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Assessing pollution prevention program by QUAL2E simulation analysis for the Kao-Ping River Basin, Taiwan

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Wise and sustainable uses of water resources are essential for an effective river-basin-management planning. Advanced management strategy further addresses that quantity and quality of water are closely interrelated, and both must be considered simultaneously for all water resources and water quality management practices. The aim of this paper is to explore the impacts of water resources redistribution and pollution prevention actions between and within river basins simultaneously in South Taiwan. Much emphasis will be placed on assessing the impacts of water transfer over natural boundary to satisfy the needs of industrial development in the Tseng-Wen River system and its resultant influence on the water quality in the downstream area of the Kao-Ping River system where the pollution prevention program is to be implemented. The Kao-Ping River was further characterized hydraulically and environmentally, based on a full investigation of discharges and withdrawals in the river reaches. QUAL2E was successfully calibrated and validated using data collected between 1998 and 1999, and the model was capable of predicting the concentrations of biochemical oxygen demand, dissolved oxygen, total phosphate-phosphorus, and ammonia-nitrogen (NH_3-N) for the entire river system. With the aid of QUAL2E simulation model, it shows removing the pig farming and constructing the sewer systems in the upstream area cannot guarantee the full compliance with water quality standards in the downstream area and water transfer in the upstream area further increases negative impacts on the water quality in the wet season. The predicted situation of water quality in the dry season may even present worse condition. Additional water pollution control policy, such as the use of economic instruments, for controlling and reducing the loadings of biochemical oxygen demand and ammonia-nitrogen is needed in the Kao-Ping River system in the long run.

Keywords: water-resources management, water-quality management, river-basin planning, environmental systems analysis, sustainable development.

Introduction

The Kao-Ping River and Tseng-Wen River are both high-gradient streams located in the semi-tropical region of South Taiwan. As the standard of living of people in this area improves, their per capita water consumption and the needs for higher quality of water increase simultaneously. Recent economic development in the Tseng-Wen River basin makes the environment under increasing pressure due to the tremendous demands of water resources for industrialization. While the Kao-Ping River owns relatively abundant water resources without any reservoirs for storage, the inherent needs and limitations of water resources redistribution via water transfer between or within river basin systems have become one of the most stringent challenges in South Taiwan. But it became evident increasingly that pig farming was impairing proper utilization of water resources for water supply due to inappropriate disposal of manure to watercourses in the middle stream and downstream areas of the Kao-Ping River system. In order to rectify the present deplorable situation in this region, the government authorities have proposed the strategy for controlling point sources based on a series of pollution prevention actions. These actions mainly include

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removing most of the pig farming in the upstream area and constructing the sewer systems in five cities in the river basin. The aim of river basin management, therefore becomes more significant once their individual features of each river basin system can be properly coordinated together to contribute a higher level of regional development in South Taiwan. While such a need of system analysis is easy to demonstrate, the real question then becomes what is the water-quality situation in the river system if such a transfer of water resources and the fulfillment of pollution prevention actions are carried out simultaneously. Those decision-makers who are responsible for the formulation and fulfillment of water quality plans or management policies must have a means to assess the resultant environmental impacts from both spatial and temporal aspects. One technique that has become progressively important during the past decade is the use of QUAL2E to verify such management process. It must be valuable for decision-making if the prediction of water-quality situations, given the changes of river flow, the quantity and quality of waste load, and the extent of pollution prevention measures designed to reduce waste discharges, is achievable in search of the solution (Willey *et al*., 1996).

QUAL2E is an US EPA-developed water-quality model that has gained wide acceptance as a planning tool in river-basin study. A number of typical applications of water-quality predictive models have been developed for and applied to various river systems in many countries, such as Poland, Spain, Slovenia, Chile, India, and the United States (Cubillo and Rodriguez, 1992; Little and Williams, 1992; Walton and Webb, 1994; Droc and Koncan, 1996; Gremiec, 1997; Dussailant and Munoz, 1997; Ghosh and McBean, 1998; Chaudhury *et al*., 1998; Droc and Koncan, 1999). Calibration and validation of QUAL2E in various conditions enhance its application potential. Because there are a wide variety of river systems, each having its own hydrologic characteristics and its own particular pollution problems, QUAL2E is designed flexibly to match a variety of applications. For instance, Tolman (1992) and DeGasperi and Khangaonkar (1997) applied QUAL2E for flow control of dissolved oxygen and phytoplankton biomass. Steynberg *et al*. (1995) and Venter *et al*. (1997) discussed the possible management of microbial water quality via the use of QUAL2E model. QUAL2E is also capable of computing required dilution flows for flow augmentation to meet any specified dissolved oxygen (DO) level in the river system. Tillman and Dortch (1993) particularly evaluated the effect of flow alterations on water quality. Wagner and Tisdale (1996) presented a sound application of QUAL2E model to assess the phosphorus transport with respect to flow routing in a lake. Furthermore, in recognition of the importance of a computer-based decision aids, the incorporation of QUAL2E into a geographical information system (GIS) environment to perform an active river-basin planning has achieved by Craig and Burnette (1996) and Yang and Merry (1999) in recent years.

In contrast to the Yang and Merry (1999), this paper ensures the essential level of water quality in the Kao-Ping River system conditional to the planned water transfer requirements and pollution prevention actions, in which QUAL2E is employed as a simulation tool. It differs from these earlier studies in several ways. First, this analysis takes both water resources and water quality impacts into account simultaneously for multiple watersheds. Second, the planning scenario was assessed on the basis of multiple criteria: economic development, level of effluent control, and pumping schedule that is consistent with the natural pattern of stream flows, the needs for future water supply, and the required levels of Biochemical oxygen demand (BOD), ammonia-nitrogen (NH_3-N) and DO in the river system. It assesses the effect of waste reduction in the pollution prevention program as well as the impact of water transfer between watersheds within one planning scenario. Third, advanced information technologies, such as the GIS and global positioning system (GPS) are coordinated together and applied to aid in the data collection, storage, verification, analysis, and presentation. The ability of GIS to examine basin geometry and query a computerized database to support modeling analysis performs a significant role in basin-wide system planning for water resources and water quality management. Overall, there is often a multitude of public agencies involved in water quantity and quality management, each having its own particular planning objectives and constraints.

Such an analysis will make planners and decision-makers in different public agencies gain deeper integrated insight of what is the interrelationship between land development and environmental quality, and what is the implication of sustainable development strategy in this region.

Site description

Geographical and hydrological features

The study area covers both the Kao-Ping and Tseng-Wen River basins in South Taiwan. Both river basins are slender and sharp where the central mountain bound them on the east and Taiwan Strait on the west. As shown in Figure 1, the Kao-Ping River flows through approximately 140 km and drains towards the south part of Taiwan Strait. With an area of 3256 km^2, including most 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. From the confluence to the union with those tributaries at the location of Li-Ling Bridge, the river carries the name Kao-Ping 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 management practices. The water

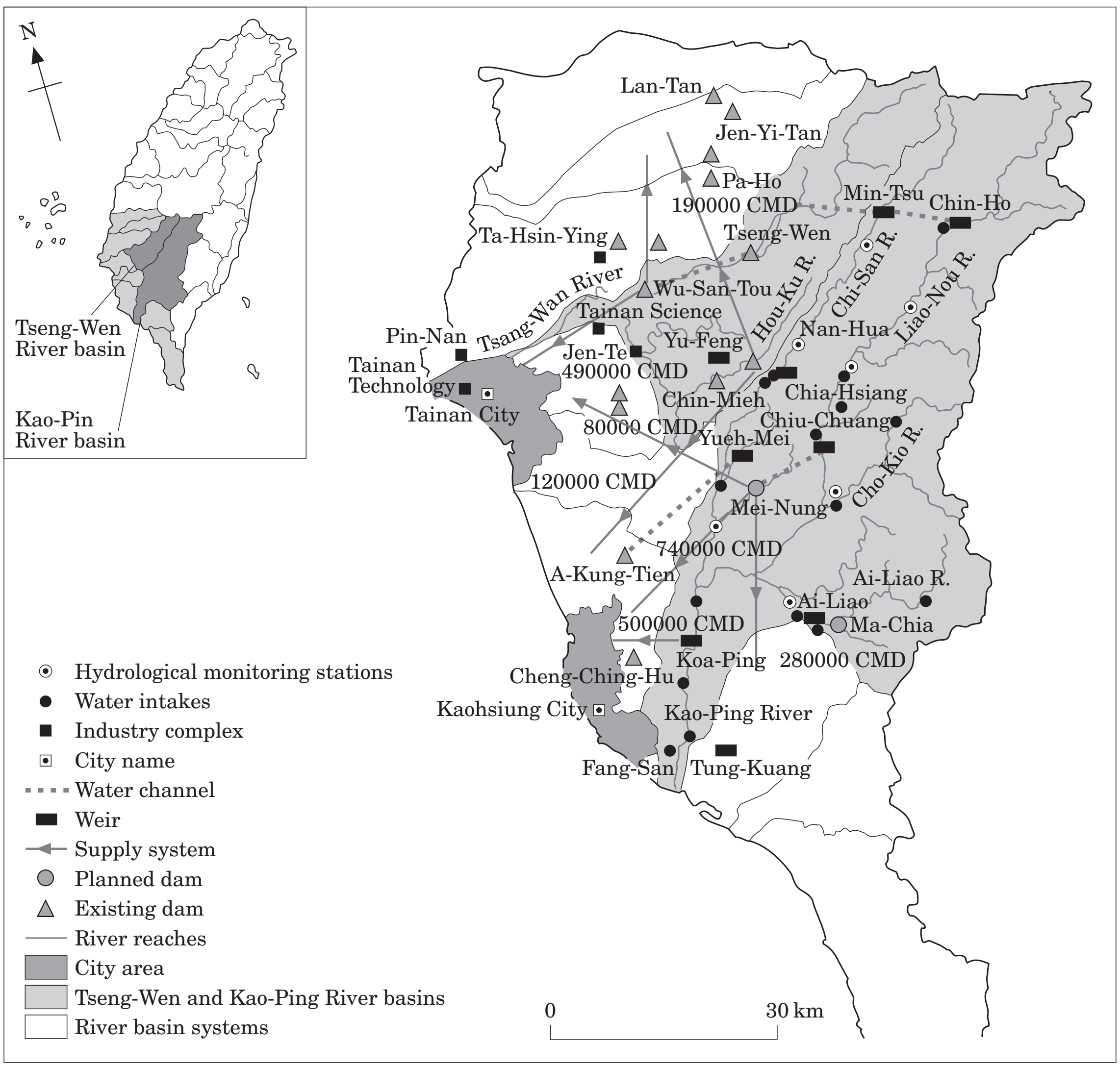

Figure 1. The water-resources-management system in the Tseng-Wen and Kao-Ping River basins.

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 remainder time period is the dry season. Although the mean annual rainfall in this river basin is close to 3000 mm, over 90% of which appears in the wet season. Summer is very hot with temperature often exceeding 30°C. The period of high flow rate in the stream usually occurs in late spring and summer due to the impacts of monsoon and typhoon. During the monsoon period, the Kao-Ping River flow increases to a level approximately 8 to 12 times higher than the dry-season flow. Uneven rainfall over seasons has resulted in severe issue 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 planned for agricultural production. Crops that are produced from the agricultural fields include: rice, sugar cane, pineapple, and a variety of vegetables. Stock farming is another active agricultural activity. However, it also contains a number of small and medium scale industries in the downstream region. In addition to agricultural production and industrial manufacturing processes, water is also essential for drinking and personal hygiene in this area. Concern and attention of water-resources management has been directed primarily to the extremely uneven distribution of rainfall and stream flows over the dry and wet seasons. While four reservoirs are in operation in the 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) in the upstream area of the Kao-Ping River system, has resulted in an intensive debate due to 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, that is located in the Tseng-Wen River basin, becomes an indispensable solution to improve the reliability of water supply for these two big cities—Tainan and Kaohsiung—in this region. Although agriculture is always the largest user of water, the latest development of three large-scale industrial complexes in the Tseng-Wen River basin requires more water transferred from the upstream area of the Kao-Ping River in the wet season. Industrial water requirements will therefore development, rising regional population, and increases in our standard of living, the total water requirements have continued to grow inevitably. From a long-term perspective, supply and demand of water resources can never reach spatial and dynamic balance in this region, as evidenced by the statistical trend of supply and demand relationships in Figure 2. Therefore, the idea of a conjunctive operation of those weirs and reservoirs in both Kao-Ping and Tseng-Wen River basins has been putting into practice since 1990. Figure 1 further describes such a watershed management complexity in South Taiwan by a GIS output in which at least three river weirs, consisting of the Chia-Hsiang, Min-Tsu, and Chin-Ho weirs, are undergoing their construction process and will be fully responsible for such a transfer of water resources over natural boundary between these two river systems at the year 2011. Table 1 particularly describes the fact that water transfer across these two watershed boundaries would obviously reduce the discrepancy of stream flows between dry and wet seasons. Based on the anticipated pumping scheme of water transfer, the ratio of stream flows between wet and dry seasons will be reduced from 8·9 at present to 7·3 at the target year on average.

Environmental aspects

While reasonable accurate estimates of water balance in the river systems are known and the impacts due to water transfer over natural boundary is predictable, information on its water quality leaves much to be desired. For the Kao-Ping River system that has a long history of higher BOD and NH_3-N due to inadequate disposal of manure from stock farming, industrial effluents, and domestic wastewater discharges, proper utilization of river water as the potable-water sources has encountered a new challenge with regards to both technological and managerial requirements. However, continuous discharge of organic, degradable wastewaters into flowing waters in 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 of a systematic policy for improving the water-quality condition.

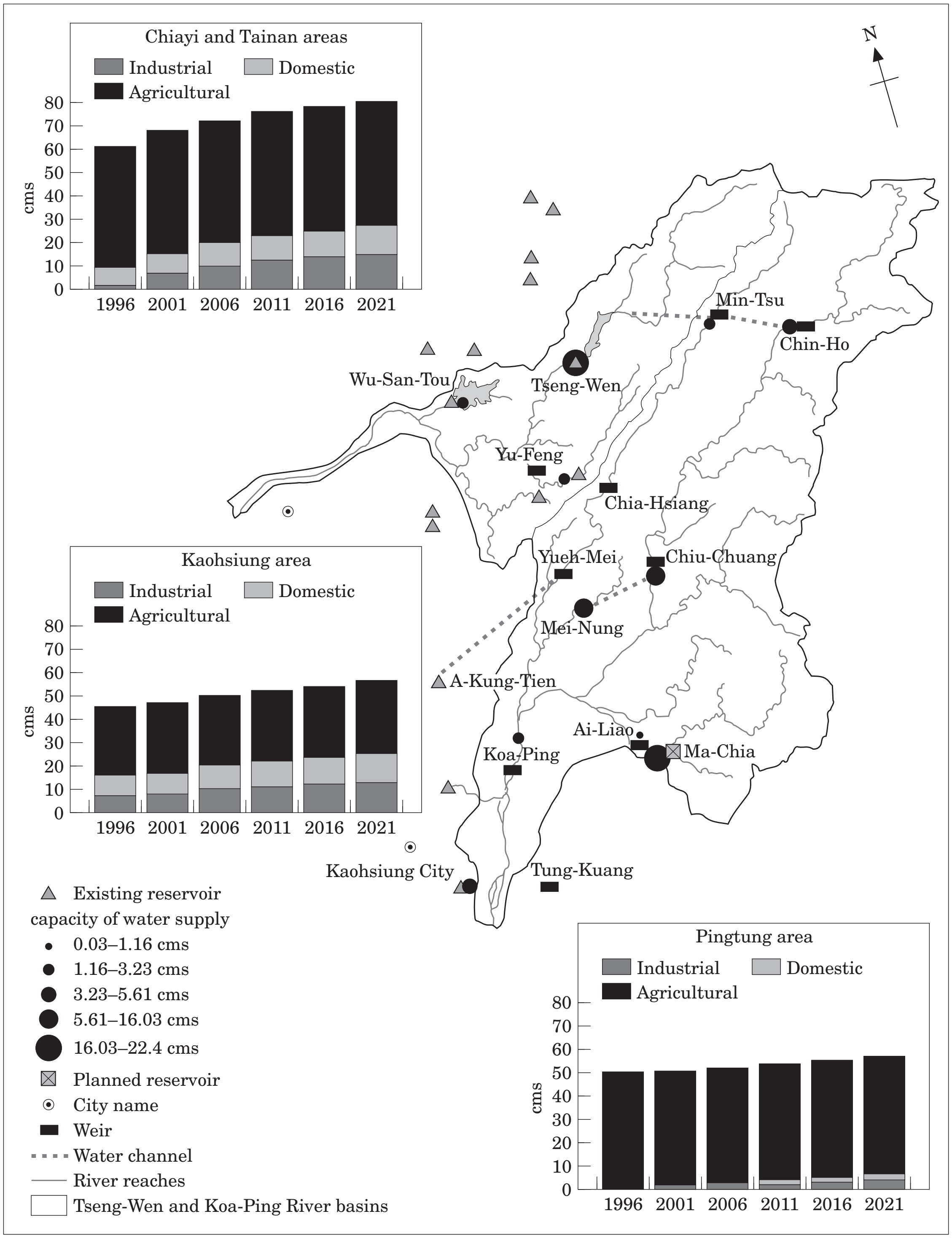

Figure 2. The relationship of supply and demand of water in the Tseng-Wen and Kao-Ping River basins.

To gain a deeper understanding of the water-quality condition in the river reaches, a large-scale sampling campaign was carried out during dry and wet seasons, respectively. Each of the dry and wet sampling programs consisted of a 96 h survey during the time periods of August 1998 and February 1999. Sampling sites cover the spots from origin of the river system to estuary location. Figure 3 not only presents the estimated conditions of stream flows prior to and after the planned water transfer program with respect

Table 1. The comparative stream flows in different seasons at present and at the target year

Gage stations	Stream flow at present (cms)			Stream flow at the target year (cms)		
	Dry season	Wet season	Ratio	Dry season	Wet season	Ratio
Mei-Shan	12·55	52·4	1 4·2	12·55	52·40	1 4·2
Lao-Nung	19·03	133·60	1 7·0	19·03	98·6	1 5·2
Min-Tsu	5·66	45·44	1 8·0	5·66	38·03	1 6·7
San-Ti-Men	6·19	66·59	1 10·8	6·19	65·43	1 10·6
Ta-Chin	5·70	74·48	1 13·1	5·70	74·48	1 13·1
Li-Ling Bridge	39·56	341·04	1 8·6	39·56	202·37	1 5·1
Kao-Ping Bridge	39·52	424·20	1 10·7	39·52	255·53	1 6·5
Average			1 8·9			1 7·3

to different locations at the target year but also indicates all selected sampling sites in the Kao-Ping River system. While the former is estimated based on the hydrological investigation, the latter has to be achieved using GIS and GPS as an integrated tool. The symbols used in Figure 3 to denote the sampling sites are further classified by K1-K17, C1-C20, L1-L6, and A1-A3, which are designed to be consistent with the local tributary patterns as well as the scale of sampling activities. There were a total of 46 stations including 27 stations along the main stem of the river, of which seven near the estuary area, and the rest of them are near the exits of wastewater drains along major tributaries. All field measurements were performed using portable meters. Temperature, pH and conductivity readings were taken in the field concurrently with the DO samples, and the rest of analyses were performed in the laboratory.

The symbol RK in the following context represents 'river kilometer' that indicates the frame of reference along the River as noted in Figure 3. It further discriminates the Liao-Nung River (RK137-RK34), Chi-San River (RK117-RK34), Ai-Liao River (RK69-RK34), and Kao-Ping River (RK34-RK0) by different expressions of River Kilometer. Table 2 describes the officially designated water quality standards 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 in Taiwan. As a result, the Kao-Ping River system can be classified by class C (approximately from RK0 to RK 2), class B (approximately from RK 2 to RK 58), and class A (the remainder areas of the upstream river reaches) in the main stream simultaneously. The collection of samples and *in situ* measurement of specific water-quality constituents indicates that violations of water-quality standards in relation to BOD, NH_3-N and TP exist in both wet and dry seasons at the present stage. But DO concentrations along all river reaches in both dry and wet seasons present fairly good condition. This is much due to the sharp topological environment that may generate stream flow with higher speed beneficial for increasing the reaeration rate in the river system. Under extreme conditions, NH_3-N concentration might raise to 4 mg/l, BOD 9 mg/l, and TP 0·7 mg/l in the downstream areas of the Kao-Ping River system. Such a situation, as indicated in Figure 4, further makes the program of water transfer over natural boundary in the upstream area become questionable. Overall, water quality indices defined for identification of water quality condition according to the good, fair, poor, and worst levels of water quality in Taiwan can be viewed as a different assessment approach. Table 3 defines these water quality indices. Figure 5 therefore expresses the current pollution levels in the Kao-Ping River system based on such an assessment approach. Over the distance of 60 RK are identified as poor and worst levels, which indicate further management policy is strongly desirable. Such a severe condition eventually motivates the EPA in Taiwan to declare this area as one of the five areas for the possible development of a Total Maximum Daily Load (TMDL) program. Potential control actions or pollution prevention actions are designed as part of the TMDL requirements. They include two planning scenarios. One is to conduct a construction program of sewer systems for five medium-scale cities in order to control domestic-wastewater discharges, while the other is to budget a large scale subsidiary program in order to remove most of the pig farming activities

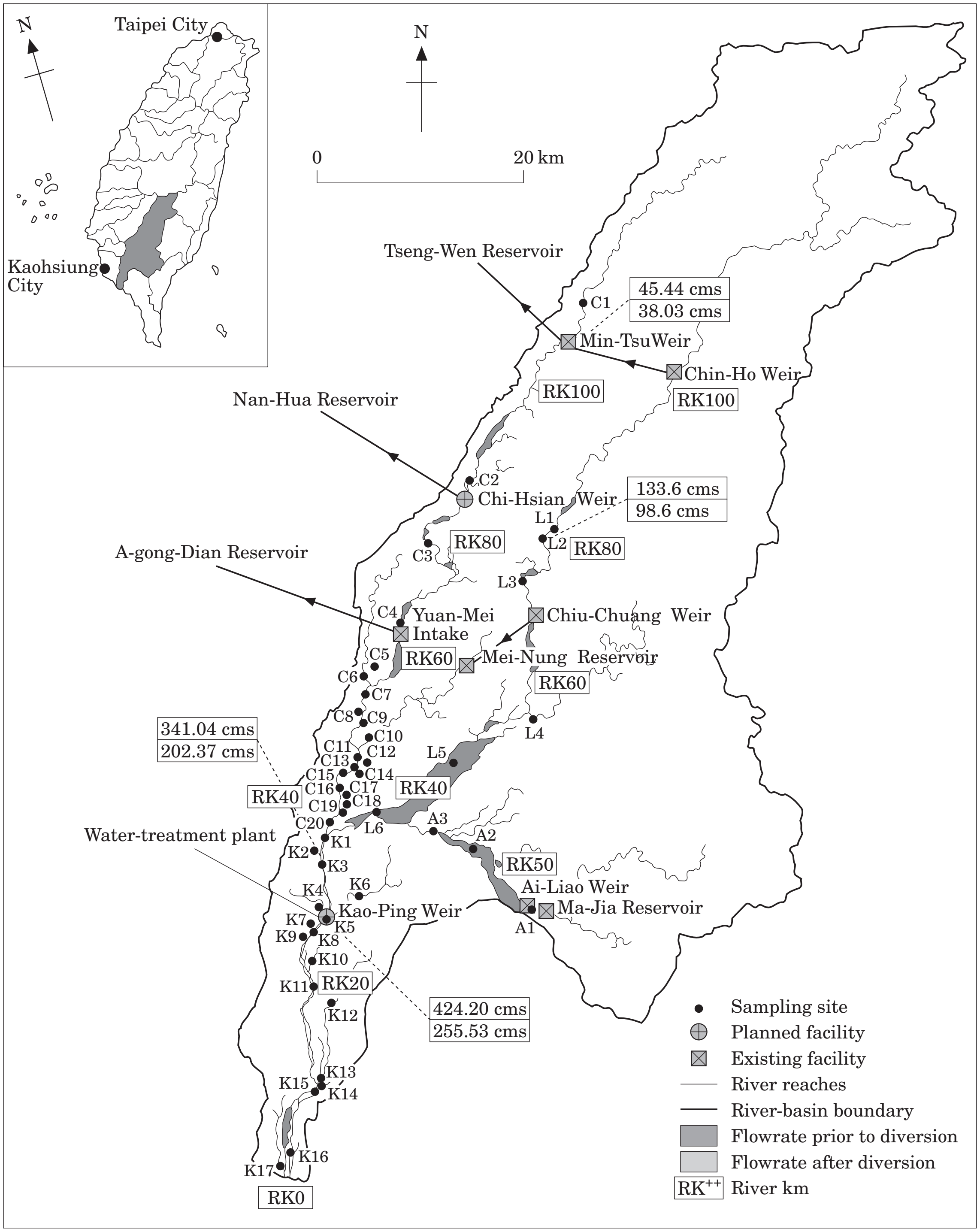

Figure 3. Estimated flow condition and sampling locations in the Kao-Ping River system.

above the main water intake—the Kao-Ping Weir—located at approximately 36 RK of the Kao-Ping River system. Figure 5 expresses the aggregate waste load distribution in each sub-basin via a GIS output. The percentage number, as listed in these parentheses of Figure 5, expresses the possible reduction of waste load at each sub-basin as the pollution prevention program progresses towards the target year. But the shaded area close to the downstream river reaches represents the area where the subsidiary program will not cover for removing the pig farming activities. The challenge faced by the decision makers

Table 2. Water-quality standards with respect to surface-water category in Taiwan

Class	Selected constitutes						
	pH	DO (mg/l)	BOD (mg/l)	SS (mg/l)	E-coil (CFU/100 ml)	NH_3-N (mg/l)	TP (mg/l)
A	6·5–8·5	6·5	1	25	50	0·1	0·02
B	6·0–9·0	5·5	2	25	5000	0·3	0·05
C	6·0–9·0	4·5	4	40	10 000	0·3	—
D	6·0–9·0	3·0	—	100	—	—	—
E	6·0–9·0	2·0	—	No oil	—	—	—

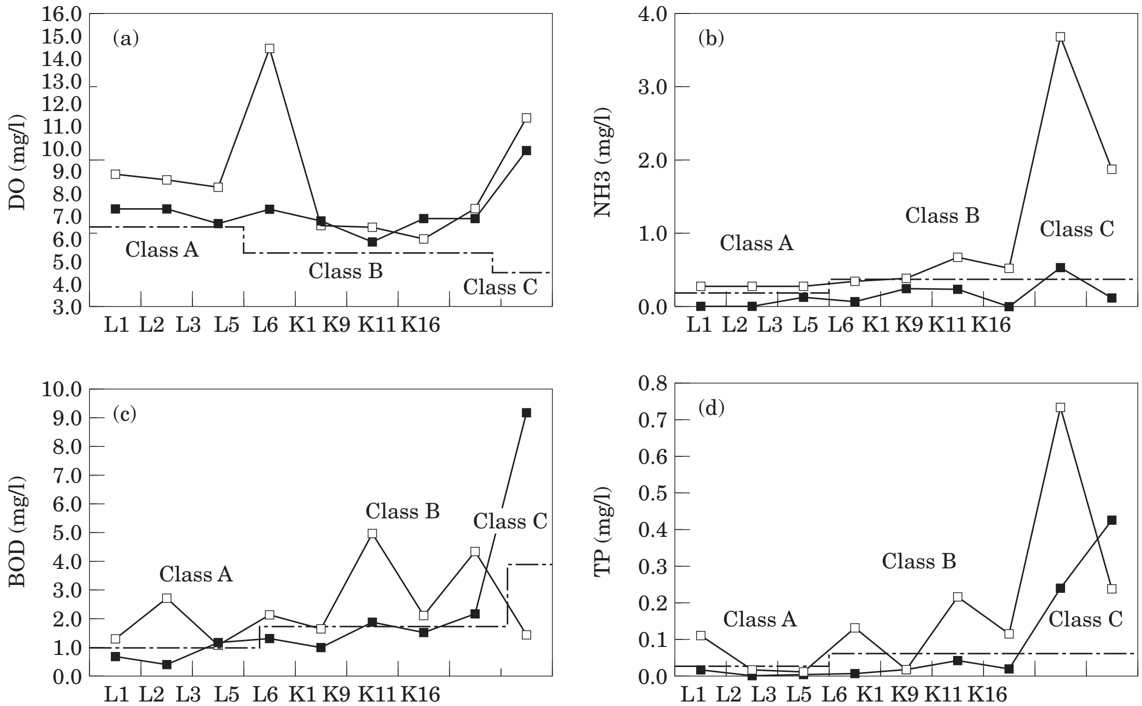

Figure 4. The comparative variations of target constituents in the Kao-Ping River system. The Comparative (a) DO —·—, (b) Nh3-N, (c) BOD, and (d) TP, variations for dry and wet seasons. Wet season (-■-); dry season (-□-).

Table 3. Water-quality indices defined for identification of water-quality condition in Taiwan

Good river reach	Fair river reach	Poor river reach	Worst river reach	
DO(mg/l)	6·5 above	4·6∼6·5	2·0∼4·5	2·0 below
BOD(mg/l)	3·0 below	3·0∼4·9	5·0∼15	15 above
SS(mg/l)	20 below	20∼49	50∼100	100 above
NH_3-N(mg/l)	0·5 below	0·5∼0·99	1·0∼3·0	3·0 above

and analysts is how to predict the positive impacts of pollution prevention actions on receiving water quality by an integrated and scientifically sound approach. In recognition of the primary importance of the Kao-Ping River to the future regional development in South Taiwan, a basin-wide assessment of the river, tributaries, and discharges under both dry and wet seasons was conducted via a QUAL2E simulation analysis in this study. The aim of this practice therefore rests upon assessing the integrated impacts of water transfer and pollution prevention programs in order to identify the relationship between land development, environmental quality, and sustainability.

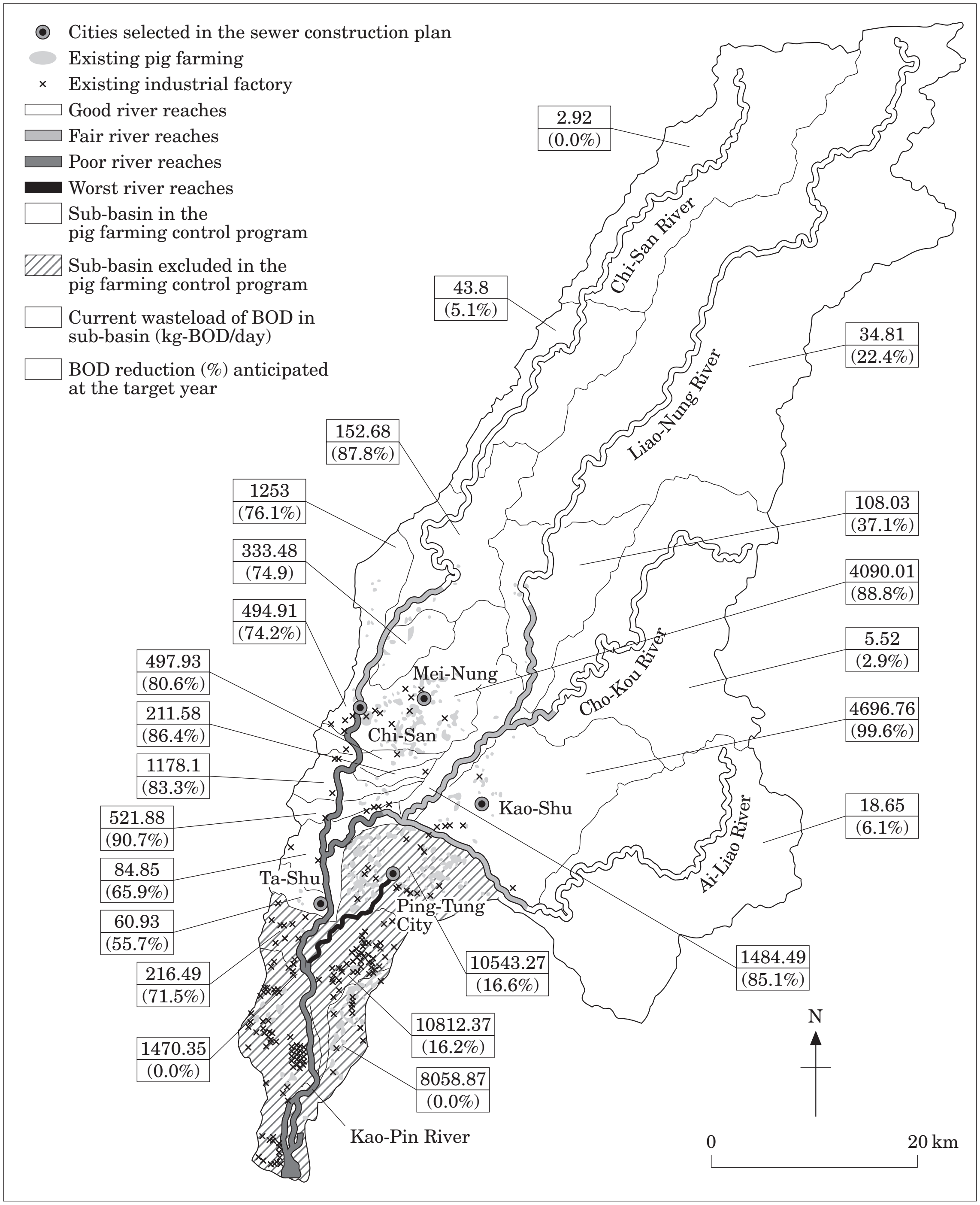

Figure 5. Waste load distribution, pollution prevention, and pollution level in the Kao-Ping River system.

QUAL2E descriptions, calibration and validation

QUAL2E model theory

The Stream Water Quality Model QUAL2E (Brown and Barnwell, 1987) is basically a steady-state model for conventional pollutants in one-dimensional streams and well-mixed ecosystems. The simulation model of QUAL2E illustrates the important physical, biological and chemical processes and their interactions for the particular water quality constitutes 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 constitutes. It allows multiple waste discharges, withdrawals, tributary flows, and incremental inflow and outflow. QUAL2E may consider up to 15 constitutes mainly including conservative mineral (C), algae (A), NH_3-N, nitrite-nitrogen (NO_2-N), nitrate-nitrogen (NO_3-N), phosphate-phosphorus (P), BOD, DO, coliform (F), and radioactive material (R). But this analysis is designed to be capable of predicting the concentrations of DO, BOD, NH_3-N, and P only.

Nowadays, QUAL2E can operate either as a steady state or dynamic simulation model. When operated as a steady state model, it is applicable for studying the impacts of waste loads with respect to magnitude, quality, and location in the river system. By operating the model dynamically, the analysts can explore the effects of diurnal variations in meterological data on DO and temperature and diurnal DO variations due to algal growth and respiration. QUAL2E is hydraulically, limited to the simulation of time periods during which both the stream flows in the river system and input waste loads are essentially steady. The steady state equations in QUAL2E allow the input of the hydraulic characteristics of the river reaches as empirical equations:

$$U=aQ^{b} \tag{1}$$

$$D=cQ^{d} \tag{2}$$

where u=stream velocity (m/s); Q=stream flow (m^3/s); D=stream depth (m); and a, b, c and d are empirical constants. Alternatively, given the relationship between depth and flow, Manning's equation may be used to define the stream velocity.

The main governing equations of QUAL2E describe deoxygenation of ultimate carbonaceous BOD (CBOD) in the stream by the first order reaction, as defined in Equation (3). It is related to the rate of change of oxygen. Each term in Equation (4) represents a major source or sink of oxygen that is interrelated with Equation (3).

$$\frac{dL}{dt}=-K_1L-K_3L \tag{3}$$

$$\frac{dO}{dx}=K_2(O^{*}-O)+(\alpha_3\mu-\alpha_4\rho)A-K_1L-K_4/D-\alpha_5\beta_1N_1-\alpha_6\beta_2N_2 \tag{4}$$

where u=stream velocity (m/day); x=stream distance (m); O=concentration of dissolved oxygen (mg/l); O^{*}=saturation concentration of dissolved oxygen at the local temperature and pressure (mg/l); α_3=rate of oxygen production per unit of algal photosynthesis (mg-O/mg-A); α_4=rate of oxygen uptake per unit of algae respired (mg-/mg-A); α_5=rate of oxygen uptake per unit of ammonia nitrogen oxidation (mg-O/mg-N); α_6=rate of oxygen uptake per unit nitrite nitrogen oxidation (mg-O/mg-N); μ=algal growth rate (day^{-1}); ρ=algal respiration rate (day^{-1}); A=algal biomass concentration (mg-A/l); L=ultimate concentration of carbonaceous BOD (mg/l); K_1=CBOD deoxygenation rate based on BOD stream profile (day^{-1}); K_2=reaeration rate (day^{-1}); K_3=rate of loss of CBOD due to settling (day^{-1}); K_4=sediment oxygen demand (g-O/m^2-day); D=stream depth (m); β_1= ammonia oxidation rate coefficient (day^{-1}); β_2=nitrite oxidation rate coefficient (day^{-1}); N_1=ammonia nitrogen concentration (mg-N/l); and N_2=nitrite nitrogen concentration (mg-N/l).

The nitrogen cycle considered in the Kao-Ping River system contains four components and are represented by the following equations:

$$\frac{dN_1}{dt}=\beta_3N_4-\beta_1N_1-\sigma_3/D-F_1\alpha_1\mu A \tag{5}$$

$$\frac{dN_2}{dt}=\beta_1N_1-\beta_2N_2 \tag{6}$$

$$\frac{dN_3}{dt}=\beta_2N_2-(1-F)\alpha_1\mu A \tag{7}$$

$$\frac{dN_4}{dt}=\alpha_1\rho A-\beta_3N_4-\sigma_4N_4 \tag{8}$$

where $F_1=P_NN_1/(P_NN_1+(1-P_N)N_3)$; N_3= nitrate nitrogen concentration (mg-N/l); N_4= the concentration of organic nitrogen (mg-N/l); β_3=organic nitrogen hydrolysis rate (day^{-1}); α_1=fraction of algal biomass which is nitrogen (mg-N/mg-A); σ_3=the benthos source rate for ammonia nitrogen (mg-N/ft^2-day); F_1=fraction of algal nitrogen uptake from ammonia pool; P_N=preference factor for ammonia nitrogen; F=fraction of algal nitrogen taken from ammonia pool.

The phosphorus cycle operates like the nitrogen cycle in which the organic forms of phosphorus are generated by the death of algae, which then convert to the dissolved inorganic state. Phosphorus discharged from the sewage treatment plants is generally in the form of dissolved inorganic matter. Such mechanisms can be represented by the following equations simultaneously:

$$\frac{dP_1}{dt}=\alpha_2 \rho A-\beta_4 P_1-\sigma_5 P_1 \qquad (9)$$

$$\frac{dP_2}{dt}=\beta_4 P_1+\sigma_2/D-\alpha_2 \mu A \qquad (10)$$

where P_1=the concentration of organic phosphorus (mg-P/l); P_2=concentration of inorganic or dissolved phosphorus(mg-P/l); α_2= phosphorus content of algae (mg-P/mg-A); ρ=algal respiration rate (day^{-1}); β_4=organic phosphorus decay rate, temperature dependent (day^{-1}); σ_2=benthos source rate for dissolved phosphorus, temperature dependent (mg-P/ft^2-day); σ_5=organic phosphorus settling rate, temperature dependent (day^{-1}).

QUAL2E model calibration and validation

The application of QUAL2E model must be in conjunction with a field sampling and laboratory measurement program that is essential to identify the magnitude of model parameters and then to make an initial prediction for ensuring the forecasting accuracy. In this study, QUAL2E has to be run with one set of observed data collected in the dry season and subsequently validated with a second set of observed data obtained in the wet season. In the modeling analysis, the total study length of 170 RK in the Kao-Ping River system was discretized into nine river reaches that consist of 85 computational elements. The measured stream flows in dry and wet seasons and the river geometry, provided in Table 4, were utilized as the essential hydraulic information to support the subsequent modeling practice. To understand the spatial and temporal variations of water quality, river water-quality samples collected in accordance with the 46 selected sampling locations in different seasons have been analyzed in terms of DO, BOD, NH_3-N, and TP, as described above. After the establishment of field and laboratory measurements through a rigorous quality assurance and quality control procedure, environmental database can then be integrated with hydraulic database and applied for model calibration and validation.

With regards to the technical settings of model parameters, the designed stream flow for the assessment of assimilative capacity at the target year in the Kao-Ping River system is Q_{50}. This would imply that only 50% of probability exists for a seasonal stream flow to exceed the designed stream flow within the dry season or wet season. Besides, QUAL2E offers eight options for estimating or reading in the reaeration rate coefficient that are all in terms of depth and velocity. Of these alternative equations, the expression derived by O'Connor *et al.* (1958) was applied for the estimation of K_2. Therefore, K_2 varies with reaches, computational elements, and different hydraulic conditions. The effluents in the wastewater drains are usually a mixture of industrial wastewater, domestic sewage, and discharges from the stock farming. As the point source contributions join the Kao-Ping River, the suspended matter in the

Table 4. River geometry and hydraulic data

River location (RK)	Flow rate (cms)		Velocity (m/s)		Depth (m)	
	Wet	Dry	Coefficient (*a*)	Exponential (*b*)	Coefficient (*c*)	Exponential (*d*)
84–68 (M)	133·57–133·57	19·31–21·31	0·3116	0·2930	0·2054	0·3203
68–38 (M)	132·39–206·87	7·17–21·31	0·3116	0·2930	0·2054	0·3203
38–34 (M)	250·27–250·27	3·03–5·10	0·6913	0·0630	0·4207	0·1414
34–24 (M)	345·92–346·03	18·04–30·48	0·4207	0·1414	0·2287	0·3326
24–0 (M)	332·86–360·02	18·93–45·91	0·0504	0·5089	0·2690	0·2066
106–94 (T1)	48·48–63·23	5·66–5·66	0·1147	0·5160	0·1801	0·3230
94–60 (T1)	65·32–97·10	5·96–9·05	0·1147	0·5160	0·1801	0·3230
60–34 (T1)	80·09–95·65	0·97–12·57	0·2369	0·2561	0·2604	0·3802
52–38 (T2)	56·59–65·16	0·01–5·31	0·5090	0·0620	0·2040	0·4440

M, main stream (Liao-Nung River + Kao-Ping River); T1, tributary 1 (Chi-San River); T2, tributary 2 (Ai-Liao River).

wastewater drains may tend to settle out in the vicinity of confluence point. The values of deoxygenation coefficient of CBOD will become more stable when the pollutants in the river move downstream and the organic matter has settled. Values of reaction kinetics for considering the settling rate (K_3) represent the final values with their range of variation estimated from the calibration of QUAL2E to the field-measured water quality for the Kao-Ping River. Attention has to be given to adjust the assumed values of model parameters that have been adopted from the literature.

Table 5 presents a set of calibration data to be used in the validation procedure of QUAL2E. Algal photosynthesis and sediment oxygen demand (SOD) were not considered in this QUAL2E modeling analysis. Figure 6 addresses the calibration of QUAL2E for part of the Kao-Ping River system. The similarity existing between the observed values and predicted values shows its application potential. It is interesting to note that concentrations of BOD, NH3-N, and TP rise sharply before the point source discharges at the proximity of RK50 due to the discharges from a local wastewater drains. Overall, these factors of BOD, NH_3-N, and TP have not dominant impacts on DO concentration due to larger reaeration rate being encountered in this river system. Comparison between field measurements and predicted values was made and Figure 7 confirmed the validation.

Table 5. Calibration data in the validation procedure of the QUAL2E model

River location (RK)	K_1 (day^{-1})	K_3 (day^{-1})	β_1 (day^{-1})	β_2 (day^{-1})	β_3 (day^{-1})	β_4 (day^{-1})	σ_3 (day^{-1})	σ_4 (day^{-1})	σ_5 (day^{-1})
84–68 (M)	0·2	0·1	0·8	2	0·7	0	0	0·1	1·6
68–38 (M)	0·2	0·1	0·8	2	0·7	0	0	0·1	1·6
38–34 (M)	0·2	0·4	1·0	2	0·9	0	0	0·1	1·6
34–24 (M)	0·1	0·2	0·8	2	1·0	0	0	0·1	3·2
24–0 (M)	0·1	1·0	1·2	2	1·0	0	0	0·1	3·2
106–94 (T1)	0·1	0·0	0·8	2	0·7	0	0	0·1	1·6
94–60 (T1)	0·1	0·0	0·8	2	0·7	0	0	0·1	1·6
60–34 (T1)	0·3	0·2	0·8	2	0·7	0	0	0·1	1·6
52–38 (T2)	0·2	0·1	0·8	2	0·7	0	0	0·1	1·6

M, main stream (Liao-Nung River + Kao-Ping River); T1, tributary 1 (Chi-San River); T2, tributary 2 (Ai-Liao River).

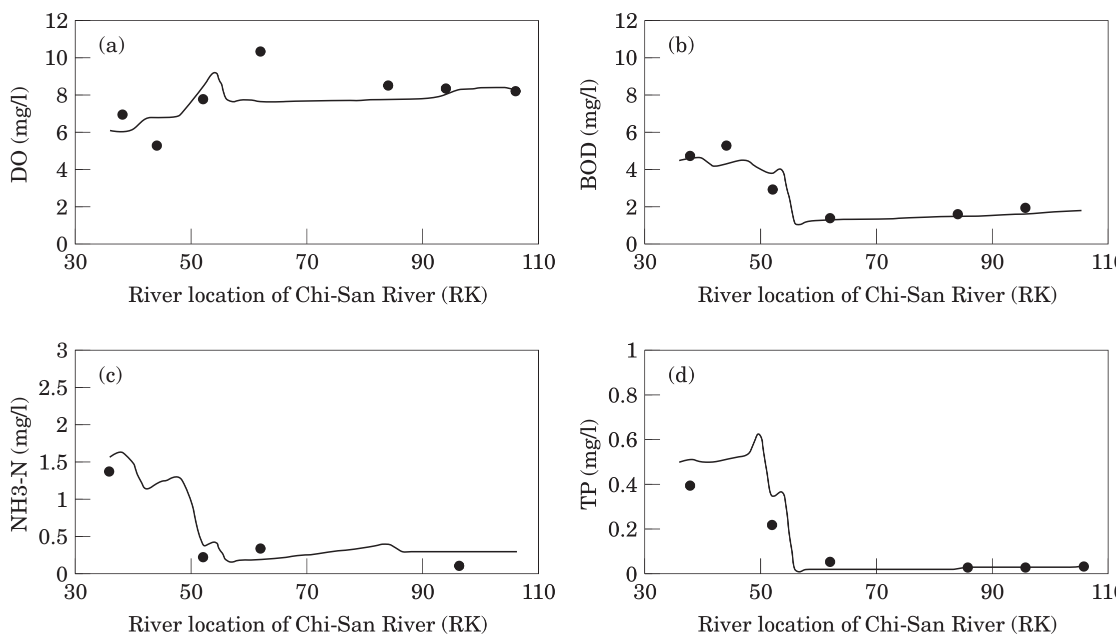

Figure 6. Calibration of QUAL2E model for the Kao-Ping River basin. Observed values (●); predicted values (——).

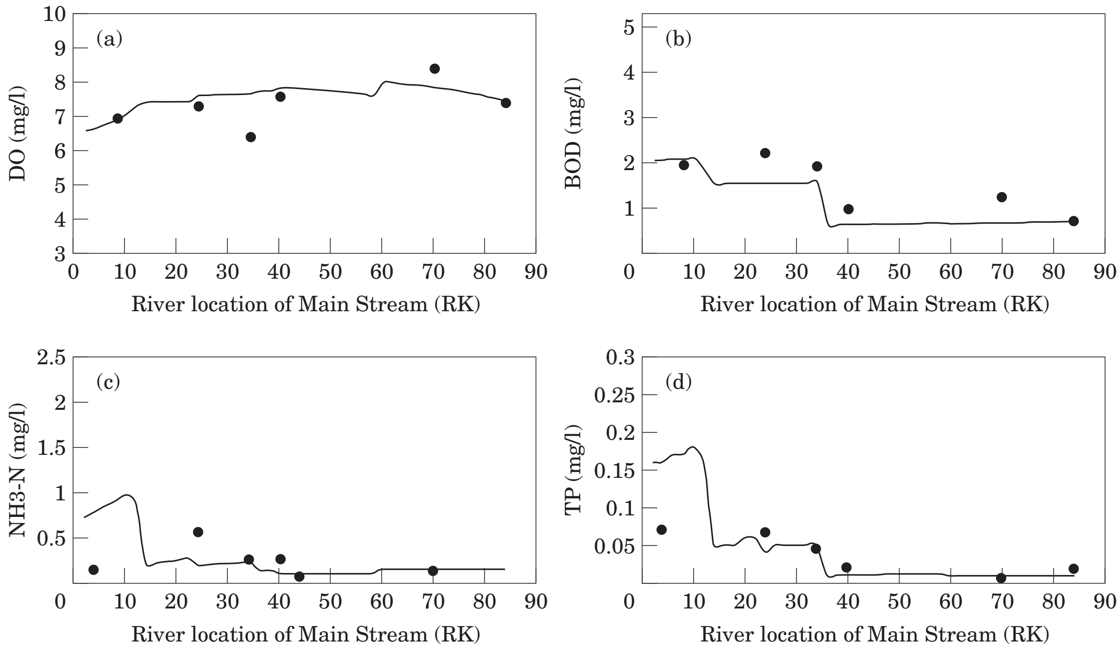

Figure 7. Validation of QUAL2E model for the Kao-Ping River basin. Observed values (●); predicted values (——).

A little bit discrepancy between predicted values and observed values exists in the river reaches from RK 2 to RK 20, that is probably due to the impacts of subsurface flow and tidal effect on the stream flows in the downstream river reaches. Overall, reasonable forecasting accuracy evidenced by a good match in this diagram warrants the use of QUAL2E for future policy decision-making.

Simulation analysis

The dynamic changes of water quality in the river system and the possible interactions through a number of weirs, water intakes, and transfer pipelines would make the later stages of its evolution of water resources and water quality management in this area become more complicated. With the aid of essential survey of waste load distribution and reduction potential, the key issues left in this study are 'to what extent must final decision of water resources redistribution strategy between watersheds be related to the findings of the environmental impact of downstream water quality?' or 'to what extent should the potential of pollution prevention actions be warranted under the circumstance of such a water transfer requirement?' Therefore, it requires the direct assessment concerning that the water transfer in the upstream area over natural boundary may provide adequate quantities of water for neighboring Tseng-Wen River basin, but the quality of water in the downstream area of the Kao-Ping River basin may become quite inappropriate for the compliance with the essential water quality standards. All the planning scenarios can be properly analyzed with respect to dry and wet seasons for the present or for the target year based on QUAL2E that has been fully calibrated and validated.

Overall, if the water resources redistribution conditional to a specific water year analysis is considered, it would first require a selection of designed stream flow in the specific water year, and then proceed a sequential allocation of available water resources to a number of sectors for agricultural production, industrial development, municipal uses, and water transfer requirements over natural boundary. Such a distribution practice must rely on an existing, certified water rights analysis program in the Kao-Ping River system. Therefore, the stream flow distribution for both dry and wet seasons can be predicted as the pollution prevention program is defined. Given a set of stream flow conditions after water transfer over natural boundary and the information of wastewater discharges after the partial fulfillment of pollution prevention actions at the target year, QUAL2E may provide a set of outputs that include values of BOD and NH_3-N concentrations for each required location in the river system. River water quality can then be assessed as a whole based on any changes of waste load through the point or nonpoint source pollution, any requirement of flow augmentation, or other conditions in the river basin. Such an outcome would be very helpful for the justification if an alternative or a policy is allowable or acceptable in the real world system. The predicted concentrations of BOD and NH_3-N in the Kao-Ping River system within dry and wet seasons, as shown in Figure 8, reveal that removing the pig farming and constructing the sewer systems in the upstream area cannot guarantee the full compliance with water quality standards in the downstream area and water transfer in the upstream area further increases negative impacts on the water quality in the wet season. The predicted situation of water quality in the dry season may even present worse condition.

Conclusions

The water resources issues in Taiwan are quite different than those currently in other industrialized countries. The problem of considering water-resource allocation with respect to both aspects of quantities and timing frequently becomes very complicated when a large number of interconnected weirs and reservoirs and designed to satisfy several demand sites of water uses. On the other hand, water-quality management with the idea of pollution prevention in a TMDL framework, without any reference to its quantity, can easily be meaningless over all planning and management purposes. Such a situation is especially acute when a series of demand sites in the neighboring Tseng-Wen River basin systems are to be considered. It is known that an increase of water demand due to industrial development will critically depend on availability of supply through large-scale water-transfer program and, more important, on the water-quality requirements in the upcoming TMDL program in the Kao-Ping River basin simultaneously.

Overall, this analysis summarized the changing situations of water resources and water-quality management in South Taiwan from the aspects of economic goals, industrial programs, agricultural production, and regional population growth. A thorough investigation, covering the stream flow duration, hydrological pattern, drainage area, reach summaries of dimension and pattern, schedule of engineering projects, waste load distribution, water-quality conditions, and the goals for controlling river assimilative capacity, was achieved for assessing the possible interaction between these two watersheds. QUAL2E typically provides greater flexibility in representing the complexity of various possible water resources management alternatives in relation to the response of water quality in the Kao-Ping River system. With the aid of simulation analysis, the planners would be able to answer significant decision-making issues, such as if the potential impacts of water transfer over natural boundary and the pollution prevention actions are related to each other? And what is the effect of these pollution prevention actions on water quality improvement? Further, with the consideration of essential stream flows prepared to maintain the environmental integrity in the Kao-Ping River basin, the scale of water resources allowable for such water transfer to the neighboring Tseng-Wen Reservoir can then be predictable. It shows With the aid of QUAL2E simulation model, it shows removing the pig farming and constructing the sewer systems in the upstream area cannot guarantee the full compliance with water-quality standards in the downstream area and water transfer in the upstream area further increases negative impacts on the water quality in the wet season. The predicted situation of water quality in the dry season may even present worse condition. Additional water pollution control policy, such as the use of economic instruments, for controlling and reducing the loadings of BOD and NH_3-N is needed in the Kao-Ping River system in the long-run. However, in the future management context of river basin planning, the availability of water does not only mean the quantity of water available for different purposes, such as domestic, agricultural, industrial,

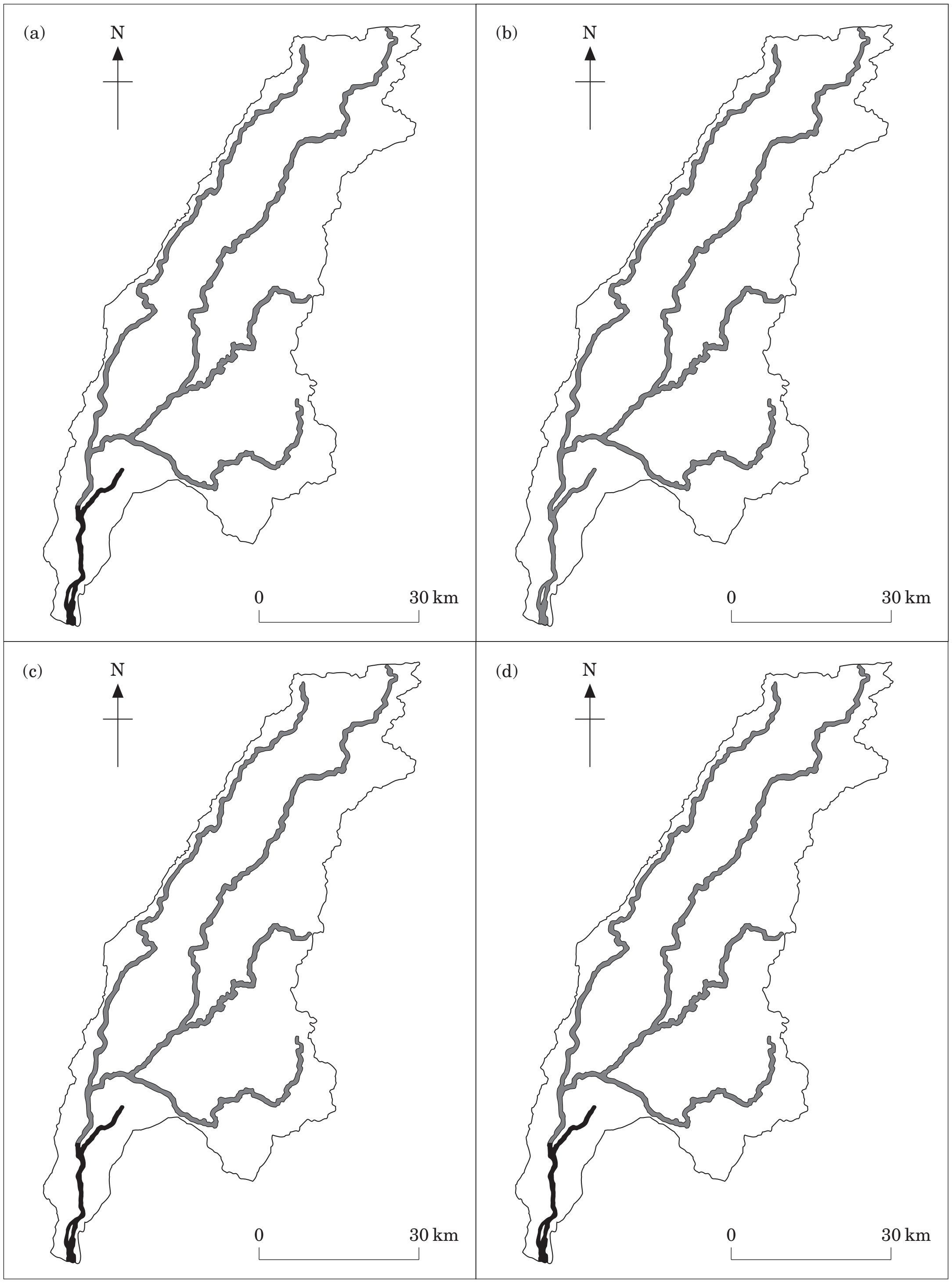

Figure 8. The effect of pollution prevention program in the Kao-Ping River basin. (a) BOD in the dry season, (b) BOD in the wet season, (c) NH_3-N in the dry season, (d) NH_3-N in the wet season. River reaches compliant with water-quality standards, ■, River reaches not compliant with water-quality standards.

hydroelectric power generation, navigation, and low flow augmentation, but also its quality for wild-life enhancement, aesthetics, and recreation. Risk and uncertainty existing in the hydrological sequence, non-point source pollution, and the subsequent water-quality management process in the Kao-Ping River basin will be incorporated into this study in the future (Brown, 1987; Melching and Yoon, 1996).

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