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An Optimization Method Based on Scenario Analysis for Watershed Management Under Uncertainty

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Abstract In conjunction with socioeconomic development in watersheds, increasingly challenging problems, such as scarcity of water resources and environmental deterioration, have arisen. Watershed management is a useful tool for dealing with these issues and maintaining sustainable development at the watershed scale. The complex and uncertain characteristics of watershed systems have a great impact on decisions about countermeasures and other techniques that will be applied in the future. An optimization method based on scenario analysis is proposed in this paper as a means of handling watershed management under uncertainty. This method integrates system analysis, forecast methods, and scenario analysis, as well as the contributions of stakeholders and experts, into a comprehensive framework. The proposed method comprises four steps: system analyses, a listing of potential engineering techniques and countermeasures, scenario analyses, and the optimal selection of countermeasures and engineering techniques. The proposed method was applied to the case of the Lake Qionghai watershed in southwestern China, and the results are reported in this paper. This case study demonstrates that the proposed method can be used to deal efficiently with uncertainties at the watershed level. Moreover, this method takes into consideration the interests of different groups, which is crucial for successful watershed management. In particular, social, economic, environmental, and resource systems are all considered in order to improve the applicability of the method. In short, the optimization method based on scenario analysis proposed here is a valuable tool for watershed management.

Keywords Scenario analysis · Watershed management · Uncertainty · Optimization

Introduction

The watershed is a natural unit for water research (Clark and others 2005). Watersheds around the world are facing serious threats to their water quality and aquatic ecosystems. Moreover, watershed management, which includes water resource utilization control, water pollution control, and economic growth policies, is an effective means of dealing with these issues at the watershed scale (Heathcote 1998).

Owing to the complexity of watersheds, uncertainty is one of the key factors influencing watershed management. Many methods have been employed to deal with the uncertainties in watershed systems (Guo and others 2001; Dórner and others 2001; Sohrabi and others 2003; Chau 2004; Hamed and El-Beshry 2004; Ogata 2004; Zou and others 2004; Hantush and Kalin 2005; Muleta and Nicklow 2005; Zheng and Keller 2006). The existing studies focused mainly on resolving the uncertainties in watershed models. In practice,

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however, in studying watersheds, the uncertainty and changes in regional social, economic, and environmental systems are very important for making suitable decisions. Since the models of existing studies do not consider system uncertainties, they cannot present a comprehensive image of the future to decision makers.

Engineering techniques are very important in watershed management. Recent years have seen more and more engineering techniques employed in watershed management practices in China. In addition, the optimization and combination of various engineering techniques can be cost effective for local governments. However, it is difficult to select and implement feasible engineering techniques for the future. Therefore, an appropriate method is warranted for effectively forecasting future changes at the watershed level, as well as for selecting appropriate techniques and policies for dealing with these changes. Scenario analysis is considered to be useful in watershed management, in that it can be used to forecast changes in uncertain socioeconomic systems and the corresponding environmental problems (Shiftan and others 2003). Engineering techniques and policies for watershed management can only be optimally designed in the context of specific scenarios.

Scenario analysis was proposed in the 1950s (Kahn and Wiener 1967) and is widely used in many fields, such as public policy (Swarta and others 2004), strategic planning (Jutta and Martin 1988), agriculture (Thornton and Herrero 2001), land use (Hubacek and Sun 2001; He and others 2004), energy (Yamamoto and others 2000; Ferng 2002; Islas and others 2003; Silberglitt and others 2003), pollution discharge (Recknagel and others 1995; Müller-Wohlfeil and others 2002), transportation (Pearman 1988), water pollution control (Kronvang and others 1999), air pollution modeling (Affum and others 2003), climate change (Matsuoka 1995; Lugo 2000; Karjalainen and others 2003), and fishery (Morin 2004) and forest management (Mohren 2003). However, scenario analysis is rarely employed in watershed management (Heathcote 1998). Though Heathcote (1998) developed management scenarios for watershed management, he did not analyze the social and economic systems that constrain decisions about countermeasures and other management techniques. Management scenarios that do not consider social and economic systems are not very useful in practice. In this paper, an optimization method for engineering techniques based on scenario analysis is proposed for watershed management. Social and economic systems are integrated into the optimization method so that it is more applicable in practice. This method was applied to the management of the Lake Qionghai watershed in China.

Scenario Analysis for Watershed Management

Watershed Management System

Watershed management is a process that comprises policies, techniques, and development on different temporal and spatial scales (Önal and others 1998; Wang 2001). At the watershed scale, a watershed management system is usually divided into social, economic, environmental, and resource subsystems. The relationships among these subsystems are complicated (Fig. 1).

Three stages, which include system analyses, forecasting, and management practices, are commonly used in watershed management. System analyses are the foundation by which complex watershed management systems can be understood. After field investigations, interviews with local stakeholders and experts, and careful consideration, different subsystems can be identified according to the characteristics of various study areas. Forecasting is the key stage in watershed management, because the main task is to deal with changes that are likely to occur in the future of a watershed. Management practices include the engineering techniques and policies that are employed to deal with environmental and resource problems at the watershed scale.

Uncertainties are associated with all three stages (Fig. 2), and can be categorized as follows: (1) intrinsic uncertainties in economic, social, and environmental systems arising mainly from social and economic development, (2) external uncertainties caused by the stress of factors beyond the watershed, (3) uncertainties associated with raw data and model parameters, and (4) uncertainties arising from anthropogenic effects (Jamieson 1996; Hamed and El-Beshry 2004). Intrinsic uncertainties are difficult to predict and address. Traditional forecasting methods do not allow intrinsic uncertainties to be dealt with effectively. A thorough analysis of the watershed management system and a forecast of potential changes in the system are required. Based on such analyses and forecasts, appropriate management practices must be selected. Different policies require correspondingly distinct techniques to ensure their performance. Therefore, an appropriate method is required for watershed management that enables efficient forecasting of watershed system changes and optimization of management practices under uncertainty at the watershed scale.

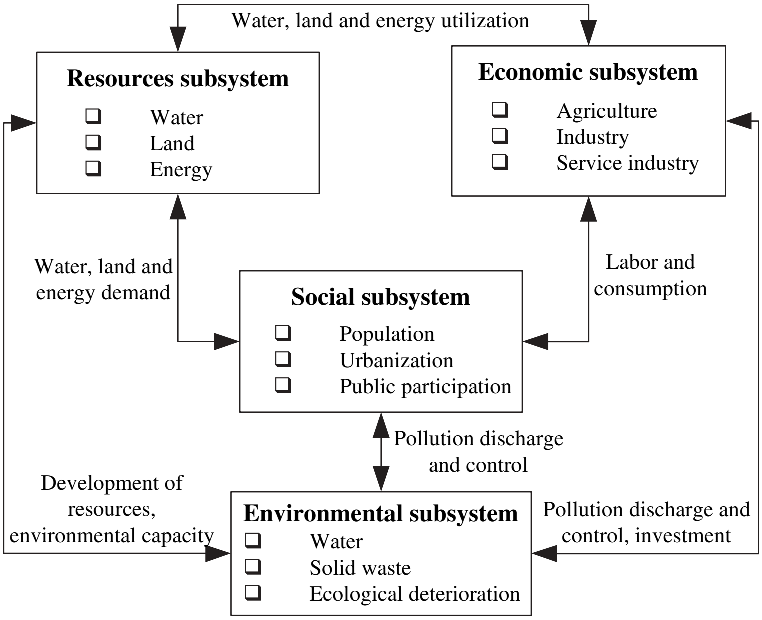

Fig. 1 The subsystems for watershed management

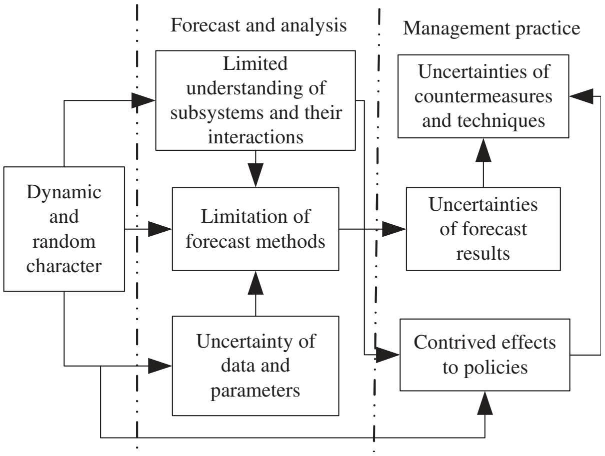

Fig. 2 The uncertainties of the different stages in watershed management

Optimization Method Based on Scenario Analysis

In this paper, an optimization method based on scenario analysis is proposed for dealing with the uncertainties of watershed management. This optimization method consists of four steps, which are summarized below (Fig. 3).

Step 1: Watershed management system analyses

The economic, social, environmental, and resource subsystems of watershed management are analyzed. System analyses focus on the potential development of economic and social subsystems, and of existing or potential problems in environmental and resource subsystems.

Step 2: Listing of potential policies and engineering techniques

Based on the system analyses, the policies and engineering techniques that can potentially be employed for watershed management are listed. Some commonly employed engineering techniques for watershed management include wastewater treatment, ecological engineering, wetland and water resource utilization techniques. However, this step creates only a list of possible policies and techniques; the list is not an optimal selection. The optimal choice of management approaches is based on the performance of each and on cost-benefit analyses (CBA) with respect to various scenarios.

Step 3: Scenario analysis

Before the optimal selection of policies and engineering techniques is performed, scenario analysis is conducted. Scenarios are constructed to forecast and simulate potential changes in the watershed management system. As in existing studies (Richard and Scott 1996; Ringland 1998; Ratcliffe 1999; Hugues 2000), scenarios here are constructed in five stages:

(1) Identify the audience, key problems, and driving forces

The audience comprises the people involved in watershed management. Some key problems are the major difficulties that currently exist, such as environmental pollution, the scarcity of water resources, and

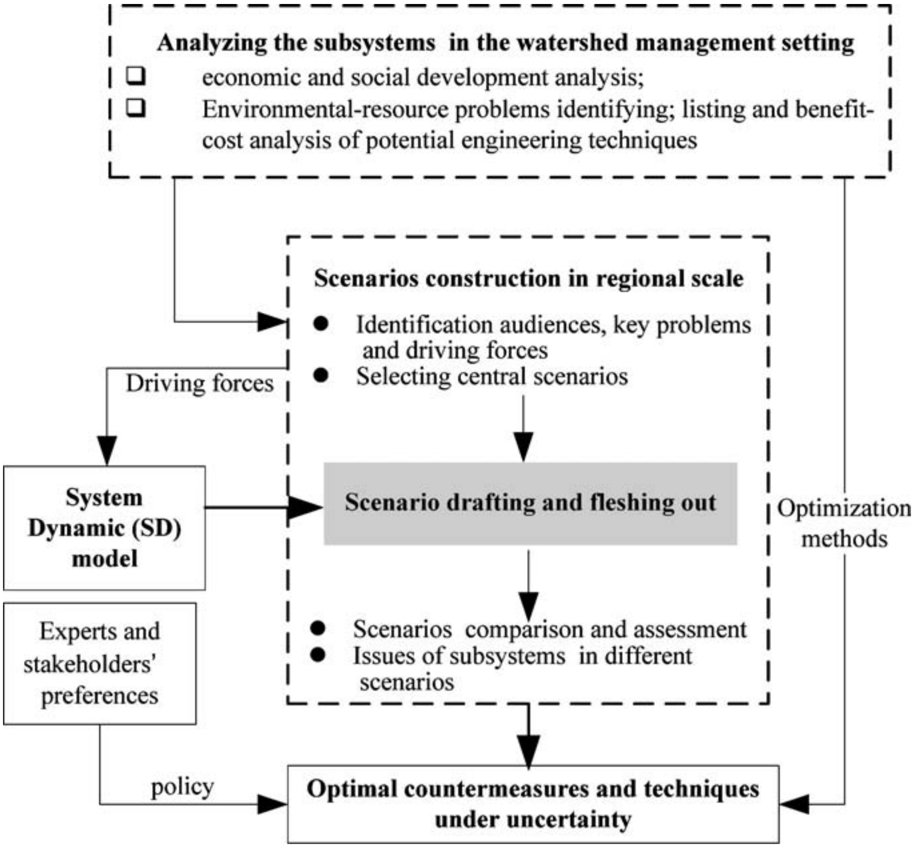

Fig. 3 The study approach of scenario analyses as an optimizing method for watershed management under uncertainty

local poverty. Such problems always provide a challenging focus for watershed management. Driving forces are essential elements, such as the financial budget and national policies, which can greatly influence changes in the watershed. Based on system analyses, the audience, key problems, and driving forces related to watershed management can be identified. Key problems and driving forces are usually identified based on the opinions of experts and stakeholders.

(2) Select central scenarios

Central scenarios are the most important combinations of driving forces. Therefore, the ranking of driving factors is the basis for central scenario selection. According to their importance and uncertainty, driving forces can be grouped into the four quadrants shown in Figure 4. The factors that are located in Quadrants I and II in Figure 4, designated as U_1, $U_2 ... U_m$, are important for central scenarios. A total of n_i different changes are present for U_i. As an example, consider the two factors U_1 and U_2, for which n_1 n_2 scenarios are drafted. In this case,

$$S = f(U_1, U_2) = f(\{U_{1,1}, \dots U_{1,j} \dots, U_{1,n_1}\}, \{U_{2,1}, \dots U_{2,j} \dots, U_{2,n_2}\}) = \{S_{1,1}, \dots S_{i,j} \dots, S_{n1,n2}\} \quad (1)$$

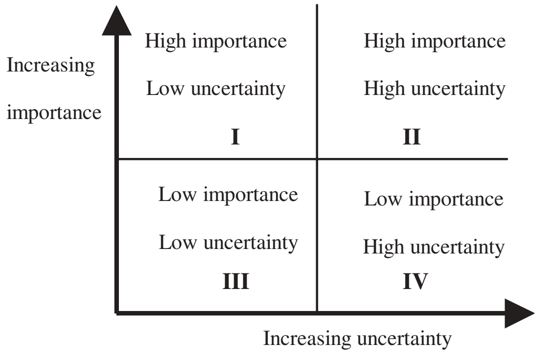

Fig. 4 Ranking of driving forces for importance and uncertainty in the scenarios building

where S is a set of scenarios, f denotes the function from U_1 and U_2 to S, $U_{1,i}$ and $U_{2,j}$ refer to the potential changes in U_1 and U_2, and $S_{i,j}$ is a scenario.

The scenarios derived from the driving factors in Quadrants I and II are the most prior of all the scenarios. Therefore, these are the central scenarios to consider in the management of the watershed.

(3) Draft and flesh out the scenarios

The preliminary scenarios are fleshed out to create complete and very detailed scenarios. Appropriate time periods are selected and the driving factors are

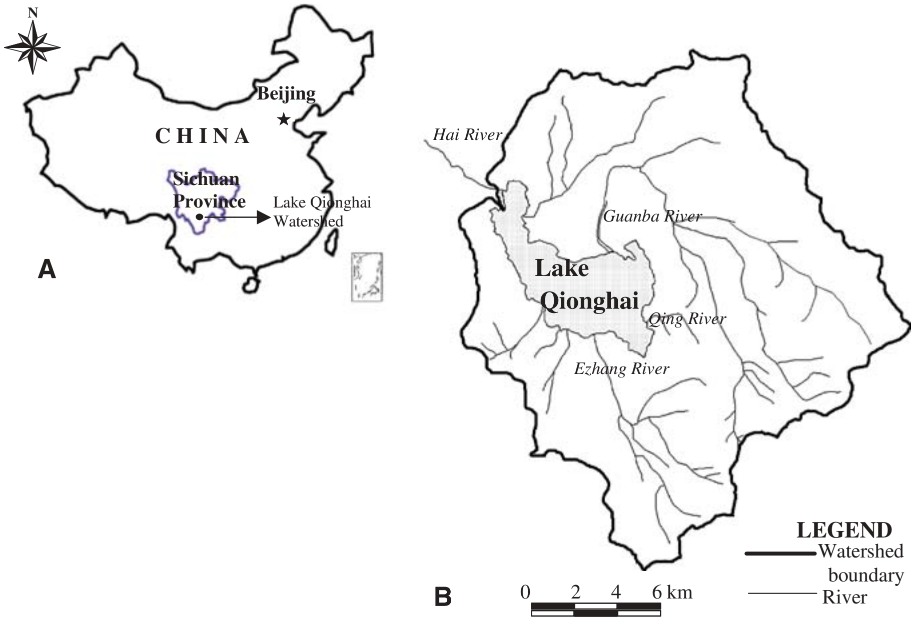

Fig. 5 Lake Qionghai Watershed in southwestern China.

put into forecasting models. A system dynamics (SD) model is applied for forecasting in this paper. It should be noted that scenario drafting and fleshing out is an interactive process involving model results, researchers, and stakeholders.

(4) Evaluate the scenarios

Although central scenarios are derived from driving forces, some central scenarios may be unreasonable and of little value. Thus, it is necessary to evaluate all central scenarios and to identify those that are the most reasonable and useful. Such an evaluation is based on discussions involving stakeholders and experts, as well as various integrated assessment tools, such as multi-criteria evaluation.

(5) Conduct comprehensive analyses

The various scenarios relate to different potential issues concerning environmental, resource, and social systems. These potential issues need to be analyzed comprehensively for the selection of future countermeasures, policies, or techniques. Thus, such issues are potential issues under specific scenarios, while the key problems mentioned above are existing issues.

Step 4: Optimize policies and engineering techniques

Once scenario analyses have been conducted, policies and engineering techniques can be selected based on CBA and various other criteria. During the selection process, the participation of experts and local stakeholders is required.

Case Study

Study Area Overview

The Lake Qionghai watershed is located in the Sichuan Province of China (Fig. 5) and has an area of 307.67 km^2. The lake's area is 27.88 km^2, and its volume is 0.289 billion m^3 (Liu and others 2006). It is a famous tourist attraction. High water quality and quantity are essential for social and economic development in the watershed.

In recent years, Lake Qionghai has come under serious stress from pollution that has been induced by point and nonpoint sources and has resulted in lake eutrophication. To protect the regional environment and aquatic ecosystem, integrated watershed management has been planned for the period of 2004–2015.

System Analyses of the Lake Qionghai Watershed

Based on the analyses of natural and social characteristics and interactive discussions with stakeholders, the six subsystems of population, agriculture, industries, service industries, water resources, and the environment were identified in the watershed.

List of Potential Policies and Engineering Techniques

The techniques that could be used to manage the Lake Qionghai watershed, as well as the problems that they were designed to address, are presented in Table 1. These techniques include the control of point and nonpoint sources of pollution, the prevention of soil

Table 1 Available engineering techniques and their corresponding costs in the Lake Qionghai watershed

	Techniqeus	Details	Potential maximum impact	Unit cost	Total coast (million US$)
Tl	(1) Point sources control	Wastewater treatment plant	17,072m^3/d	$\$378.4/\mathrm{m}^3\ \mathrm{d}^{-1}$	6.46
	(2) Nonpoint sources control	Marsh gas pool and reduced use of fertilizers	Marsh gas pool and reduced use of fertilizer in 3600 ha	$5572/ha	20.06
T2	(3) Preventive engineering of soil loss and debris flows	Building embankments and planting trees and grasses	249.07km^2	$\$70.4$ thousand/km^2	17.53
T3	(4) Dredging of lake sediments	Dredging and sediment disposal	12 million m^3	$\$1.25/\mathrm{m}^3$	14.95
T4	(5) Water resource development and flood prevention	Saving water and constructing river banks to prevent floods	20 million m^3 31.6 km	$\$50.7$/million m^3 $\$10.0$/km	13.01
T5	(6) Restoration of natural wetlands in riparian areas	Migration of inhabitants and restoration of wetlands from crop fields	425.8 ha	$66.8 thousand/ha	28.44
	(7) Ecological restoration of riparian areas	Riparian area restoration, including wetlands construction	27.26 ha, including 12 constructed wetlands	$0.149 million/ha	4.90
	(8) Forest tiiaintenance	Planting trees and restoring forests to crop fields	24,380 ha	$304.7/ha	7.43
	(9) Rural ecological engineering	Planting trees and protecting water resources	329,600m^2	$\$29.33/\mathrm{m}^2$	9.67

Table 2 Annual benefits from applying these techniques in the Lake Qionghai watershed

Techniques	Annual Benefits (million US$)	Ratio of annual benefit to total cost (B/C)	Calculation methods
Tl	4.70	0.177	Equivalent nutrient reserve[a]; equivalent pollution reduction[b]
T2	3.68	0.210	Equivalent nutrient reserve; equivalent pollution reduction; equivalent cubage increase in the lake through reduction of soil accumulations[c]
T3	0.98	0.066	Equivalent cubage increase in the lake
T4	2.10	0.161	Water conservation and flood frequency reduction
T5	10.62	0.211	Equivalent nutrient reserve; equivalent pollution reduction; ecological service increase

[a] "Equivalent nutrient reserve" involves the conversion of reducing nutrients through ecological engineering, mainly N and P, and the infusion of equivalent amounts of nitrogenous and phosphate fertilizers into the farmland (Pan arid others 2002)

[b] "Equivalent pollution reduction" involves the conversion of reducing nutrients through ecological engineering, mainly N and P, and the construction of wastewater treatment plants capable of removing equivalent amounts of N and P (Pan and others 2002)

[c] "Equivalent cubage increase in the lake" involves the conversion of the cubage increase caused by soil loss prevention for the construction of a reservoir with equivalent cubage (Pan and others 2002)

loss and debris flows, the reduction of lake sedimentation, better water resource utilization, and ecological maintenance techniques, which are denoted by T1 through T5, respectively.

The preliminary technical assessment indicated that all of these techniques were applicable to the watershed. These techniques were also evaluated using CBA (Table 2).

Scenario Analysis

After the system analyses for the Lake Qionghai watershed had been conducted, scenarios were built according to the five stages discussed in Scenario Analysis for Watershed Management

(1) Identify audiences and driving forces

According to the preliminary analysis and discussions with local experts, the audience could be classified into seven primary groups: fishermen (Group A); the staff of the Bureau for the Lake Qionghai watershed (Group B); the staff of related bureaus for environmental protection, forestry, fishery, agriculture, and tourism (Group C); local residents (Group D); the rural population upstream of the watershed (Group E); tourists (Group F); and the staff of tourism firms and wastewater treatment plants (Group G). Sample interviews of these different groups, which focused mainly on the interests, concerns, and opinions of watershed management, were carried out between

April 2003 and July 2004. A cluster analysis was conducted based on these interviews, and the results provided some useful information with which to assess the concerns of different stakeholders.

Based on this analysis, the audience groups of the Lake Qionghai watershed were combined into three groups, according to the similarities of their concerns, as "core," "marginal," and "external" (Liu and others 2006). The core audience comprised residents and fishermen adjacent to Lake Qionghai and the Bureau for the Lake Qionghai watershed, which is the direct administrative agency for the watershed. Other related administrative agencies, such as the local Bureau of Forestry, Fishery, Agriculture, and Tourism, were classified as the marginal audience. Other agencies and persons, such as tourists to the watershed, were considered an external audience. Our interviews showed that these groups had different opinions about environmental problems and also had distinct concerns.

From the system analyses, field investigations, and interviews with stakeholders and experts, six driving forces were identified: economic growth, social development, engineering techniques, regional environmental policy, related national planning, and external effects on the watershed.

(2) Select central scenarios

The six driving forces were ranked according to their importance and uncertainty, as evaluated by the various audiences, experts, and stakeholders (Fig. 6). The four driving forces in Quadrants II and I, economic growth, engineering techniques, related national planning, and regional environmental policy, were identified as important for the watershed. National planning and regional environmental policy were combined into one driving force, i.e., government decisions. Engineering techniques were not selected as a driving force, since they appeared as countermeasures under various scenarios. The key driving forces that formed the central scenarios were economic growth (U_1) and government decisions (U_2). The key issue was then to determine the potential changes in U_1 and U_2, the effects of these changes on the watershed, and the corresponding countermeasures that should be used to deal with these changes.

From further discussions with officials, audiences, experts, stakeholders, and researchers, four scenarios under U_1, denoted S_{E1}, S_{E2}, S_{E3}, S_{E4}, and two scenarios under U_2, denoted S_{P1} and S_{P2}, were identified for consideration (Table 3):

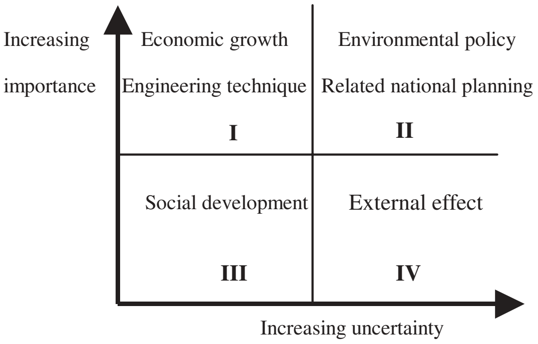

Fig. 6 Ranking of driving forces for importance and uncertainty in the scenarios construction in Lake Qionghai Watershed

1. S_{E1}: maintain the existing growth rate
2. S_{E2}: induce a relatively high growth rate
3. S_{E3}: limit the growth of industry while promoting the growth of the service industry
4. S_{E4}: promote the growth of industry
5. S_{P1}: maintain the existing policies and plans concerning watershed management
6. S_{P2}: adopt strict policies concerning pollution and resource utilization in the watershed

$$S = f(U_1, U_2) = f(\{S_{E1}, S_{E2}, S_{E3}, S_{E4}\}, \{S_{P1}, S_{P2}\}) \\ = \{S_{1,1}, S_{1,2}, S_{1,3}, S_{1,4}, S_{2,1}, S_{2,2}, S_{2,3}, S_{2,4}\} \quad (2)$$

(3) Draft and flesh out the scenarios

A system dynamics (SD) model was selected for fleshing out the scenarios because of its ability to handle complex systems. The watershed system was divided into six subsystems (Fig. 7). The software package Vensim PLE, Version 5.2a, developed by Ventana Systems, Inc. (Tracing and Checking 2002), was employed to formulate the SD model of watershed management for the Lake Qionghai watershed (SD-LQW).

The population subsystem, as displayed in Vensim PLE, is shown in Figure 8. The symbols in Figure 8 are described below. The symbol ☁ represents a sink or source, and ⧗ represents the rate of change (Guo and others 2001). The variables in boxes are level variables. The symbol denotes a simulation period, and variables in are also used in other subsystems. For a level variable A at time t (*Level.A*), the fundamental equation is given by:

$$Level.A(t) = Level.A(t - dt) + Rate.A \cdot dt, \quad (3)$$

where t and dt indicate simulation time and its variations, *Level.A(t)* and *Level.A(t–dt)* denote the level variable A at times t and $t–dt$, and *Rate.A* denotes the rate of change from $t–dt$ to t. The fourth-order

Table 3 The central scenarios matrix for watershed management in Lake Qionghai Watershed

	S_{E1}	S_{E2}	S_{E3}	S_{E4}
SP_1	$S_{1,1}$: S_{P1} & S_{E1}	$S_{2,1}$: S_{P1} & S_{E2}	$S_{3,1}$: S_{P1} & S_{E3}	$S_{4,1}$: S_{P1} & S_{E4}
SP_2	$S_{1,2}$: S_{P2} & S_{E1}	$S_{2,2}$: S_{P2} & S_{E2}	$S_{3,1}$: S_{P2} & S_{E3}	$S_{4,2}$: S_{P2} & S_{E4}

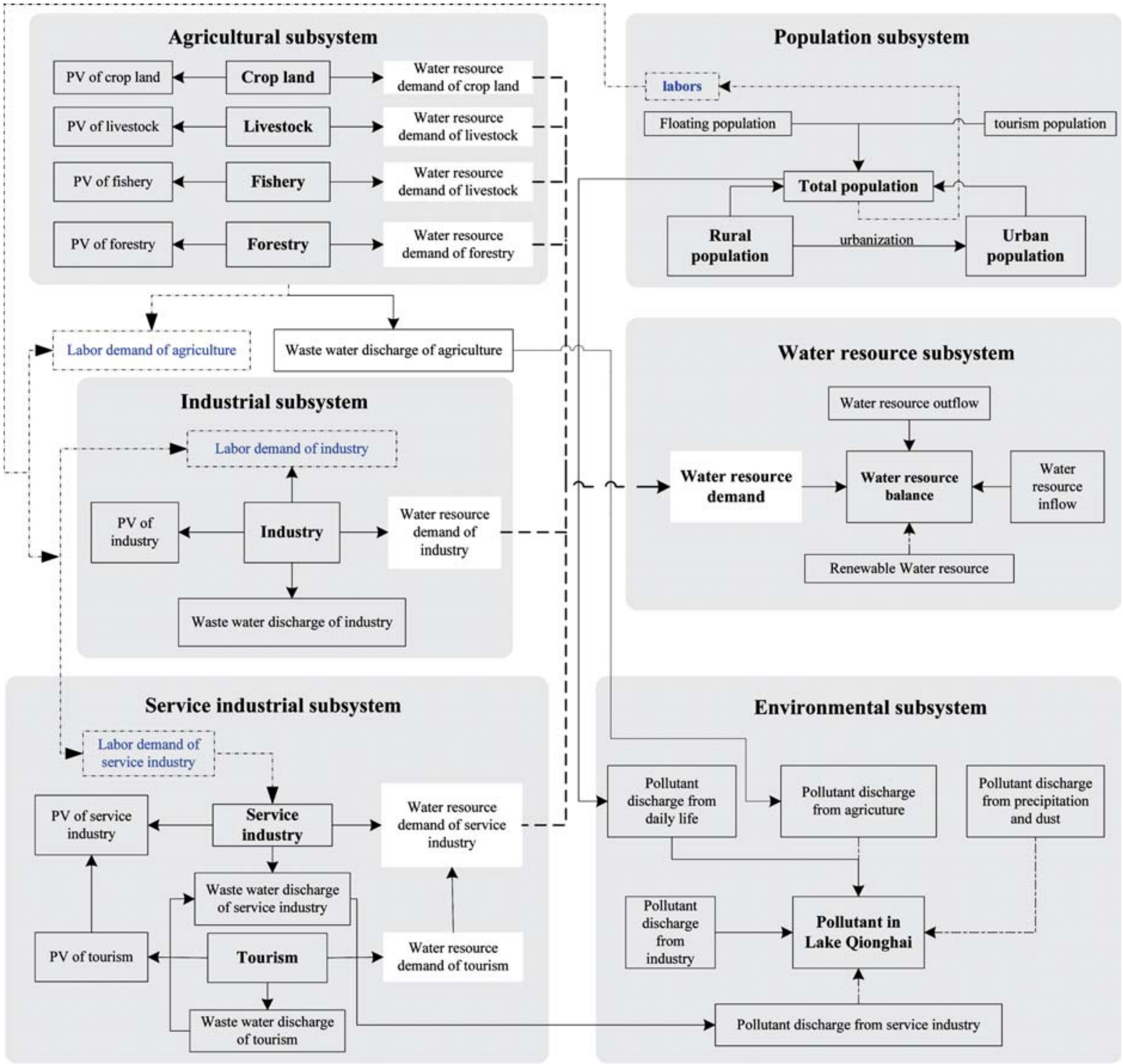

Fig. 7 The interactions among the subsystems of watershed management in Lake Qionghai Watershed

Runge-Kutta method was applied to this model for the purpose of integration (Liu and others 2006).

The simulation period was set to range from 2004 to 2015, and the model was verified using data for the period of 1998–2003. The reference year was selected to be 2001. The verified variables included GDP, total population (TP), annual total water resource demand (WRD), annual domestic sewage discharge (DSD), agricultural production values (APV), industrial production values (IPV), and the production values of the service industry (SIPV). Fourteen variables were used for the sensitivity analyses, following Guo and

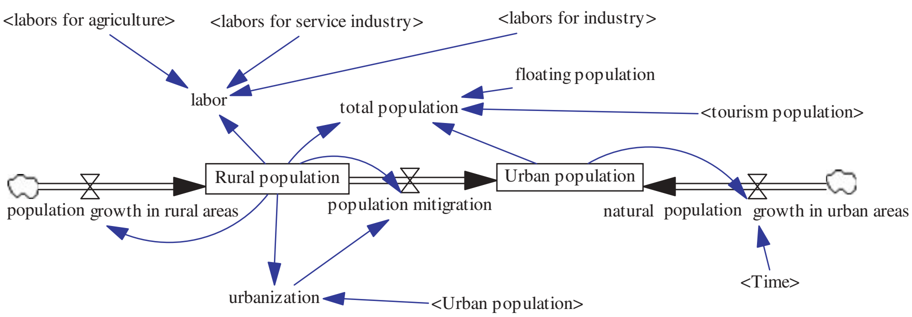

Fig. 8 The population subsystem of SD-LQW model

Table 4 S_{E1}, S_{E2}, S_{E3} and S_{E4} in 2005, 2010 and 2015 of Lake Qionghai Watershed

		2005				2010				2015			
	2001	S_{E1}	S_{E2}	S_{E3}	S_{E4}	S_{E1}	S_{E2}	S_{E3}	S_{E4}	S_{E1}	S_{E2}	S_{E3}	S_{E4}
GDP (Million $)	31.80	37.77	46.11	40.56	42.92	51.20	91.06	68.01	71.27	74.49	199.43	113.85	120.00
GDPP($)	376.5	435.7	504.7	444.2	483.7	571.9	896.3	666.6	759.1	806.7	18318.0	1047.5	1215.6
TP (thousand)	84.1	86.4	91.0	91.0	88.4	89.2	101.4	101.4	93.5	92.0	108.5	108.5	98.4
UR (%)	19.50	27.55	35.01	47.54	40.12	36.43	39.88	65.98	47.66	44.09	47.34	74.38	52.66
TPU (thousand)	16.4	23.8	31.9	43.3	35.5	32.5	40.4	66.9	44.6	40.6	513.8	80.7	51.8
WRD (million m^3)	57.00	51.00	53.00	52.00	52.00	47.00	54.00	51.00	51.00	47.00	62.00	53.00	54.00
WRDI (million m^3)	2.40	2.30	3.00	2.40	2.70	2.70	6.00	3.10	4.00	3.10	11.00	3.80	5.90
WRDA (million m^3)	51.00	44.00	44.00	44.10	44.10	39.00	41.00	40.40	40.40	37.00	40.00	40.00	40.00
WRDSI (million m^3)	0.30	0.30	1.00	0.50	0.50	0.50	1.00	1.30	1.00	0.90	3.00	2.20	1.70
WRDD (million m^3)	3.60	4.30	5.00	5.20	4.80	5.00	7.00	6.60	5.60	5.50	7.00	7.50	6.20
IWWD (million m^3)	1.891	1.864	2.480	1.940	2.126	2.178	4.600	2.500	3.204	2.490	8.410	3.030	4.690
DSD (million m^3)	0.947	1.551	2.820	2.820	2.312	2.117	4.361	4.361	2.905	2.643	5.260	5.260	3.375
SIWWD (million m^3)	0.241	0.287	0.463	0.421	0.410	0.485	1.233	1.136	0.921	0.790	2.969	1.954	1.565

Notes: GDPP: GDP per person; TP: total population; UR: urbanization rate; TPU: total population in urban areas; WRD: annual total water resource demand the watershed; WRDI: water resource demand of industry; WRDA: water resource demand of agriculture; WRDSI: water resource demand of service industry; WRDD: water resource demand of domestic use; IWWD: wastewater discharge from industry; DSD: annual domestic sewage discharge; SIWWD: wastewater discharge from service industry

others (2001). Most of the relative errors for these validation and sensitivity analyses were less than 5%, and the study system responded to most of the parameters with low sensitivity. Consequently, the SD-LQW model could be used for effective prediction of the system's behavior (Liu and others 2006). The scenarios S_{E1}, S_{E2}, S_{E3}, and S_{E4} for the years 2005, 2010, and 2015 were fleshed out using the SD-LQW model (Table 4). The scenarios S_{P1} and S_{P2} were controlled by decision makers, since these involved actual policies rather than watershed changes. In China, more uncertainties concern watershed changes than the policy-making process. As a result, these were analyzed together, in conjunction with the optimal selection of countermeasures and engineering techniques in S_{E1}, S_{E2}, S_{E3}, and S_{E4}.

(4) Evaluate the scenarios

Different opinions existed concerning S_{E1}, S_{E2}, S_{E3}, and S_{E4}. The economic growth under S_{E2} was much the higher than under the other three, but induced pollution was also more serious in this context. After discussing four scenarios, the stakeholders and experts agreed that the four scenarios were reasonable and

Table 5 GDP and AEI, RGI in the eight scenarios

	$S_{1,1}$	$S_{1,2}$	$S_{2,1}$	$S_{2,2}$	$S_{3,1}$	$S_{3,2}$	$S_{4,1}$	$S_{4,2}$
Total GDP from 2004 to 2015 (million $)	576.90	490.37	1546.20	1314.27	884.60	751.91	932.30	792.46
AEI (million $)	7.50	6.38	20.10	17.09	11.50	9.78	12.12	1.30
Investment for T1 (million $)	2.74	2.19	6.81	5.45	6.81	5.45	4.37	3.50
RGI (million $)	4.76	4.19	13.29	11.64	4.69	4.33	7.75	6.80

Notes: RGI = AEI Investment for Tl; AEJ = 1.3% of the Total GDP from 2004 to 2015

Fig. 9 Evaluating matrix of the techniques using the three decision criteria of S, F, and O. ★: High priority; ▲: Priority; □: Sub-priority; ×: Deferment.

	$S_{1,1}$				$S_{1,2}$				$S_{2,1}$				$S_{2,2}$			
	S	F	O	C	S	F	O	C	S	F	O	C	B	F	O	C
T1	▲	□	★	★	▲	□	★	★	▲	▲	★	★	▲	□	★	★
T2	▲	□	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
T3	×	×	□	×	×	×	□	×	×	×	□	×	×	×	□	×
T4	×	□	□	×	×	▲	□	×	▲	□	□	▲	▲	▲	□	▲
T5	▲	□	▲	▲	▲	▲	▲	▲	▲	□	▲	▲	▲	▲	▲	▲

	$S_{3,1}$				$S_{3,2}$				$S_{4,1}$				$S_{4,2}$			
	S	F	O	C	S	F	O	C	S	F	O	C	S	F	O	C
T1	▲	▲	★	★	▲	▲	★	★	▲	▲	★	★	▲	▲	★	★
T2	▲	□	▲	▲	▲	▲	▲	▲	▲	□	▲	▲	▲	▲	▲	▲
T3	×	×	□	×	×	×	□	×	×	×	□	×	×	×	□	×
T4	×	□	□	×	×	▲	□	×	×	□	□	×	×	▲	□	×
T5	▲	□	★	▲	▲	▲	★	▲	▲	□	★	▲	▲	▲	▲	▲

practical. The main issues arising under the different scenarios are summarized in Table 4 and primarily involved environmental problems.

Optimal Selection of Policies and Engineering Techniques

Three criteria were used to evaluate the importance of different engineering techniques for watershed management under each scenario. The first of these, represented by ***S*** in Figure 9, depended on the scenario itself, for the environmental problems differed across the scenarios. The differences in the environmental problems led directly to different technical arrangements for watershed management. The second criterion, represented by ***F*** in Figure 9, concerned the techniques themselves and the financial abilities of the local governments. The techniques were assessed based on CBA, as shown in Table 2. The third criterion, represented by ***O*** in involved the opinions of stakeholders. Since eutrophication is becoming increasingly severe in Lake Qionghai, among the engineering techniques to remove nutrients from the lake both T1 and T5 were considered the most important after discussions were conducted with experts and local stakeholders. Based on these three criteria, *S*, *F*, and *O*, a comprehensive assessment of the techniques, represented by ***C*** in Figure 9, was obtained using multicriteria evaluation.

(1) Optimal selection under $S_{1,1}$ and $S_{1,2}$

Under scenario $S_{1,1}$, the existing rate of growth and existing policies and plans for watershed management would be maintained. Under scenario $S_{1,2}$, the existing rate of growth would be maintained but strict policies concerning pollution and resource utilization in the watershed would be implemented.

Under $S_{1,1}$, GDP should increase to US$74.49 million in 2015, with total GDP for the period from 2004 to 2015 reaching US$576.9 million. According to the policy issued by SEPA in 2001, affordable environmental investment (AEI) should equal about 1.3% of regional GDP. Thus, the available annual investment for ecological engineering techniques should reach US$7.5 million between 2004 and 2015 in this case (Table 5). Under $S_{1,2}$, strict policies concerning pollution and resource utilization would be carried out that should influence both GDP and water resource consumption. According to the estimates of local governments, GDP in this case should reach only 85% of that under $S_{1,1}$, and water resource demand should decrease to 20% of that under $S_{1,1}$, at most. In consequence, the AEI under $S_{1,2}$ should total US$6.38 million between 2004 and 2015.

Under $S_{1,1}$, the WRD should decrease from 51.00 million m^3/a in 2005 to 47.00 million m^3/a in 2015, due to the rapid decrease in the WRDA. The DSD forecast in Table 4 indicates that the DSD under $S_{1,1}$ should reach 2.643 million m^3 in 2015. According to discussions with local experts and stakeholders, T1 was viewed as the most important technique for Lake Qionghai watershed management. In consequence, investment in T1 should be the first priority under this scenario. The investment needed for T1, the product of the DSD and the unit cost of T1 listed in Table 1, should reach US$2.74 million. The remaining government investment (RGI), the difference between the AEI and the investment in T1, should be only US$4.76 million, which would not be sufficient to cover any investment required for T2, T3, or T5 (Table 5). Under $S_{1,1}$, only some of the engineering techniques could be put into practice because of this limited investment. Among the techniques included in T5 and T2, the ecological restoration of riparian areas and the preventive engineering of soil loss and debris flows should be priorities.

Under $S_{1,2}$, the investment required for T1 would be US$2.19 million, and the remaining government investment would be total US$4.19 million (Table 5). This amount would not be sufficient to cover any investment in T2, T3, or T5. Thus, under both $S_{1,1}$ and $S_{1,2}$, the major constraint would be a lack of ability to pay for the implementation of engineering techniques. Therefore, it would be necessary for local decision makers to raise more funding.

(2) Optimal choices under alternative scenarios

Using the methods described above, the optimal choices under the other scenarios were identified. The optimization results for the techniques under the different scenarios, based on the assessments of the three criteria noted above, are presented in Figure 9.

Under $S_{2,2}$, strict policies and plans concerning industries should be implemented to reduce water resource utilization and the discharge of wastewater. The DSD could be reduced by means of economic policies, such as increasing the price of water and wastewater discharge fees; such policies would reduce the cost of the investment in T1 by about US$1.36 million. In addition, various policies to combat agricultural pollution could be adopted, so that the investment required for T4 could also be reduced. The most challenging problems under $S_{2,1}$ and $S_{2,2}$ would be investment scarcity and limited water resources.

In the cases of $S_{3,1}$ and $S_{3,2}$, water resources would not be a limiting factor for local development, if proper policies were taken for water utilization. Among all the techniques, T1 and T5 would be the highest priority. The DSD under $S_{3,1}$ would reach 5.260 million m^3 in 2015, and the needed treatment investment in T1 would be US$6.81 million. The RGI under $S_{3,1}$ would amount to US$4.69 million, which would not be sufficient to cover any of the investment needed for T5, T2, or T3.

Under $S_{4,1}$ and $S_{4,2}$, T1 and T5 would be the highest priority. The DSD under $S_{4,1}$ would reach 3.375 million m^3 in 2015, and the necessary treatment investment for T1 would be US$4.37 million. The RGI under $S_{4,1}$ would amount to US$7.75 million, allowing the ecological restoration of riparian areas (part of T5) to be fully implemented (Table 5). According to CBA, T3 could be deferred due to the scarcity of investment, and part of T2 and the remainder of T5 could be carried out.

Discussion

The scenarios and the modeling results were presented to the local stakeholders in late 2004 and received some responses. $S_{2,2}$ was thought to be the ideal scenario by local government and stakeholders based on further interviews performed. The stakeholders also realized the uncertainties in the future development. A comprehensive watershed management plan is now under implementation in Lake Qionghai Watershed based on the modeling results. Some advice was proposed by the stakeholders according to the scenario analysis, such as adjusting the driving forces and the corresponding modeling results in the next years dynamically to better support the watershed management plans, and adopting adaptive management in the future to reflect the dynamic and uncertain changes in the watershed.

Integrated watershed management, including countermeasures and techniques for protecting and restoring environmental subsystems, is an important area of study. The AEI can cover only some of the ecological engineering techniques considered. Therefore, it is urgent that enough money is raised, or that institutional incentives and economic policies are implemented to induce more external corporations to join in developing and implementing these ecological engineering techniques in the watershed. For example, building-operating-transferring (BOT) mechanisms could be used in wastewater treatment plants.

Other economic policies, including raising the price of water in urban areas, the development of water-saving agriculture, the implementation of cleaner production methods, and the establishment of a subsidiary system for developing water saving techniques, could be adopted to reduce water resource utilization and, hence, to reduce wastewater discharge. The goal of these policies would be to protect water quality and reduce the financial burden of environmental investment in the Lake Qionghai watershed.

In the context of the scenarios analysis, T1 was of very high priority in every scenario. In addition, T2 and T5 were of high priority, while the importance of T4 depended on water resource demand. As a result of investment scarcity, T3 was omitted from the eight scenarios. From the above analysis, $S_{3,2}$ was clearly the preferred scenario. Under this scenario, the techniques for controlling point and nonpoint sources of pollution and the ecological techniques for restoring the riparian area were appropriate based on the scenario analysis and the CBA.

Conclusions

Watershed management is a complex and uncertain process. In this paper, an optimization method based on scenario analysis is proposed for implementing watershed management under uncertainty. This optimization method integrates system analysis, traditional forecast methods, scenario analysis, and the interactive participation of experts and stakeholders into a single framework. The proposed optimization method can be used to deal efficiently with uncertainties at the watershed scale, and can incorporate the interests of different groups, which are an important component of watershed management. Social, economic, environmental, and resource systems can be taken into consideration to improve the applicability of the method. The optimal selection of engineering techniques and policies can be achieved based on scenario analysis. The proposed method was applied to the case of the Lake Qionghai watershed. The results of the case study indicate that the proposed method is a valuable tool for watershed management.

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