goal programming model. The goal programming model is designed to elicit the essential information of preference weights drawn from the questionnaire outputs. On the basis of this decision weight analysis, the second stage then utilizes a multi-objective optimization approach to simultaneously search for the optimal expansion and relocation strategies for water quality monitoring stations in a river basin.

Study area description

The Kao-Ping River flows for approximately 140 km and drains towards the southern Taiwan Strait. With an area of 3256 km^2, the main stream of the Kao-Ping River originates from four small tributaries (Chi-San, Liao-Nung, Cho-Kou and Ai-Liao Rivers) as shown in Fig. 1. From the confluence to the union with these tributaries, the river carries the name Kao-Ping River. The mean annual rainfall in this river basin is close to 3000 mm, over 90% of which arrives in the wet season when the Kao-Ping River flow increases to a level approximately 8–12 times higher than in the dry season. Owing to the impacts of monsoon and typhoon, the period of highest flow rate usually occurs in late summer. Field crops include: rice, sugar cane, pineapple and a variety of vegetables. Stock farming is an active agricultural activity. However, the basin also contains a number of small- and medium-scale industries in the downstream region.

The Kao-Ping River system has a long history of high biochemical oxygen demand (BOD) and NH_3-N concentrations due to inadequate disposal of manure from stock farming, industrial effluents and domestic wastewater discharges. The continuous discharge of various types of wastewater into flowing water in the middle and downstream areas, where most water intakes are located in this region resulting in 3
a need to use the river water as a potable water supply, requires the application of a systematic policy to improve water quality. A TMDL program was started in 1998, which requires a 4
sound water quality monitoring system to support the essential assessment of the cost-effectiveness in the later stage.

Determination of preference weights

The design procedure for the optimization of monitoring systems needs to identify several significant planning objectives and to consider a series of inherent constraints simultaneously. The consideration of multiple objectives may require further decision analysis to determine the preference weights so as to 5
aid in the trade-off procedure in the multi-objective decision-making process. This may require an optimization study to extract such information and evaluate the overall effectiveness of locating strategies. This paper emphasizes that the mathematical programming technique is capable of investigating the preference weights with respect to a set of designated planning objectives. With a pre-emptive goal programming model, the implicit decision weights can be elicited from the questionnaire outputs when a knowledge of how the domain experts take the objectives into account separately and collectively is apparent. This paper represents the first effort to apply such a new scheme to solve environmental problems.

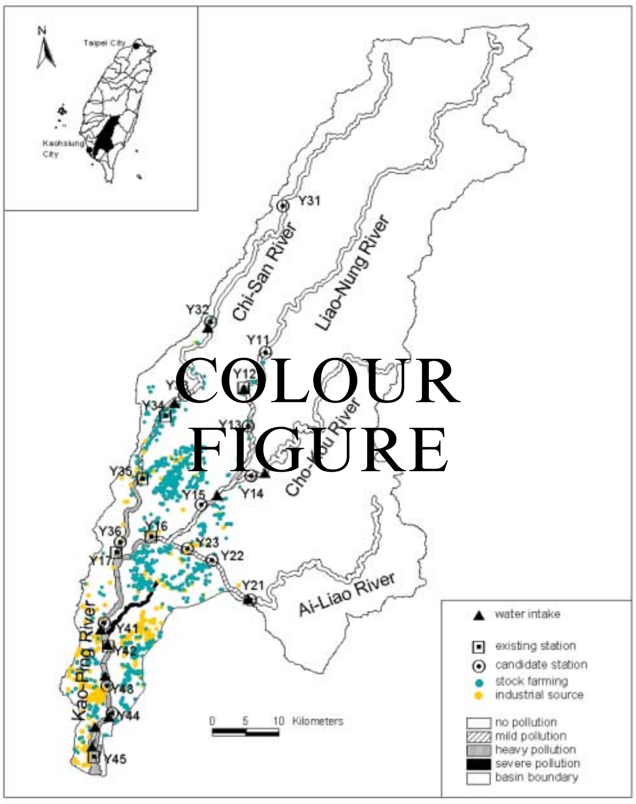

Fig. 1 The candidate stations of the water quality monitoring network and the current situation in the Kao-Ping River Basin, Taiwan.

Questionnaire investigation

The planning objectives considered in this analysis were designed to address the degree of protection of those areas in the river system with high population density, to enhance the detection probability for low compliance areas, to enhance the potential detection sensitivity by better locating strategies, to reflect the utilization potential of the water body at different locations and to monitor the water quality upstream of all water intakes. Five main river basins in Taiwan were selected as candidates for further assessment of how well the 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 were requested to grade the monitoring system situated in each river basin sequentially with regard to the objectives. The possible grade range should be defined in advance in order to obtain a set of consistent
6 outputs. Until all similar monitoring systems under evaluation had been graded, all experts in the evaluation committee had to proceed with an overall justification with regard to the integral performance of each system subjectively. Final consensus was made by the evaluation committee to pinpoint exactly which monitoring project in the river basin was best in a logical sense, and a priority list was produced for subsequent goal programming analysis.

Fig. 2 shows the 21 river basins in Taiwan. Five of them, including the Dan-Shui, Tou-Qian, Da-Jia, Tseng-Wen and Kao-Ping, are regarded as the main river basins, which have been selected as candidates for evaluation in this analysis. To perform an effective investigation through questionnaire, information on the water quality monitoring networks being planned and built in these five main river basins was collected, including population density, locations of water intakes, severity of water pollution and utilization levels of water body

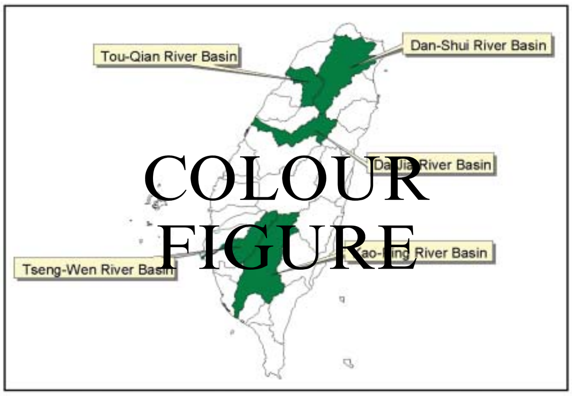

Fig. 2 The five river basins in Taiwan selected for questionnaire investigation in preference weights analysis.

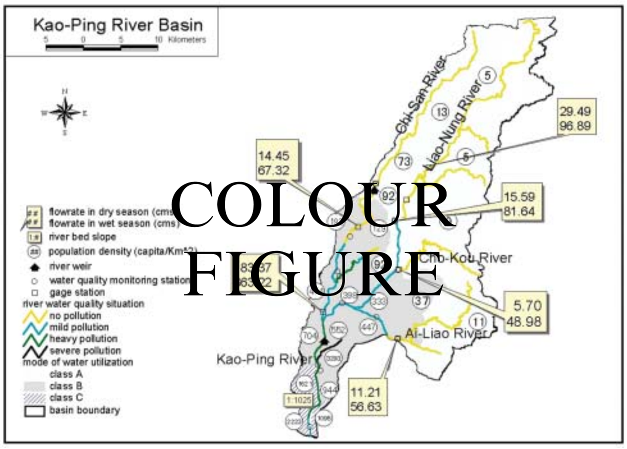

Fig. 3 The current situation in the Kao-Ping River Basin.

along the river reaches. Fig. 3 demonstrates a typical example in the Kao-Ping River Basin, while Table 1 summarizes all the related information based on a comparative approach.

The grade range used to determine the possible achievement of each objective was 1–5. Table 2 presents the mean scores with respect to each objective for the five river basins selected in this survey. The normalization of the preference weights requires the collection of more information. The final consensus with regard to the integral evaluation of the five main river basins includes: (i) the Dan-Shui River is generally better than the Tou-Qian River; (ii) the Dan-Shui River is generally better than the Da-Jia River; (iii) the Dan-Shui River is generally better than the Tseng-Wen River; (iv) the Da-Jia River is generally better than the Tseng-Wen River; and (v) the Kao-Ping River is generally better than the Tseng-Wen River.

Based on the outputs with respect to each objective and the 7
integral evaluation with respect to the current deployment performance of five basin-wide monitoring programs, the final

Table 2 Investigation outputs ($G_{i,j}$)of questionnaire

River basin	Objective 1	Objective 2	Objective 3	Objective 4	Objective 5[a]
Dan-Shui	3.75	2.75	4.25	2.50	1.75
Tou-Qian	4.25	3.25	2.25	1.75	3.50
Da-Jia	4.75	3.00	3.5	1.75	2.00
Tseng-Wen	4.25	3.50	3.00	2.75	1.50
Kao-Ping	3.00	3.00	4.00	1.75	3.25

[a]Objective 1, to enhance the detection probability of lower compliance areas. Objective 2, to reflect the utilization potential of the water body at different locations. Objective 3, to promote the potential detection sensitivity by better locating strategies. Objective 4, to increase the degree of protection for those areas with higher population density in the river system. Objective 5, to monitor the water quality at all upstream water intakes.

Table 1 Information from questionnaire investigation for the five selected river basins

	Dan-Shui River			Tou-Qian River			Da-Jia River			Tseng-Wen River			Kao-Ping River		
	Up-stream	Middle stream	Down-stream	Up-stream	Middle stream	Down-stream	Up-stream	Middle stream	Down-stream	Up-stream	Middle stream	Down-stream	Up-stream	Middle stream	Down-stream
Pollution situation[a]	A	B–C	D	A	A	A	A	A	B	A	B	C	A	B	C–D
Average slope of river bed	1/37	—	1/6700		1/190			1/90			1/200			1/150	
Population density[b]	A	D	D	A	B	D	A	C	D	A	B	C	A	B	D
Existing gage station	9	12	0	4	2	0	12	5	0	0	2	2	3	3	0
Existing water quality monitoring station	1	38	13	4	2	2	0	5	3	0	4	2	2	7	3

[a]A, no pollution; B, mild pollution; C, heavy pollution; D, severe pollution. [b]A, sparse (<50 capita km^{-2}); B, moderate (50–500 capita km^{-2}); C, many (500–1000 capita km^{-2}); D, crowded (>1000 capita km^{-2}).

assessment left was to apply an advanced optimization analysis to predict and normalize the preference weights systematically. The goal programming model produced the preference weights for all objectives simultaneously. The normalization scheme linked the fragmented information of each grade in each monitoring project and the integral evaluation with respect to all comparable projects and verified the inherent preference weights embedded in the experts' overall justification. This approach may exhibit more consistent outputs than a method taking a straightforward mean value over all individual grades subject to the constraint that the summation of all related weights should be equal to one directly.

Pre-emptive goal programming analysis

The approach used to elicit the preference weights is based on goal programming analysis (see Appendix 1 for details). The database obtained from the 15 questionnaires was used in a goal programming model to elicit final preference weights for all objectives. The weight associated with each objective was initially set to fall above 0.1 in the constraint set. Such technical setting preserves the minimum sensitivity for each objective considered in this survey. Otherwise, some may be excluded in the trade-off process. The algorithm yielded final normalized weights of {0.21, 0.10, 0.27, 0.19 and 0.23} respectively.

Multi-objective programming

The second stage analysis eventually leads to a multi-objective mixed integer programming model subject to several inherent constraints for screening the candidate sites in a river system with respect to the preference weights determined above. The detailed formulae are described in Appendix 2. The planning objectives are designed to address the degree of protection of those areas with a high population density in the river system, to enhance the detection possibility for low compliance areas, to promote the potential detection sensitivity by better locating strategies, to reflect the utilization potential of the water body at different locations and to monitor the water quality upstream of all water intakes. The constraint set contains the budget limitations, the implication of equity concerns and the detection sensitivity in the water environment. Four factors, including dissolved oxygen (DO), biochemical oxygen demand (BOD), total phosphorus (TP) and ammonia-nitrogen (NH_3-N), are considered in this case study for screening the monitoring stations in the optimization scheme. The year can be divided into two seasons in a hydrological sense in this river system. The wet season generally covers the time period from May to October, and the remaining time period is the dry season. As there is a difference in stream flow rate between the wet and dry seasons, only the situation in the dry season needs to be considered in the design procedure of the water quality monitoring network.

Twenty-one monitoring station sites have been selected as candidates in the Kao-Ping River system, of which seven are current (Fig. 1). Most of the existing stations are located in the downstream area close to the high population region. The use of a geographical information system (GIS) to help determine the essential parameters for each site is viewed as an indispensable tool in this analysis. With the aid of QUAL2E[31] simulation outputs, the half-life distance (see Appendix 2, sub-objective 3 for an explanation) for each pollutant of concern around each candidate site may be obtained.[32] Such information is used in the formulation of the third objective function [eqn. (12) in Appendix 2] and the second constraint [eqn. (17) in Appendix 2]. The situation of attainment or non-attainment of water quality in the river system, needed for the first objective function, can be acquired from the previous sampling and analysis program.[32] Spatial analysis, such as that in the ArcView® GIS software package,[33] may be helpful in determining the population density within a 10 km radius of each monitoring station. 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 intake. The spatial information associated with the three utilization levels of the water body must also be included in the model formulation. The optimal relocation and expansion strategies for the water quality monitoring network can be realized as a multi-objective optimization analysis, solved using a software package such as LINDO®.[34]

The final planning scenarios depend critically on the chosen upper bound of the total number of stations in the constraint and whether the existing stations are included or not. They are listed at the bottom of Fig. 4. Given the preference weights previously obtained, the conflict and compromise between the five planning objectives can be observed. For example, the second objective tries to emphasize the importance of conserving the higher water quality regions in the upstream area, while the fourth objective focuses on the protection of those non-attainment areas close to the estuary region where the population density is higher than the others. Equity concerns force the final selection of candidate sites to be uniformly distributed throughout all tributaries in both the relocation and expansion scenarios.

When considering the relocation strategy, the trade-off mechanism in the multi-objective evaluation framework clearly differentiates the potential of all candidate sites. The resulting locating strategies of scenarios (1) and (2), defined in Fig. 4, show that the deployment of the current water quality monitoring network in the Kao-Ping River Basin does not conform to an optimal design. At least previous deployment 8
has no special consideration for monitoring those water intakes there will have little chance of simultaneously choosing adjacent sites in an optimal scheme when applying the multi-objective evaluation framework. For example, scenario (2) excludes adjacent sites in the river system at least twice. Such differentiation covers the adjacent sites denoted by Y_{16}/Y_{17} and Y_{34}/Y_{35}. On the other hand, although a planning scenario involving network expansion results in a smaller impact for the managerial authority, it may lose part of its integrity because

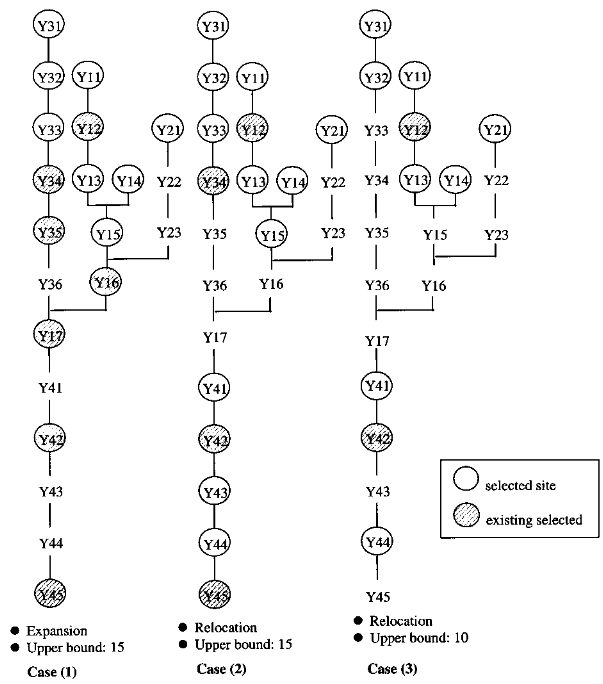

Fig. 4 The results of optimal planning programs of the water quality monitoring network.

the optimal locating strategy will be limited by the existing pattern and cannot exhibit a better overall spatial distribution. Candidate monitoring stations located in the upstream area are frequently included in the optimal locating process as a result of the requirements for higher detection sensitivity, larger utilization potential and an early warning system for preserving water quality around the water intakes. This is shown by solutions (2) and (3).

Conclusions

Planning a sound water quality monitoring network in a river basin in response to the needs of a national water quality monitoring goal is a complex and challenging task. This paper illustrates how preference weights analysis, calibrated simulation modeling and multi-objective optimization analysis can be combined to achieve the system-based planning goals, leading to a search for both optimal relocation and expansion strategies for the water quality monitoring system in the Kao-ping River Basin in south Taiwan. It is believed that this unbiased and trustworthy decision procedure may provide a powerful means to establish many other optimal designs of water quality monitoring networks in river systems.

Appendix 1: Formulation of goal programming model

The following formulation is a generic form of the pre-emptive goal programming model:

$$\min \sum_{i=1}^{m} P_i \cdot (d_i^+ + d_i^-) \tag{1}$$

subject to:

$$Z_i(x) + d_i^- - d_i^+ = T_i \quad \forall i \tag{2}$$

$$d_i^+ \cdot d_i^- = 0 \tag{3}$$

$$x \geq 0 \tag{4}$$

$$d_i^+ \text{ and } d_i^- \geq 0 \quad \forall i \tag{5}$$

where µ stands for 'for all' in mathematics, the subscript i represents the numeric order of objectives considered in the model (unitless), m is the total number of objectives included in the model, P_i represents the priority factor associated with the ith objective that should be applied in the optimization analysis (*i.e.* $P_i > P_{i+1}$) (unitless), Z_i stands for the expression of each objective in the goal constraint, x is the decision variable in the decision analysis and $d^+{}_j$ and $d^-{}_j$ are the unitless positive and negative deviational variables that describe the degree of distance from a selected target value. These two variables are mutually exclusive in a logical sense; therefore, their multiplication should be equal to zero ($d^+{}_j \cdot d^+{}_j = 0$). T_i is a selected unitless target value that can be predetermined before analysis.

Fragmented information in relation to the preference order of all similar projects may not be strong enough to decide
9 all the priority relationships (P_i), but the more the priority relationships show, the higher reliability the decision analysis may exhibit. Owing to the inherent limitations of the questionnaire investigation, there may be a need to use an optional constraint, as defined in eqn. (8), to ensure that the preference weight elicited in the optimization analysis becomes positive; otherwise, the removal of some objectives that yield zero
10 preference weights is inevitable. To build up a sound constraint set, the presence of logical conflict in the way to summarize the preference order among similar projects, as defined in eqn. (7), is summarized should be looked for before the optimization analysis is performed. The modified model formulation is as follows: min

$$\sum_{i=1}^{m} (d_i^+ + d_i^-) \tag{6}$$

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$$\sum_{j=1}^{m} W_j G_{i,j} + d_i^- - d_i^+ \geq \sum_{j=1}^{m} W_j G_{i+1,j} + d_{i+1}^- - d_{i+1}^+ \tag{7}$$

µ the ith project is better than the i + 1th project

$$W_j \geq W_{\min} \forall j \tag{8}$$

$$G_{ij}, d_j^+, d_j^- \geq 0 \quad \forall i, j \tag{9}$$

where W_j represents the preference weight of the jth objective (decision variable) (unitless), $G_{i,j}$ is the grade of the jth objective in the ith similar project (unitless) and $W_{\min}$ is the minimum value of the preference weight required in the weight-matching process (unitless).

The weights can be determined by optimization analysis and software packages, such as LINDO®.[34]

Appendix 2: Formulation of multi-objective programming model

Objective function

The components (sub-objectives) of the final objective function [eqn. (15)] are as follows.

(1) Maximization of the detection possibility for lower compliance areas. Compliance monitoring, *i.e.* detecting violations of regulations is a primary requirement. This objective indicates that the monitoring network to be built (or expanded) should exhibit the highest potential capability to detect the severely polluted areas with respect to the set of pollutants of concern. It can be expressed as:

$$Z_1 = \sum_{i=1}^{p} \sum_{j=1}^{q_i} Y_{ij} \sum_{k=1}^{r} w_{ijk} \frac{C_{ijk} - S_{ijk}}{C_{ijk}}, \ \forall i, j, k \tag{10}$$

where C_{ijk} represents the mean concentration of the kth pollutant of concern in the dry season at the jth monitoring station in the ith tributary (mg L^{-1}), S_{ijk} is the water quality standard of the kth pollutant in the river reach of concern where the jth monitoring station in the ith tributary is located (mg L^{-1}), p is the total number of tributaries in the Kao-Ping River Basin, q is the total number of candidate stations, r is the total number of pollutants of concern, w_{ijk} are the weights for individual pollutants and Y_{ij} is a binary variable in which 1 means that the candidate location is included and 0 otherwise (unitless)

(2) Maximization of the utilization potential of the water body at different locations. The higher the utilization potential of a water body in the river reach, the greater is the requirement to the monitoring station(s) in it. This may be expressed as:

$$Z_2 = \sum_{i=1}^{p} \sum_{j=1}^{q_i} Y_{ij} R_{ij}, \ \forall i, j \tag{11}$$

where R_{ij} is the surveillance weight associated with each mode of utilization in a water body where the jth monitoring station in the ith tributary is located, in which a linear trend is presumed from the lowest level to the highest. In this survey, accordingly, the value of R_{ij} may be set to 1.0, 0.8, 0.6, 0.4 and 0.2 for each utilization level of water body from A to E, respectively.

(3) Maximization of the potential of detection sensitivity by better locating strategies. The monitoring station locations in the river system must take pollutant transport and degradation capability into account. This is strongly related to the

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assimilative capacity of the local environment. The design criterion emphasizes that the spatial locations of sites in an optimal monitoring network should be based on the overall detection sensitivity or alarm potential with respect to the set of pollutants of concern. A parameter, the half-life distance, is defined in advance according to the output from the simulation model. The longer the half-life distance for a pollutant in the proximity of a specific candidate site, the lower the chance for a neighboring candidate site to be selected as an alternative. This is obtained by:

$$Z_3 = \sum_{i=1}^{p}\sum_{j=1}^{q_i} Y_{ij} \sum_{k=1}^{r} w_{ijk} L_{ijk},\ \forall i, j, k \qquad (12)$$

where L_{ijk} is the half-life distance, the geographical distance required for the decay to half concentration of the kth pollutant, for the jth monitoring station in the ith tributary (km).

(4) Maximization of the degree of protection of those areas with high population density in the river system. Monitoring stations should be sited as close as possible to the locations in where most population resides in the river basin. This criterion is designed as:

$$Z_4 = \sum_{i=1}^{p}\sum_{j=1}^{q_i} Y_{ij} P_{ij},\ \forall i, j \qquad (13)$$

where P_{ij} is the population covered within a 10 km radius of the jth monitoring station in the ith tributary (capita).

(5) Maximization of 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 situated. This is given by:

$$Z_5 = \sum_{i=1}^{p}\sum_{j \in S}^{q} Y_{ij} \frac{1}{E_{ij}},\forall i,\ \forall j \in S \qquad (14)$$

where E_{ij} is the distance between the jth monitoring station in the ith 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).

The final objective function is then given by:

$$\max \sum_{i=1}^{5} W_i Z_i \qquad (15)$$

where W_i are the preference weights in decision analysis.

Constraint set

The formulation of the constraint set is illustrated as follows.

(1) Budget constraint. The total number of monitoring stations included in the alternative should be less than an upper bound, defined with respect to budget limitations:

$$\sum_{i=1}^{p}\sum_{j=1}^{q} Y_{ij} \le M,\ \forall i, j \qquad (16)$$

where M is the upper bound on the total number of monitoring stations (unitless).

(2) Detection sensitivity constraint. The overlap of the half-life distance between each pair of adjacent monitoring stations should be minimized. A one-dimensional coordinate system is defined starting from the estuary location and continuing to the origin, *i.e.* the farthest location of the upper stream area. Fig. 5 illustrates the coordinate system. The 'effectiveness of coverage' of each monitoring station in a spatial sense is addressed using an aggregate index relating to the half-life distance of all constituents of concern. Several external runs *via* simulation analysis are required to illustrate how far the half-life distance of each monitoring station is with respect to all pollutants of

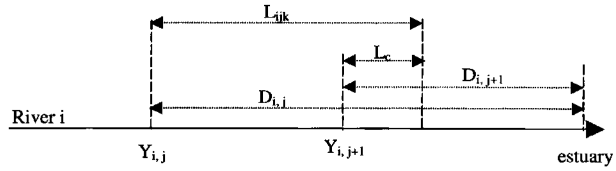

Fig. 5 Coordinate system diagram used in this study. Y_{ij}, the jth candidate site located at the ith tributary; D_{ij}, the distance between the jth monitoring station located at the ith tributary and the reference point of estuary location (km); L_{ijk}, the half-life distance associated with the candidate site (km); L_c, limitation of the overlapped influential distance allowed in this systems analysis (km).

concern. Preference can be assigned to a specific monitoring station or pollutant by setting w_{ijk} in the equation:

$$Y_{i,j+1} D_{i,j+1} - Y_{ij}\left[D_{ij} - \sum_{k=1}^{r} (w_{ijk} L_{ijk})\right] < L_c, \forall i, j \qquad (17)$$

where D_{ij} is the geographical distance between the jth monitoring station located on the ith tributary and the reference point at the estuary area (km), L_c is the maximum overlapped half-life distance allowed (km) and j is defined sequentially from the origin to the estuary region.

(3) Equity constraint. This ensures that each tributary in the river basin contains at least one monitoring station:

$$\sum_{j=1}^{q_i} Y_{ij} \ge 1, \forall i \qquad (18)$$

(4) Non-negativity constraint. All the binary decision variables (Y_{ij}) are defined as non-negative.

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