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Sizing an Off-stream Reservoir with Respect to Water Availability, Water Quality, and Biological Integrity

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Abstract Sizing a new reservoir is a challenging task, which normally requires simultaneously a cost-effective, risk-informed, and forward-looking decision analysis with respect to basin-wide hydrological features, environmental quality, and biological integrity. Such a sustainable planning approach takes into account the global trend to balance the needs of economic growth, ecological conservation, and environmental protection. To achieve the goal of sustainability, emphasis in this paper was placed upon the correlation of three physical, chemical, and biological indices, including the dissolved oxygen (DO), the 5-day biochemical oxygen demand (BOD_5), and the index of biotic integrity (IBI), for the optimal planning of a reservoir in a river basin. This new methodological paradigm has been employed for sizing an off-stream reservoir in the Hou-Lung River Basin, central Taiwan. The internal linkage between the water quality parameters (DO and BOD_5) and the IBI levels further enables us to formulate a special biotic integrity constraint which reflects fish community attributes to suit a relatively low-density and unspecialized freshwater fish fauna in response to the changing water quality conditions in the river basin. The tradeoffs among economic, environmental, and ecological aspects for reservoir sizing can then be based on the river flow patterns, the water demand, the water quality standards, and the anticipated biological integrity in some critical river reaches. Findings in a preliminary case study suggest that an optimal pumping scheme may be smoothly maintained on a yearly basis within a combined multi-criteria and multiobjective decision-making process.

Keywords Reservoir sizing · Environmental flow · Water quality management · Ecological conservation · Water resources management · Sustainable development

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1 Introduction

The development of new reservoirs to meet the growing demand of water supply, increasing standard of living, urbanization, and industrialization inevitably involves a substantial degree of environmental risk. The appreciation for environmentally and ecologically sound economic growth has become an important guideline to aid traditional approaches to determining the size of new reservoirs. To help achieve this goal of the optimal sizing of new reservoirs, the development of an effective assessment matrix adequately considering environmental and ecological resources may become one of the challenging tasks for reservoir planning and design. Loucks et al. [21] propagated the techniques of systems analysis as an indispensable tool for water resources management. System-based approaches using integrated simulation and optimization models provide an important set of tools to characterize the dynamic and complex interrelationships of quantity and quality of water resources for economic use that may be subject to a host of intrinsic attributes collectively. These attributes, whether physical, chemical, or biological, can favor, limit, or completely inhibit economic activity and subsequent societal development.

Within the last two decades, much system-based research has addressed the related issues of reservoir capacity planning and design using mathematical programming models. Some earlier work, which made linear programming one of the most promising approaches, focused on the impact of hydrological patterns [9, 12, 13, 25, 30]. The main focus in reservoir planning at that stage was to derive a schedule of seasonal optimal releases under uncertainty using a stochastic programming model [26]. Extended research efforts cover the interesting aspect of marginal costs analysis [23], marginal benefits analysis [27], nonconvexities analysis [37], an integrated simulation–optimization analysis [2], the generation of synthetic stream flows [31, 35], the reservoir reliability analysis [29], the integration of water demand, storage loss due to sedimentation, physical characteristics and hydrological features of the watershed [32], and a hydrometeorological forecasting technique [35]. One later effort striving to size reservoirs in a multiple-reservoir-capacities design problem using a network flow programming model was designed to optimize the flow in a multiperiod framework [19]. More detailed and elaborate analyses may include, but are not limited to, the assessment of marginal negative environmental impact caused vs. the incremental benefit generated by sizing a new reservoir [34], the global change impacts associated with the warm phase (El Niño) and positive anomalies with the cold phase (La Niña) [22], and the use of optimal control theory for handling multireservoir systems for water supply [24].

Factoring the information on environmental quality and biological integrity into a reservoir sizing process turns out to be essential due to the possible decrease of flow rate after the construction and operation of the reservoir. Some environmental management programs started assessing the intrinsic characteristics of a reservoir and the possible water quality impacts on downstream river reaches in the late 1990s [1, 3]. Using a wealth of water quality simulation models, the environmental impact due to sizing a new reservoir can become understandable. However, effective tools are needed to measure the health of rivers at scales large enough to be useful for water resources management [11]. River health can be defined as the degree to which three main physical and chemical attributes of a river (i.e., its energy sources, water quality, and flow regime), plus its biota and their habitats, match the natural condition at all scales [15–17]. Indicators for assessing the complex of variables that constitute river health need to be ecologically based, efficient, rapid, and consistently applicable in different ecological regions [11]. The most common approaches to such assessment of environmental degradation from a biological point of view involve the use of (1) indicator taxa or guilds; (2) indices of species richness, diversity, and evenness; (3) multivariate methods; and (4) the index of biotic integrity (IBI). The IBI uses metrics of species richness, abundance, and community structure [15, 16] and provides a comprehensive, sensitive, and quantitative tool for integrating and assessing the condition of each of the four components above [20]. It can overcome the limitations of some physical and chemical tools by comprehensively assessing the condition of all the main components of aquatic ecosystems [11]. As an aggregation of community information, the IBI-type indices provide a way to organize complex data and reduce it to a scale that is interpretable against communities of known condition [39]. Applications of IBI, which expresses a relative value of aquatic community health and well-being, can be used to visualize relative levels of biological integrity in various watersheds [10, 18, 28].

For solving the reservoir sizing issue in a river system, one may expect to size the reservoir to satisfy the water demand and operate it for water quality assurance. However, if the river system downstream had already been polluted, then the environmental restoration program must be well planned at the same time as the reservoir is sized. This paper addresses such a unique situation at the watershed scale by linking hydrological, environmental, and biological factors together in the context of an integrated simulation and optimization model. A case study carried out in the Hou-Lung River Basin, central Taiwan, demonstrates the potential of the model. The model was developed for an off-stream reservoir with a focus on water supply, water quality standards, and biotic integrity. It seeks to understand the complex web of environmental and ecological feedbacks at both temporal and spatial scales in a coupled human and natural system—the reservoir and its linked river reaches.

2 Background

Taiwan is located in the west Pacific Rim of Asian Continental Shelf with an area of about 36,000 km^2 and a population of over 23 million. In recent decades, the relationships and interactions between land, water resources, and the human exploitation within 21 major river basins have been especially complex. The conservation of water resources is under increasing pressure because of tremendous demands from population growth, economic development, and industrialization. The extremely uneven stream flows between dry and wet seasons in Taiwan result in additional complications between the development of new reservoirs and the conservation of water quality and ecosystems in almost all river basins. Facing water shortage and fast regional development, there is a need to build an off-stream reservoir in the Hou-Lung River Basin, which is located between the Hsin-Chu County and the Tai-Chung County in central Taiwan.

Designing the surface off-stream reservoir at the Tien-Hua Lake necessitated a preliminary reservoir sizing assessment in the late 1990s. According to long-term observations, about 80% of rainfall occurs between April and September in the Hou-Lung River Basin, which complicates the reservoir planning. Such hydrologic conditions increased the anxiety of environmentalists about degraded water quality and ecological conservation. This concern also implies that a proportion of the natural flow regime of a river should be reserved as environmental flow when major reservoir planning alternatives are considered for regional economic development.

The Ho-Lung River system is well known for its long-term pollution downstream because of several sources, predominantly from household wastewater, on occasion with industrial and stock farming discharges, and return flows from agricultural land. The water body in Hou-Lung River system was officially classified into three different categories for management purposes. The observations obtained from water quality monitoring stations showed that current waste loads along the river system could result in a long-term violation of water quality standards in the downstream areas. Figure 1 summarizes the distribution of the waste loads (pink dots), gage stations (green stars), and water quality monitoring stations (HL 1~10) in the Hou-Lung River system along the river kilometer. The larger the size of the pink circle, the higher are the waste loads, and hence the larger is the pollution impact. In fact, the waste load distribution may reflect the varying population density locally along the river corridor. Thus, the size of such a new reservoir should not exceed an essential level that guarantees the planning goal to be satisfied in the form of water supply, while the water quality and ecosystem integrity downstream may be maintained or restored at the lowest treatment cost level. To include concerns about environmental flows, an integrated simulation and optimization model may be formulated which simultaneously incorporates consideration of water availability, water quality, and biological integrity.

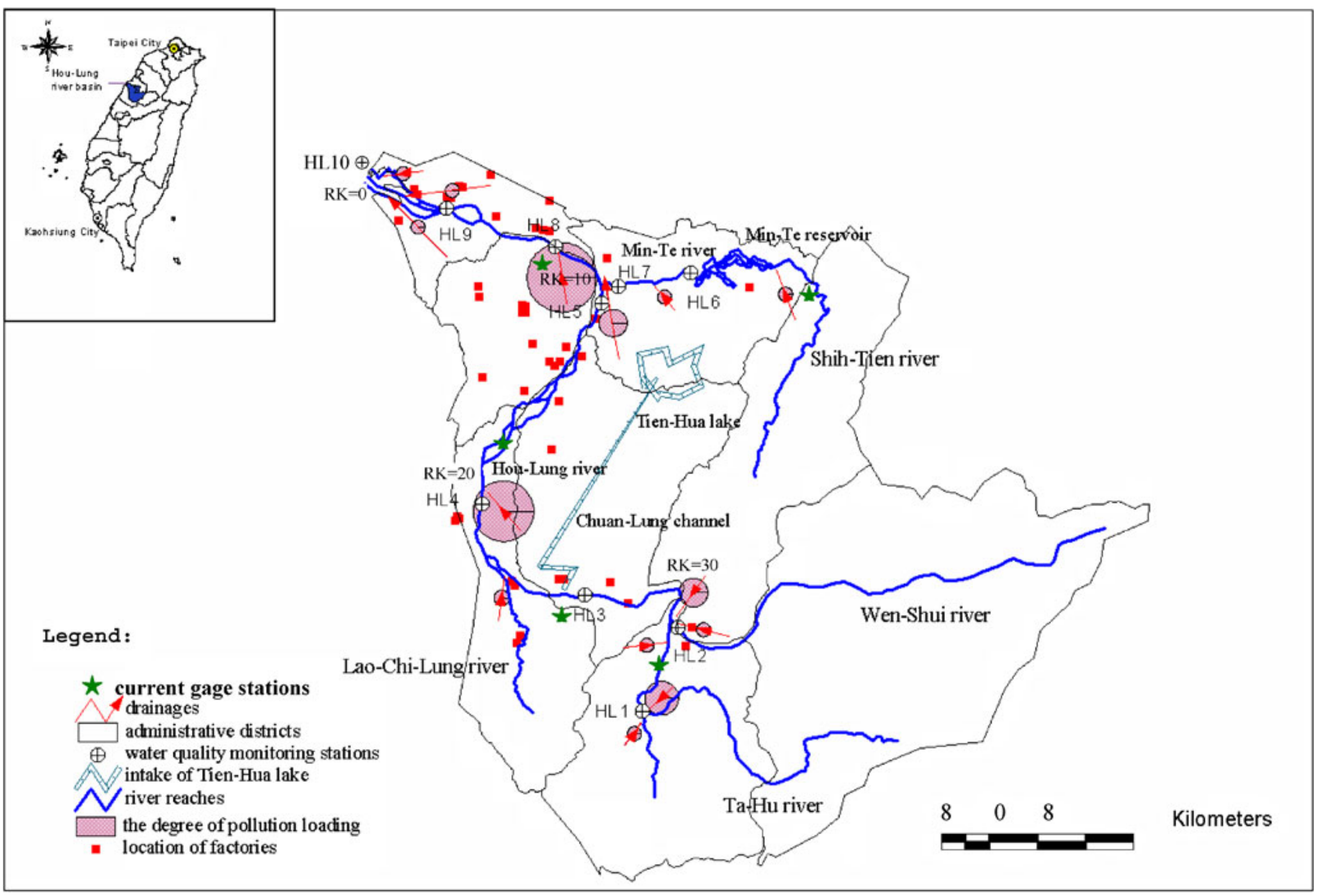

Fig. 1 Distribution of the waste load and monitoring stations in Hou-Lung River system

3 The Schematic of the River System

Disregarding water quality changes in the reservoir may prove to be an unjustified simplification. However, it is known that the water quality upstream in the Hou-Lung River Basin is pristine. To model the water quality conditions downstream in the river in an easy and effective way, the water quality model developed by Streeter and Phelps (the SP model hereafter) was employed for teaming up with the analysis of biotic integrity [33]. By including relevant mass balance equations for all associated river elements based on the discretized scheme, such a simplified water quality submodel (e.g., SP model) may be linked to the reservoir operation submodel for the purpose of optimal planning and sizing. The philosophy of such a formulation in this paper is therefore similar to the yield model developed before with the addition of river health consideration [21, 38].

To meet such a planning goal, a series of symbolic representations from the viewpoint of different spatial scales were defined to help perform simulation, optimization, and impact assessment. In Fig. 2, "part A" shows the basin configuration and study area. "Part B" interprets the flow routing scheme. In this analysis, river elements are identified hydraulically and hydrologically with considerations of the interactions among flow rate, water intake, waste discharge, water quality, and river health. "Part C" implies the environmental transformation mechanism. Each element, as shown in "part C," was considered as a continuous stirred tank reactor where existing environmental characteristics, including deoxygenation rate coefficient, volumetric reaeration coefficient, and so on, were deemed homogeneous in the modeling analysis. Within each element, physical and/or chemical reactions took place, which can be refined for further optimization analysis to identify the most suitable reductions of waste loads along the designated river reaches further downstream. "Part D" indicates environmental transport where the waste loads can be discharged into the water body. All parameters and decision variables used hereafter are summarized in the Appendix of this paper. The symbols defined in Fig. 2 will be used again later on in the model formulation.

Various complications concerning water resources usage occurred temporally and spatially during the course of allocation of water resources. In Fig. 3, the Hou-Lung river system was reorganized into a schematic diagram composed of eight waste discharges (I_1~I_8) and five water intakes (D_1~D_5). It presents the nontidal stream as a combination of six river reaches in our modeling framework according to the hydraulic characteristics. Within each river reach, several elements of 0.5-km length were defined in support of the SP simulation analysis. Such a schematic setting allows us to address the interfaces and interactions between water avail-

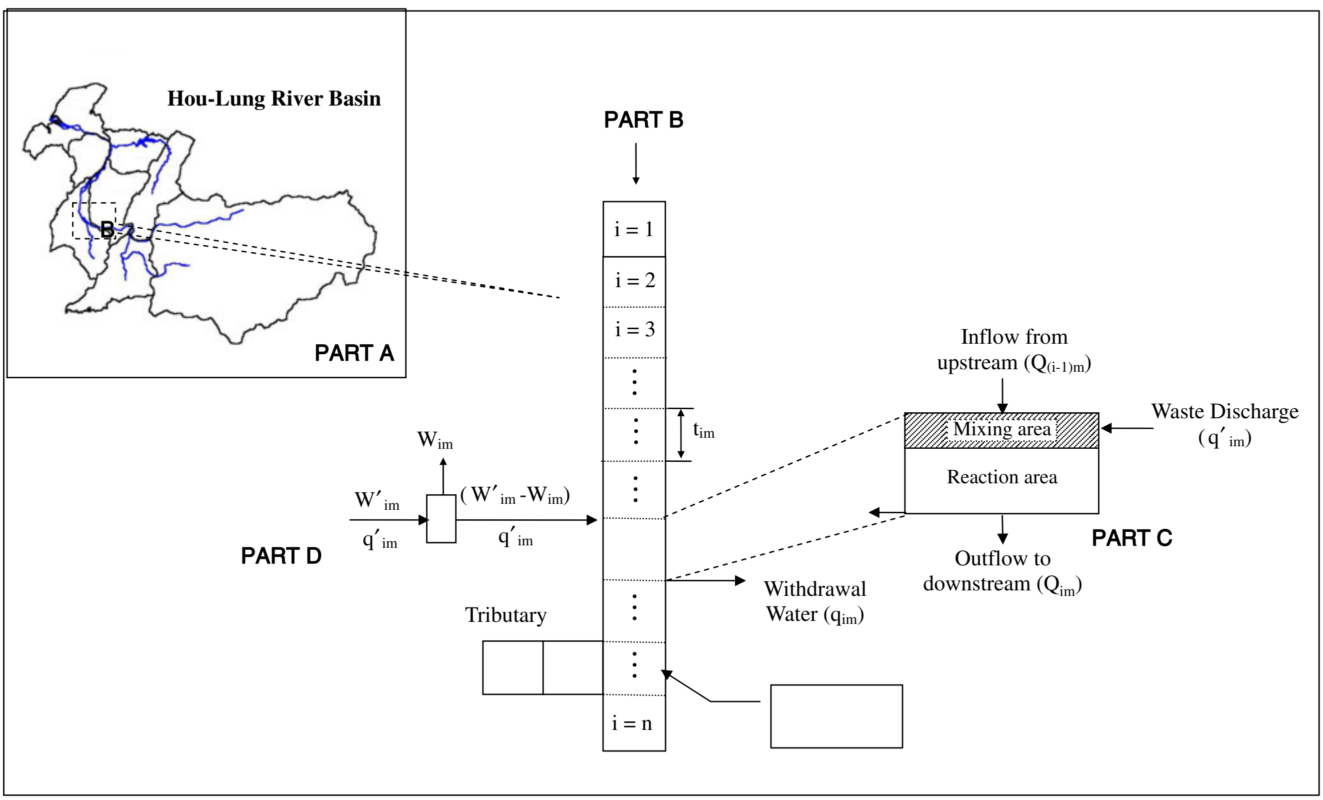

Fig. 2 The schematic representation of subscripts and parameters used in the model

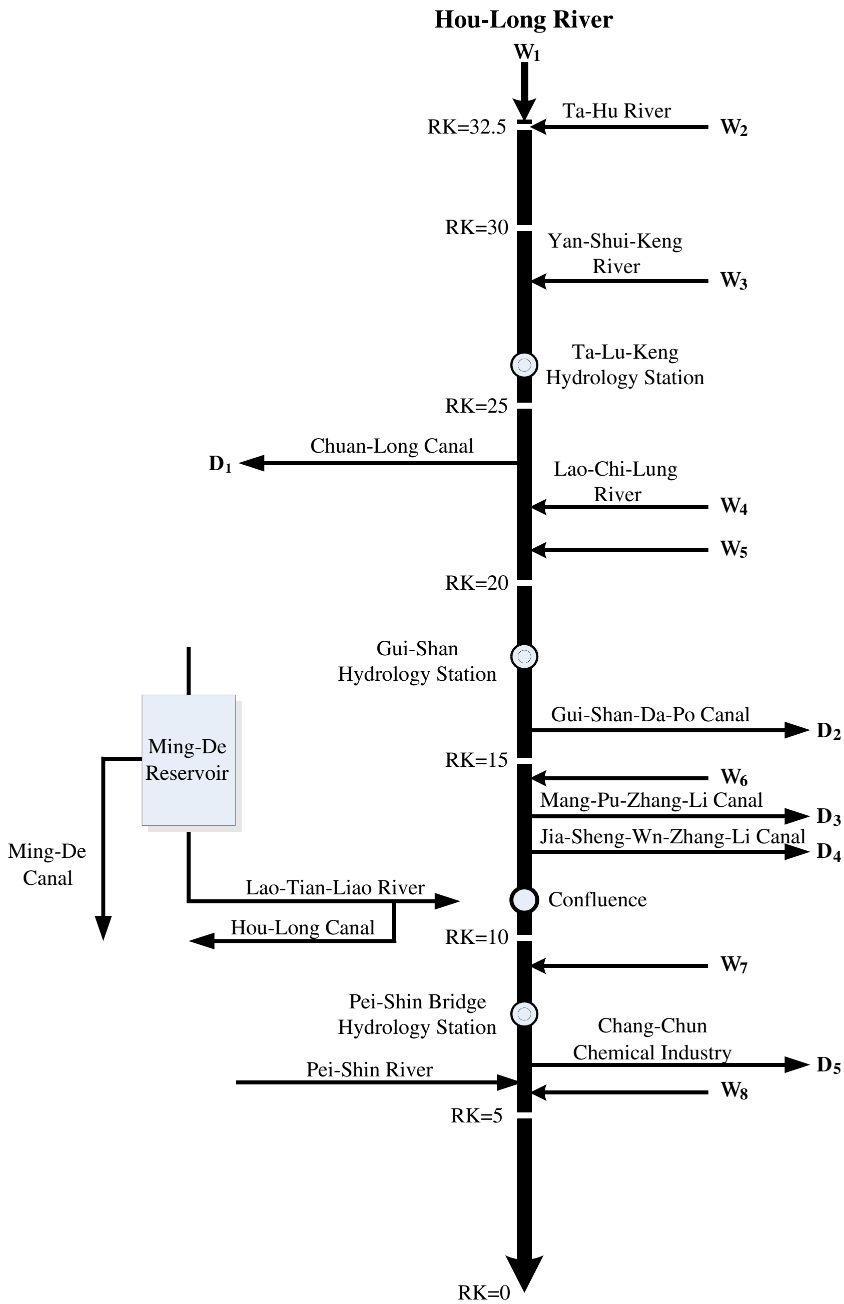

Fig. 3 Schematic diagram for modeling analysis in the Hou-Lung River Basin

ability, water quality, and biological integrity as an integral part of the constraint set used for optimization analysis.

4 Data Analysis, Synthesis, and Simulation

4.1 Water Supply and Demand Analysis

Information about stream flow rates, hydrological patterns, drainage areas, and stream flow durations, together with discharges and withdrawals, were collected and used in support of the modeling analysis. The average monthly flow rates from 1981 to 2005 at four gage stations were analyzed and summarized. The results show that natural variations of stream flows over seasons are more than sufficient in the sense that certain periods in the wet season are more suitable for pumping water from HL3 to feed the reservoir—the Tien-Hua Lake. Due to higher water demand, this off-stream reservoir should be designed as a single-purpose reservoir solely supporting water supply. However, in the water rights management program, five legitimate water withdrawals were permitted as summarized in Table 1, which should be taken into account simultaneously.

4.2 Water Quality Monitoring and Simulation

The river system was further characterized environmentally by performing field sampling and laboratory analysis. Sampling campaigns were conducted during the dry and wet seasons in 1997 to capture the variations of the uneven stream flow rate across seasons. These ten selected sampling locations, denoted HL1~HL10, are shown in Fig. 1. Sampling in the period of low flows gave a true worst-case scenario yielding with high but variable pollutant concentrations whereas sampling in the period of high flows presented an optimistic scenario characterizing the upper bound of stream assimilative capacity. However, in periods of low flow, the optimization model might result in inoptimal solutions depending on the actual flow regime. Note that the water intake of the Tien-Hua Lake is located in the vicinity of the sampling location HL3.

The deoxygenation and reaeration coefficients in the SP model (i.e., k_1 and k_2) associated with all river reaches of concern were estimated based on the monitoring data set collected by the authors. Table 2 summarizes part of the results of laboratory analysis. These data enable us to derive the ultimate formulation in the constraint set of the optimization model. Collectively, Figs. 4 and 5 demonstrate the agreement between the simulated and observed data indicative of the water quality impact in low-flow seasons. The water quality standards as marked by the dashed lines in both figures reveal that the compliance issue is apparent downstream in terms of both 5-day biochemical oxygen demand (BOD_5) and dissolved oxygen (DO).

4.3 Biotic Sampling and Analysis

Field biotic sampling was also performed in 1997 to evaluate the impairment of fish communities throughout the Hou-Lung River Basin. Figure 6 describes the locations of biotic sampling (i.e., from B1 to B13) and the corresponding water quality situation at those locations. Fish community data, as indicated in Table 3, were analyzed using the modified IBI scheme [16, 17]. The reason for not including the biotic and water quality sampling record at B12 and B13 is that no fish survived to the downstream section due to heavy water pollution. Six categories were classified in the analysis, as shown in Table 4. This modification was necessary if the IBI metrics were to be a meaningful measure in response to the corresponding water quality standards. Thus, the ranges of modified IBI scores can be mapped to the classified water body in terms of water quality indices for various uses. Since the IBI scores in most of the portions of the river system can be treated as a function of known BOD_5 and DO levels, an empirical function of IBI defined in terms of BOD_5 and DO must be developed to support the optimization analysis. This would enable us to comprehend the interactions between the chemical and biological impacts within the constraint set directly. The nonlinear regression Eq. 1 was thus developed. Despite the negative coefficient associated with the square term of DO, the total impact of DO on IBI was positive in the range of observation owing to the positive coefficient of the linear term. The value of the adjusted coefficient of determination (R^2), which measures

Table 1 Distribution of temporal water rights in the Hou-Lung River Basin

	Chuan-Long Canal (D1)	Gui-Shan-Da-Po Canal (D2)	Mang-Pu-Zhang-Li Canal (D3)	Jia-Sheng-Wn-Zang-Li Canal (D4)	Chang-Chun Chemical Industry (D5)	Total
Jan	1.980	0.900	0.062	0.140	0.242	3.694
Feb	1.973	0.900	0.067	0.140	0.242	3.692
Mar	1.961	0.982	0.020	0.166	0.242	3.741
Apr	1.961	0.982	0.072	0.166	0.242	3.793
May	1.961	0.900	0.063	0.141	0.242	3.677
Jun	1.961	0.900	0.063	0.141	0.242	3.677
Jul	1.961	0.900	0.073	0.166	0.242	4.342
Aug	1.961	0.900	0.062	0.141	0.242	4.306
Sep	1.961	0.900	0.062	0.141	0.242	4.306
Oct	1.961	0.909	0.061	0.130	0.242	4.303
Nov	1.423	0.466	0.035	0.125	0.242	2.661
Dec	1.480	0.668	0.070	0.110	0.242	2.940
Total	22.544	10.307	0.71	1.707	2.904	45.132

Unit: centimeter

Table 2 Parameter identification of water quality model

Number of river reach	Wet season		Dry season	
	k_1 (1/day)	k_2 (1/day)	k_1 (1/day)	k_2 (1/day)
1	0.002	0.7629	0.400	0.4629
2	0.001	0.4215	0.400	0.1215
3	0.001	1.2650	0.010	0.6650
4	0.350	1.1960	0.450	1.4960
5	0.200	0.6116	0.100	0.2616
6	0.100	0.8276	0.200	0.6876

the percentage of total variation in the response variable that is explained by the least-squares regression line, can be up to 0.773. For an optimization process, the assumption that IBIs are expressed in terms of BOD_5 and DO is useful, as it simplifies the degree of complexity by coupling the physical, chemical, and biological processes as a whole.

$$\mathrm{IBI} = -3.25 - 1.20\mathrm{BOD}_5 - 0.36\mathrm{BOD}_5{}^2 + 10.12\mathrm{DO} - 0.56\mathrm{DO}^2 \mathrm{adj}{-}R^2 = 0.773 \quad (1)$$

4.4 Cost Data Analysis

A cost function describing the relationship between the relative size of the reservoir and the construction cost required must be available to support the model formulation in this optimization analysis (Table 5). Operating costs are deemed trivial in comparison to the construction cost in this case. Besides, a causal relationship is also needed to correlate the wastewater treatment levels or responses with the associated water pollution control cost in the river system. In short, these two cost functions would play a critical role as driving forces providing essential tradeoffs among multiple purposes or criteria in the reservoir sizing analysis. To effectively derive these functions, this study combines several cost data sources and develops several functional forms relating wastewater treatment and reservoir construction costs to treatment performance and reservoir capacity, respectively. With this setting, choices of the level of treatment to be achieved by the treatment plant and the volume of water to be stored by the reservoir would constitute the solution space later on in the optimization process. The structure of the objective functions may provide the translation of environmental criteria/constraints into equivalent currency as derived below.

4.4.1 Derivation of Cost Function for Water Supply

The costs of 17 existing/planned reservoirs in Taiwan were collected to meet the need for the cost analysis. Figure 7 presents the distribution of these cost data in which there is a remarkable inflection point with the capacity, which is about 45 million tons of stored water. It shows the obvious feature of diseconomy of scale in cost analysis. The regression equation of average cost gives a functional form of C=0.27ln(V), and the coefficient of determination is 0.748. The t-ratio (=8.28) is very high, indicative of the corresponding 99% significance level. Significance level assumes that individual demand functions are known for all of the participants in this river basin. Such a nonlinear cost function is also supportive in

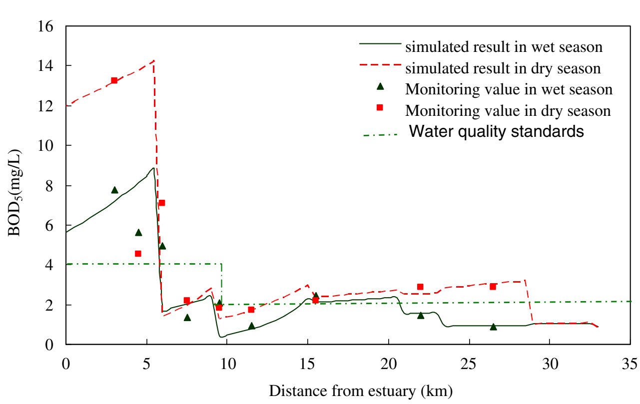

Fig. 4 The agreement analysis of BOD concentrations over different seasons

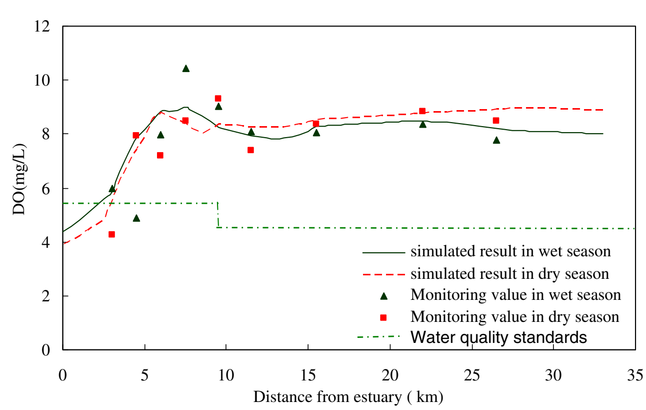

Fig. 5 The agreement analysis of DO concentrations over different seasons

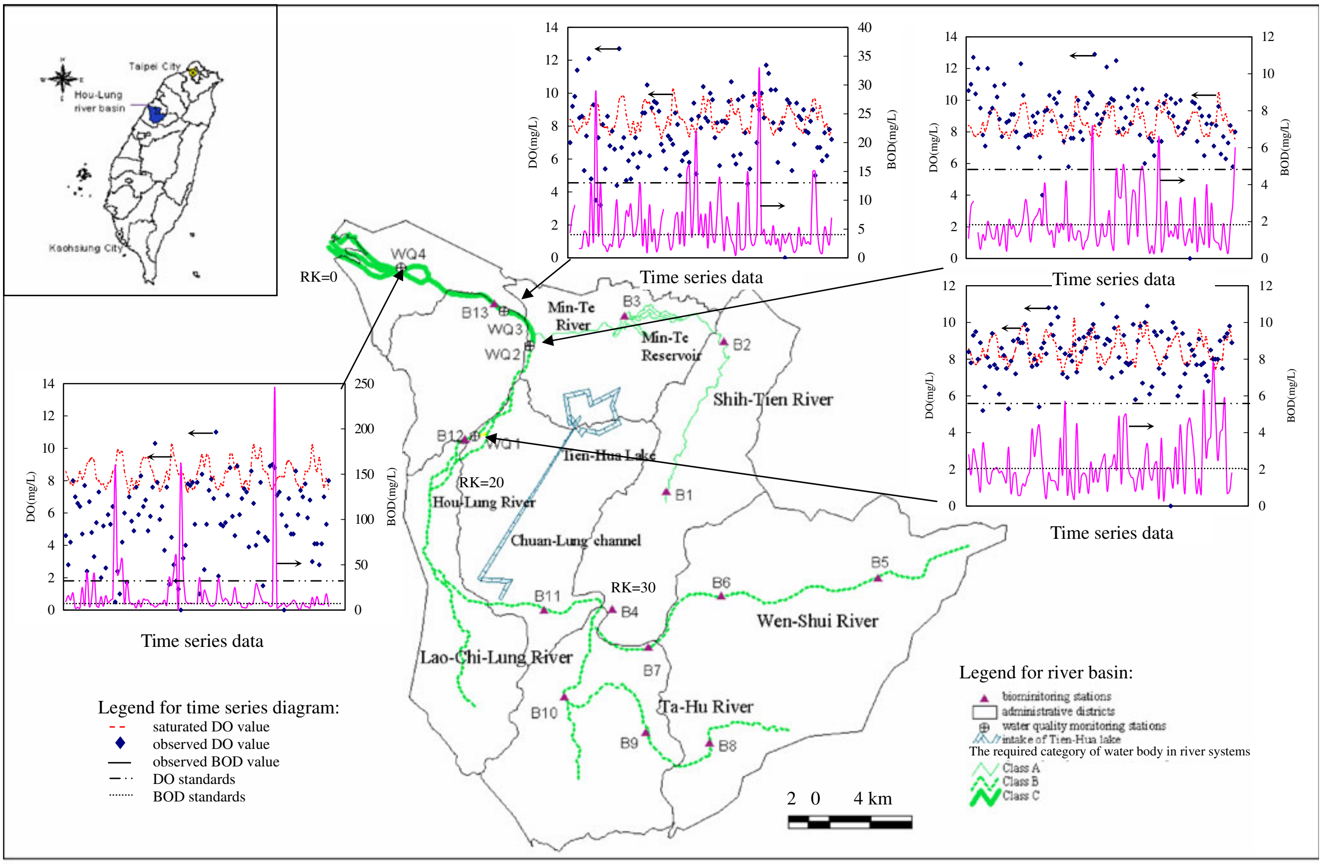

Fig. 6 The locations of biotic sampling and associated water quality conditions

determining the varying marginal cost of water supply due to the fluctuation of water demand.

In the present water market in Taiwan, the government needs to tighten up policy and search for some substituted water resources to maintain a stable water supply in case a drought year occurs or should the predicted economic boom turn out to be real. Therefore, although it is notable that traditional market transactions are based on information about prices rather than costs, the cost for water supply would not normally be considered changeable to any great extent, and the price of water did not depend on the sources of substitution of water resources in the past. Hence, cost instead of price information is more useful at the preliminary planning stage in Taiwan. Being an island surrounded by ocean, sea water desalinization is the most likely new water source of substitution in Taiwan in the future to mediate the insufficiency of regional water supply. Thus, to reflect such a possibility, this paper also built a three-part cost function formulated as Eq. 2 trying to address the floating relationship between varying cost and the water supply when the demand and supply sides cannot remain balanced.

Within Fig. 7, the slope of segment A, which is delineated with the two bold dots, stands for the marginal cost that is deemed as one scenario which exactly conforms to the target level of water supply (contract) with no gap between supply and demand. When the ultimate level of water supply is greater than the anticipated level in the project, the marginal average cost in water supply would be decreased due to the additional income by selling the surplus water resources. Conversely, when the ultimate level of water supply is less than the anticipated level in the contract (i.e., target level of water supply), the marginal average cost in water supply would be increased. These two

Table 3 The outcome of biotic and water quality sampling

	B1	B2	B4	B5	B6	B7	B8	B9	B10	B11
IBI	34	38	42	40	42	38	30	42	30	36
BOD (mg/L)	3.9	0.7	1	1.6	1	0.4	1.6	1.7	3.9	5
DO (mg/L)	6.2	6.3	9	7.2	7.2	6.5	7.7	7.5	6.7	6

Table 4 Modified IBI with respect to water quality classification

Class	Karr's Index Number[a]	Simplified class	Index number
Excellent	50~60	Excellent	50~60 (A)
E–G	53~56	Good	47~54 (A)
Good	48~52	Fair	38~46 (B)
G–F	45~47	Poor	26~37 (C)
Fair	39~44	Very poor	<24 (D)
F–P	36~38	No fish	–(E)
Poor	28~35		
P-VP	24~27		
Very poor	<24		

[a] Karr [15–17]

extremata thus denote the revised marginal average cost functions addressing the changing effect in zone B as presented in Fig. 7. With these three scenarios considered fully, Eq. 2 thus depicts a semiempirical cost function with three parts derived for water supply in this region.

$$C_{1m} = \begin{cases} (0.27\mathrm{Ln}V) \times q + 24(q - q_m) & q_m < q \\ (0.27\mathrm{Ln}V) \times q & q_m = q \quad \forall m \\ (0.27\mathrm{Ln}V) \times q - 4(q_m - q) & q_m > q \end{cases} \tag{2}$$

in which C_{1m} is the amortized total construction cost of a new reservoir required for water supply in month m (NT$); V stands for the design capacity of the reservoir ($10^4\mathrm{m}^3$); q is the pumping rate for monthly water supply from the Hou-Lung river to the Tien-Hua Lake ($10^4\mathrm{m}^3$), which is a decision variable; and q_m is the actual water supply from the Tien-Hua Lake to agricultural, municipal, and industrial end users in month m ($10^4\mathrm{m}^3$), which is an input variable.

4.4.2 Derivation of Cost Function for Wastewater Treatment

The cost database, including 48 domestic wastewater treatment plants and 29 industrial wastewater treatment plants, stores the construction cost of wastewater treatment plants. The derivation of such a cost function can be seen in a companion study [7]. The collected samples from the wastewater treatment plant were basically classified by the level of primary, secondary, and tertiary treatment [7]. Consequently, the cost information applied for addressing the corresponding cost term on a monthly basis in the

Table 5 Average construction cost of reservoirs in Taiwan

Reservoir name	Construction year	Average cost (NT$/$\mathrm{m}^3$ adjusted to 2001)	Capacity ($10^4\mathrm{m}^3$)
Bai-He	54	1.53	2,509
Min-Gte	59	0.90	1,770
Xin-Shan	68	2.25	1,000
Fong-Shan	73	0.29	920
Yon-Ghe-Shan	73	1.03	2,958
Bao-Shan	74	1.32	547
Ren-Yi Lake	76	1.36	2,911
Carp Lake	88	3.17	12,612
Nan-Hua	87	2.52	15,800
Mu-Dan	84	4.41	2,940
Shin-Kang Dam	89	0.80	338
Second Bao-Shan	94	4.52	3,218
Hu-Shan[a]	–	1.97	3,270
Mei-Nung[a]	–	2.87	32,380
Ba-Bao Dam[a]	–	2.05	270
Ji-Yang Man-made Lake[a]	–	2.74	6,500
Tseng-Wen Water channel[a]	–	1.94	6,900

[a] Planned reservoirs

Source: Bureau of Water Resources, Ministry of Economics, Taiwan, R.O.C.

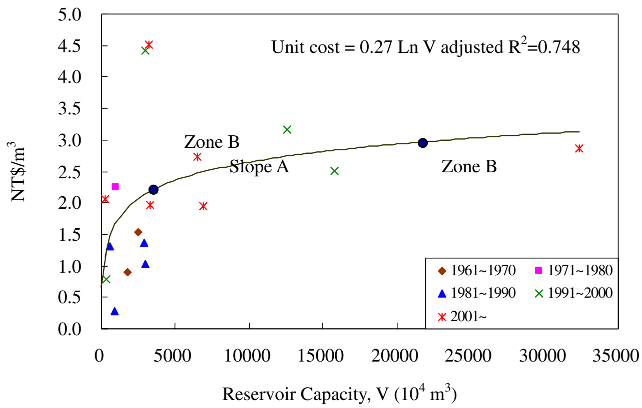

Fig. 7 Analysis construction costs based on existing and planned reservoirs in Taiwan

objective function of the optimization model can be amortized by making timescale consistent with the monthly pumping scheme. Equation 3 is the construction cost function required for water pollution control in the river system.

$$C_2 = \sum_m \sum_i 0.079 {W_{im}}^{0.88} \quad (3)$$

in which C_2 is the total construction cost required to achieve the removal of waste loads W_{im} at element i in month m (kg-BOD_5/month). Such a nonlinear (concave) function shows the positive influence of the economy of scale in cost analysis.

5 Systems Analysis

This systems analysis develops a methodology for reservoir planning, which takes into account not only the traditional economic factors but also ecological conservation and environmental protection issues. This is a sustainable goal, particularly given the hugely documented (negative) impacts that reservoir projects have had on the environment in various parts of the world. The methodology was applied to the planning of a pumped storage of off-stream Tien-Hua Lake (reservoir) which will abstract water from the Hou-Lung River in central Taiwan. Given that the Hou-Lung River receives substantial effluent discharges, it is therefore important that extractions of its water to fill the pumped storage reservoir are carefully managed so that water quality standards in downstream sections of the river are not violated; hence, the year-round efforts to include environmental or water quality constraints in the optimization context.

For sizing such an off-stream reservoir under dynamic hydrologic conditions, a multiobjective programming model was designed to maximize the monthly water supply

Table 6 The optimal waste load reduction strategy downstream and pumping scheme at the water intake HL3

	W_1[a] (kg-BOD/day)		W_2 (kg-BOD/day)		W_3 (kg-BOD/day)		W_4 (kg-BOD/day)		W_5 (kg-BOD/day)		W_6 (kg-BOD/day)		W_7 (kg-BOD/day)		W_8 (kg-BOD/day)		Pumping rate (cm)
Jan	0.0[b]	0%[c]	0.0	0%	0.0	0%	0	0%	672.8	78%	493.3	90%	1539.3	64%	6,537.8	88%	0
Feb	0.0	0%	0.0	0%	0.0	0%	0	0%	690.1	80%	493.3	90%	1491.2	62%	6,463.5	87%	0
March	0.0	0%	0.0	0%	0.0	0%	90.6	18%	793.6	92%	449.4	82%	986.1	41%	6,463.5	87%	2.3
April	0.0	0%	0.0	0%	0.0	0%	135.9	27%	759.1	88%	394.6	72%	673.4	28%	6,686.4	90%	3.4
May	0.0	0%	0.0	0%	0.0	0%	176.1	35%	776.3	90%	372.7	68%	529.1	22%	5,794.8	78%	4.6
June	0.0	0%	0.0	0%	0.0	0%	211.4	42%	767.7	89%	334.3	61%	481.0	20%	6,612.1	89%	10.2
July	0.0	0%	0.0	0%	0.0	0%	166.1	33%	733.2	85%	438.5	80%	1370.9	57%	6,092.0	82%	4.2
Aug	0.0	0%	0.0	0%	0.0	0%	161.0	32%	724.6	84%	301.4	55%	336.7	14%	6,686.4	90%	6.5
Sep	0.0	0%	0.0	0%	0.0	0%	110.7	22%	707.3	82%	389.1	71%	914.0	38%	6,537.8	88%	5.8
Oct	0.0	0%	0.0	0%	0.0	0%	100.6	20%	707.3	82%	383.7	70%	1154.5	48%	6,612.1	89%	0
Nov	0.0	0%	0.0	0%	0.0	0%	0	0%	681.4	79%	487.8	89%	1539.3	64%	6,017.7	81%	0
Dec	0.0	0%	0.0	0%	0.0	0%	0	0%	664.2	77%	482.3	88%	1587.4	66%	6,834.9	92%	0

[a] The locations of discharge in association with Wi are shown in Figs. 2 and 4

[b] The amount of waste load reduction (kg-BOD/day)

[c] Reduction percentage

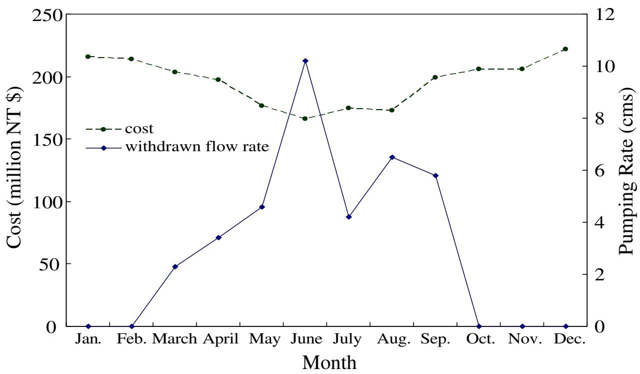

Fig. 8 The relationship between pumping rate and cost for pollution control

from reservoir storage and minimize the total costs incurred for the construction of those related facilities with respect to the flow, water quality, and river health constraints. For demonstration purposes, this study assumes that the flow regime applied in this deterministic model addresses the average flow over the past 30 years. The goal is to identify the operating policy for this reservoir. In an effort to identify the optimal pumping scheme on a monthly basis, the objective functions can then be presented as Eqs. 4 and 5.

$$\text{Maximize } Z_1 = \sum_i \sum_m q_{im} \tag{4}$$

$$\text{Minimize } Z_2 = \sum_m C_{1m} + C_2 \tag{5}$$

Thus, Eq. 5 is composed of two amortized cost functions required for water supply and water pollution control in the river system, respectively.

Hence, the amount of pumping upstream may vary in regard to its ability to bear the uneven stream flows over seasons and to allow the maximum use of assimilative capacity in the river while not offending the river health status, especially in the fish community, due to the changing conditions of water quality. Such a modeling structure would allow decision makers to realize the interactions of water quality and river health status in all relevant river reaches and present an interactive framework when constraints or objectives in the optimization process have to be flexibly adjusted. The constraint set of this model is defined as below.

(a) Constraints for flow balance in river reaches: Flow balance in stream segments or river reaches needs to be confirmed. These constraints can be defined as Eqs. 6 to 9 for all confluence, discharge, and withdrawal points. Specifically, the in-stream flow constraints are formulated as Eq. 6 according to mass balance principle as described in part C of Fig. 2, in which Q_{im} is the outflow from element i to element i+1 in month m (10^4m^3/month), q'_{im} is the amount of flow rate discharged into element i in month$m$ (10^4m^3/month), and q_{im} is the amount of flow rate withdrawn from element i in month$m$ (10^4m^3/month). Equation 7 is a specific setting to reflect the variations of flow rate in the optimization process. By changing the value of α_{im}, a different risk level associated with the maximum in-stream flow rate, $q'_{im,\max}$, may be addressed indirectly. In this paper, the initial values of α_{im} are defined as 0.5 and decision makers may make changes later on.

$$Q_{(i-1)m} + q'_{im} - q_{im} = Q_{im} \qquad \forall i, m \tag{6}$$

$$q'_{im} \geq \alpha_{im} q'_{im,\max} \qquad \forall i, m \tag{7}$$

$$1 \geq \alpha_{im} \geq 0 \qquad \forall i, m \tag{8}$$

$$Q_{im}, q'_{im}, \; q_{im}, q'_{im,\max} \geq 0 \qquad \forall i, m \tag{9}$$

(b) Constraints for sizing a reservoir and its operation: a reservoir is considered as a subsystem in the Hou-Long River Basin. All factors that could influence the water quantity in reservoir operation may be included in Eq. 10 in order to balance the relationships between water demand and water supply, in which i is the designated river section that accommodate the reservoir intake. Equation 11 ensures that, no matter what the operating policy (i.e., the optimal pumping scheme) might be, the release should never exceed the capacity of the reservoir. Equation 12 ensures that the final storage in month$m$ will be less than the storage capacity of the reservoir. Equations 13 and 14 delineate the initial storage of the reservoir with a defined reliability level (β=0.5 in this study).

$$V_m = V_{m-1} + T(q_{im} + q_{wm} - q_m - L_m) \qquad \forall m \tag{10}$$

$$T(q_m + L_m) \leq V_m \qquad \forall m \tag{11}$$

$$V_m \leq V \qquad \forall m \tag{12}$$

$$V_0 = \beta V \quad (13)$$

$$0 \le \beta \le 1 \quad (14)$$

$$V, V_m, V_0, q_{wm}, L_m \ge 0 \qquad \forall m \quad (15)$$

in which V_m is the active storage in month m ($10^4 m^3$/month); q_{wm} is the water inflow drained from the reservoir watershed in month m ($10^4 m^3$/month); L_m is the evaporation loss in month m ($10^4 m^3$/month), and V_0 is the initial storage of the reservoir in the first month of the year ($10^4 m^3$/month), and T is the parameter for unit conversion (unitless).

(c) Constraints for water quality in river reaches: To avoid negative impact on water quality due to the pumping operation upstream for reservoir storage, the assimilative capacity in the downstream areas must be reconfirmed over each step in the context of the optimization analysis.

The physical and chemical reactions in river elements can be formulated according to the SP model [33, 36]. With this submodel available, water quality constrains for all elements can be established in the context of the optimization scheme. Such a mechanism ensures that, when the optimal solution is obtained, the simulation outputs of water quality associated with each element must be realized and confirmed at the same time. Thus, Eqs. 16 and 17 show the water quality constraints with respect to the BOD_5 and DO constrained based on the water quality standards to ensure the compliance. In essence, Eqs. 16 and 17 are defined to generate the concentrations of BOD_5 and DO levels iteratively which can be influenced by the amount of waste loads discharged into the river as well as the inherent assimilative capacity in the river reach collectively. In Eq. 16, waste load reduction by weight (W_{im}) is defined as one of the decision variables in order to determine the optimal waste allocation scheme in the reservoir sizing process. It is basically used to confirm that all the wastewater effluents generated in the natural drainage subbasins are treated for the compliance with respect to the prescribed water quality standards at each control point in Eqs. 18 and 19. Obviously, no waste load reduction is required if the standards can be confirmed. Otherwise, finding out the required waste load reduction level and corresponding river heath status via essential equations in each reach would dominate the movement in the tradeoff process.

$$C_{im,\mathrm{B}} = C_{(i-1)m,\mathrm{B}} e^{-k_{1,im} t_{im}} = \frac{C_{(i-1)m,B} q_{(i-1)m} + \left(W'_{im} - W_{im}\right)}{q_{(i-1)m} + q'_{im}} e^{-k_{1,i} t_{im}} \qquad \forall i, m \quad (16)$$

$$C_{im,\mathrm{D}} = C_{im,\mathrm{DS}} - \frac{k_{1,i} C_{im,\mathrm{B}}}{k_{2,i} - k_{1,i}} \left(e^{-k_{1,i} t_{im}} - e^{-k_2 t_{im}}\right) + \left(C_{im,\mathrm{DS}} - C_{im,\mathrm{D0}}\right) e^{-k_2 t_{im}} \qquad \forall i, m \quad (17)$$

in which $C_{im,\mathrm{B}}$ is the BOD_5 concentration in element i and in month m (mg/L); $k_{1,i}$ is the deoxygenation rate coefficient associated with BOD_5 decay in element i (1/day); t_{im} is the time needed for in-stream flow to pass the element i in month m (day); $C_{im,\mathrm{D}}$ is the DO concentration in element i and in month m (mg/L); $C_{im,\mathrm{D0}}$ and $C_{im,\mathrm{DS}}$ stand for the initial DO concentration and saturated DO level, respectively, in element i and in month m (mg/L); $k_{2,i}$ is the volumetric reaeration coefficient associated with DO in element i (1/day), and W'_{im} is total waste load by weight in element i and in mth month.

(d) Constraints for compliance with the water quality standards in river reaches: These constraints, as shown in Eqs. 18 and 19, ensure that the essential water quality standards downstream are satisfied after the completion of the reservoir project. Both BOD and DO standards must be confirmed for each officially classified type of water body.

$$C_{im,\mathrm{B}} \le \hat{C}_{i,\mathrm{B}} \qquad \forall i, m \quad (18)$$

$$C_{im,\mathrm{D}} \ge \hat{C}_{i,\mathrm{D}} \qquad \forall i, m \quad (19)$$

in which $\hat{C}_{i,\mathrm{B}}$ and $\hat{C}_{i,\mathrm{D}}$are the official water quality standards of BOD_5 and DO concentrations in each element i.

(e) River health constraints: The river health constraints were formulated as Eq. 20 to satisfy the need for ecological conservation. The IBI value serves as a composite index that integrates attributes of fish communities on the basis of accurate measurements of relative abundance. The required IBI level in the river system should be satisfied in some designated river reaches in relation to required water quality standards. In this context, a small improvement of IBI might represent tradeoffs with respect to cost or benefit terms associated with water quality improvements in the solution space. Such a set of biotic integrity constraints can be applicable for reflecting the fish community conditions grossly, which should be influential in the multicriteria and multiobjective tradeoff processes while assessing the optimal pumping scheme for sizing an off-stream reservoir.

$$\mathrm{IBI}_{\min} \le \mathrm{IBI}_{im} \le \mathrm{IBI}_{,\max} \qquad \forall i, m \quad (20)$$

in which IBI_{im} is the IBI level within a designated river reach i in mth month and IBI_{min} and $IBI_{,max}$ are the minimum and maximum of IBI levels within a designated river, respectively, which reflects an ecologically acceptable range in an eco-region (unitless).

6 Results and Discussion

The optimization model was solved by MS EXCEL® in a PC environment. Weighting factors between the two objective functions involved are assumed equal in dealing with the multiobjective decision-making process because the concerns of water quantity and quality are deemed equally important. During the modeling analysis, Visual Basic scripts were organized and integrated with the MS EXCEL® tables for conducting the integrated simulation and optimization analysis. The quantity of water and the amount of money was normalized by using Eq. 21 and then aggregated for the possible tradeoff as expressed below:

$$Z = \frac{Z_k*(x) - Z_k(x)}{Z_k*} \tag{21}$$

in which the $Z_k^*(x)$ is the maximum or minimum value associated with each individual objective to be maximized or minimized, which can be obtained from the payoff table.

In this paper, all environmental conditions in wet and dry seasons were included in the optimization process. The results from the water quality simulation model show that most of river reaches in the dry reason and some of river reaches that are close to the estuary region in the wet season might have compliance problems (see Figs. 4 and 5). This leads us to consider the essential waste load reduction scheme along these problematic river reaches. Apparently, when an extremely low-flow period occurs in the dry season, additional managerial effort is needed to get the situation back to the regulatory level. Hence, the numbers listed in the parentheses in Table 6 reveal the removal efficiency (%) of waste loads required at each designated location (i.e., drainage subbasin), which may provide managerial insights for region-wide water pollution control. The optimal pumping schedule is listed in the last column of Table 6 as well. The far-right column of Table 6 shows the proposed optimal pumping pattern based on the deterministic approach. It implies that rainfall is congregated in the period of wet season in the Hou-Lung River Basin, and available water resource for pumping to the Tien-Hua Lake in dry season is usually insufficient. As a result, the outputs recommend that most pumping efforts be conducted from March to September. Research findings suggest that the maximum flow rate at the pumping station associated with the diversion pipeline for water transfer from HL3 to the Tien-Hua Lake is approximately 10.2 cm, and the active storage capacity required for the Tien-Hua Lake is close to 48,013,040 M^3. This construction plan may resolve the water shortage issue of 90 million tons of water per year for municipal, industrial, and agricultural consumption in this basin.

It is also interesting to see how the cost items vary systematically over months with respect to the proposed optimal pumping scheme. Figure 8 presents the interactive relationships between the pumping rate and the cost for pollution control on a monthly basis. This sensitivity analysis confirms that the inclusion of river health constraints would drive the reduction of waste loads up to a higher level. It also helps realize the varying situations of BOD_5 and DO concentrations in Hou-Lung River after the completion of the optimal waste load reduction program in wet and dry seasons. These findings can be used to guide the sustainable development plan of the Tien-Hua Lake project.

Overall, the model was used successfully to perform a preliminary screening of alternatives for water resources management and to identify storage capacities at the candidate site. An integrated simulation and optimization approach was used to generate the monthly operational pattern in terms of the pumping rate at the candidate site in the river system. A target aggregate firm yield from the surface water system was specified in the objective function. Decisions on the failure of firm yield at the reservoir site during a critical period for stream flow can be made within such a modeling framework too. A case study with data from the Hou-Lung River Basin in Taiwan demonstrates the utility of the model for an off-stream reservoir–pumping station development. Historically, the health of aquatic systems was monitored primarily through physical and chemical means in environmental systems analysis. Since the inclusion of IBIs via an IBI/BOD/DO correlation is a novel approach that has not previously been applied in the literature, attention is placed upon whether the reservoir size in conjunction with the pumping scheme may still be acquired by including such a linkage. The optimal pumping scheme illustrates the temporal trend of the system explicitly.

Nevertheless, it is also important for decision makers to consider the negative impact and managerial risk resulting from the unstable climate conditions although waste load reduction may ensure the water quality in Hou-Lung River in the future. It implies that environmental uncertainties could result in a higher risk in terms of water quality management if both interannual and intra-annual rainfall variability over the entire Ho-Lung river system has to be taken into account. Besides, considering only the floating relationship between varying cost and the quantity of water supply in the model might not be enough. Efforts to control water pollution bring substantial direct and indirect benefits, such as ecological and recreational benefits. None of these benefits can be easily quantified and included in the objective function although the treatment costs for water quality improvement can be easily considered in the model formulation [8]. In acknowledging such costs, however, society also benefits from rivers in many aspects. We must also recognize the inherent positive societal impact via water quality improvements in the future. The social benefits of in-stream water quality improvements may be considered as forms of ecological and recreational benefits for adaptive water resources management in an uncertain environment [4–6, 14].

7 Conclusions

The intelligent design of long-term water resources management strategies requires not only comprehensive understanding of the systems and their associated problems but also new approaches for systems analysis. This paper focuses on broad solutions that most effectively address the greatest number of current concerns in sizing of a new reservoir with integrated economic, environmental, and biological considerations that are all manifested in a quantifiable manner. The systems analysis in this study might be able to provide some of the evidence, yielding a more profound understanding of the spatiotemporal distribution of environmental resources and a greater appreciation for the complexity and heterogeneity of risk factors, especially the water quality and biotic integrity. The systems analysis technique provides us with such a function for decision makers to quantify the risk when available resources are under dynamic change in time scale. In a planning and management context, effort was placed on generating the optimal pumping scheme and waste load reduction in a fast-growing river basin in Taiwan. With the aid of such a systems analysis, the sustainable development plan for the Hou-Lung River Basin becomes understandable and applicable to the public.

In acknowledging the role environmental and ecological concerns can and should play in the planning process, one must also recognize the inherent societal impact due to reservoir construction that could be involved in a multi-objective decision-making process in the future. It may enable various interested groups or stakeholders in the river basin to work together in order to develop a unified program that balances individual needs, maintains essential environmental quality and biotic integrity, and achieves economic plans for new development. In any circumstance, sizing such a reservoir for use as a public water resource should firstly be concerned with the available water resources and their optimal operational strategy. Some uncertainties embedded in the input data, management objectives, and assumptions concerning the physical, chemical, and biological reactions that take place in the river system may then be included for an informed public in the future.

Appendix

Table 7 Definition of variables and parameters in this paper

Name	Definition	Unit
α_{im}	The different risk levels of withdrawing stream flows associated with the maximum in-stream flow rate, $q'_{im,\max}$, in element i and in month m	%
β	The ratio of initial capacity to planned capacity	Unitless
$C_{im,\mathrm{B}}$	The BOD_5 concentration in element i and in month m	mg/L
$C_{im,\mathrm{D}}$	The DO concentration in element i and in month m	mg/L
$C_{im,\mathrm{D0}}$	The initial DO concentration in element i and in month m	mg/L
$C_{im,\mathrm{DS}}$	The saturated DO level in element i and in month m	mg/L
$\hat{C}_{i,\mathrm{B}}$	The official water quality standard of BOD_5 concentration in element i	mg/L
$\hat{C}_{i,\mathrm{D}}$	The official water quality standard of DO concentration in element i	mg/L
IBI_{im}	the IBI level in element i and in month m	Unitless
$k_{1,i}$	The deoxygenation rate coefficient of BOD in element i	1/day
$k_{2,i}$	The volumetric reaeration coefficient of DO in element i	1/day
L_m	The evaporation loss at the Tien-Hua Lake in month m	$10^4 m^3$/month
q	The pumping rate for monthly water supply from Hou-Lung River to the Tien-Hua Lake	$10^4 m^3$/month
q_m	The actual water supply from the Tien-Hua Lake to agricultural, municipal, and industrial end users in month m	$10^4 m^3$/month
q'_{im}	The flow rate discharged to element i in mouth m	$10^4 m^3$/month
q_{im}	The amount of flow rate withdrawn from element i in month m	$10^4 m^3$/month
$q'_{im,\max}$	The maximum available flow rate withdrawn from element i in mouth m	$10^4 m^3$/month
$q_{\mathrm{w}m}$	The water inflow drained from the reservoir watershed in month m	$10^4 m^3$/month
q'_{im}	The flow rate discharged from the Tien-Hua Lake to Hou-Long river for ecological conservation in month m	$10^4 m^3$/month
Q_{im}	The outflow from element i to element i+1 in mouth m	$10^4 m^3$/month
t_{im}	The time needed for in-stream flow passing the element i in month m	day
T	The parameter for unit conversion between volumetric flow rate and storage in the reservoir	Unitless
V	The design capacity of the reservoir	$10^4 m^3$
V_0	The initial storage of the reservoir in the first month of a year	$10^4 m^3$
V_m	The active storage of the reservoir in month m	$10^4 m^3$

Table 7 (continued)

Name	Definition	Unit
W'_{im}	The total waste load by weight in element *i* and in month *m*	kg-BOD/month
W_{im}	The waste load reduction by weight in element *i* and in month *m*	kg-BOD/month
C_{1m}	The cost for construction of a reservoir for water supply in month *m*	NT$
C_2	The cost for water pollution control	NT$

The symbol for New Taiwan Dollars (TWD) can be written NT$, and the currency ratio had varied from over 26 TWD per USD in the mid-1990s to 30 TWD per USD in the early 2000s

References

1. Avogadro, E., Minciardi, R., & Paolucci, M. (1997). A decisional procedure for water resources planning taking into account water quality constraints. *European Journal of Operation Research, 102*, 320–334.
2. Barlishen, K. D., Simonovic, S. P., & Burn, D. H. (1989). Simulation–optimization algorithm for reservoir capacity calculation: The effect of inflow data set length. *Canadian Journal of Civil Engineering, 16*(4), 477–482.
3. Benoist, A. P., Brinkman, A. G., Vandiepenbeek, P. M. J. A., & Waals, J. M. J. (1998). BEKWAAM, a model fit for reservoir design and management. *Water Science and Technology, 37*(2), 269–276.
4. Chang, N. B., Parvathinathan, G., & Dyson, B. (2006). Multi-objective risk assessment of freshwater inflow on ecosystem sustainability in San Antonio Bay, Texas. *Water International, 31* (2), 169–182.
5. Chen, H. W., & Chang, N. B. (1998). Water pollution control in the river basin by genetic algorithm-based fuzzy multi-objective programming modeling. *Water Science and Technology, 37*(8), 55–63.
6. Chen, H. W., & Chang, N. B. (2006). Decision support for allocation of watershed pollution load using grey fuzzy multi-objective programming. *Journal of the American Water Resources Association, 42*(3), 725–745.
7. Chen, H. W., Wu, C. C., & Chang, N. B. (2002). A comparative analysis of methods to represent uncertainty in estimating the cost of constructing wastewater treatment plants. *Journal of Environmental Management, 65*(4), 383–409.
8. Chen, H. W., Chang, N. B., & Shaw, D. G. (2005). Valuation of in-stream water quality improvement via fuzzy contingent valuation method. *Stochastic Environmental Research and Risk Assessment, 19*(2), 158–171.
9. Curry, G. L., Helm, J. C., & Clark, R. A. (1973). A chance-constrained model of system reservoirs. *Journal of Hydraulic Division, 99*(12), 2353–2366.
10. Fausch, K. D., Karr, J. R., & Yant, P. R. (1984). Regional application of an index of biotic integrity based on stream fish communities. *Transactions of the American Fisheries Society, 113*, 39–55.
11. Harris, J. H., & Silveira, R. (1999). Large-scale assessments of river health using an index of biotic integrity with low-diversity fish communities. *Freshwater Biology, 41*, 235–252.
12. HelmGuy, J. C., Curry, L., & Hogg, G. L. (1984). Capacity expansion of linked reservoir systems. *Computers & Industrial Engineering, 8*(2), 119–128.
13. Houck, M. H., & Cohon, J. L. (1978). Sequential explicitly stochastic linear programming models: A proposed method for design and management of multipurpose reservoir systems. *Water Resources Research, 14*(2), 161–169.
14. Ji, J. H., & Chang, N. B. (2005). Risk assessment for optimal freshwater inflow in response to sustainability indicators in a semi-arid coastal bay. *Stochastic Environmental Research and Risk Assessment, 19*(2), 111–124.
15. Karr, J. R. (1981). Assessments of biotic integrity using fish communities. *Fisheries, 6*, 21–27.
16. Karr, J. R. (1987). Biological monitoring and environmental assessment: A conceptual framework. *Environmental Management, 11*, 249–256.
17. Karr, J. R. (1991). Biological integrity: A long-neglected aspect of water resource management. *Ecological Applications, 1*, 66–84.
18. Karr, J. R., Yant, P. R., & Fausch, K. D. (1987). Spatial and temporal variability of the index of biotic integrity in three Midwestern streams. *Transactions of the American Fisheries Society, 116*, 1–11.
19. Khaliquzzaman, C. S. (1997). Network flow programming model for multireservoir sizing. *Journal of Water Reservoir Planning and Management, 123*(1), 15–22.
20. Kurt, D.F., Lyons, J., Karr, J.R., & Angermeier, P.L. (1990). Fish communities as indicators of environmental degradation, in biological indicators of stress in Fish. In S. M. Adams (Ed.), American Fisheries Symposium 8, Bethesda, Maryland.
21. Loucks, D. P., Stedinger, J. R., & Haith, D. A. (1984). *Water resource systems planning and analysis*. Englewood Cliffs: Prentice-Hall.
22. Mesa, O., Poveda, G., Carvajal, L., & Salazar, J. (1997). Reservoir reliability design under interannual climate and hydrologic variability. In Coping with Scarcity and Abundance Proceedings, Congress of the International Association of Hydraulic Research (pp 470–475), IAHR, ASCE, New York, NY, USA
23. Miltz, D., & White, D. C. (1987). Sedimentation and the economics of selecting an optimum reservoir size. *Water Resources Research, 23*(8), 1443–1448.
24. Mousavi, H., & Ramamurthy, A. (2000). Optimal design of multi-reservoir systems for water supply. *Advances in Water Resources, 23*, 613–624.
25. Mutreja, K. N., & Yevjevich, V. (1978). Sizing of reservoirs for periodic-stochastic input and periodic output. *Journal of Hydrology, 39*(3–4), 323–338.
26. Nathan, B. (1985). An application of mathematical programming in planning surface water storage. *Water Resources Bulletin, 21* (6), 1013–1021.
27. Oamek, G., Schluntz, L., Bottorff, L., & Johns, E. (1990). Methodology for analyzing alternative reservoir sizing, shortage, and operating criteria. In Proceedings of the Seventeenth Annual Conference, Boston Society of Civil Engineers, Boston, MA, USA, 192–198.
28. Oberdorff, T., & Hughes, R. M. (1992). Modification of an index of biotic integrity based on fish assemblages to characterize rivers of the Seine Basin, France. *Hydrobiologia, 228*, 117–130.
29. Plate, E. J. (1989). Reliability concepts in reservoir design. *Nordic Hydrology, 20*(4), 231–248.
30. ReVelle, C. S., Joeres, E., & Kirby, W. (1969). The linear decision rule in reservoir management and design: development of stochastic model. *Water Resources Research, 5*(4), 767–777.
31. Savic, D. A., Burn, D. H., & Zrinji, Z. (1989). Comparison of stream generation models for reservoir capacity-yield analysis. *Water Resources Bulletin, 25*(5), 977–983.
32. Singh, K. P., & Durgunoglu, A. (1990). Economic reservoir design and storage conservation by reduced sedimentation. *Journal of Water Resources Planning and Management, ASCE, 116*(1), 85–98.
33. Streeter, H.W., Phelps, E.P. (1925). A study of the pollution and natural purification of the Ohio River. U.S. Public Health Service, Publication Health Bulletin, 146, Washington.

34. Takeuchi, K. (1997). Least marginal environmental impact rule for reservoir development. *Journal of Hydrological Sciences, 42*(4), 583–597.
35. Takeuchi, K., & Sivaarthitkul, V. (1995). *Assessment of effectiveness of the use of inflow forecasts to reservoir management. Modeling and management of sustainable basin-scale water reservoir systems. International Association of Hydrological Sciences No. 231* (pp. 299–309). Wallingford: IAHS.
36. Thomann, R. V., & Mueller, J. A. (1987). *Principles of surface water quality modeling and control*. New York: Harper and Row.
37. Turgeon, A., & Brosseau, G. (1987). On the non-convexity of the reservoir design problem. *Water Resources Research, 23*(8), 1689–1691.
38. Vogel, R. M., & Stedinger, J. R. (1987). Generalized storage–reliability–yield relationships. *Journal of Hydrology, 89*(3/4), 303–327.
39. Yoder, C. O., & Rankin, E. T. (1998). The role of biological indicators in a state water quality management process. *Environmental Monitoring and Assessment, 51*, 61–88.