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An Inexact Two-Stage Water Quality Management Model for Supporting Sustainable Development in a Rural System

N. Zhang[1,2], Y. P. Li[1,*], W. W. Huang[3] and J. Liu[1]

[1]*MOE Key Laboratory of Regional Energy Systems Optimization, Resources and Environmental Research Academy, North China Electric Power University, Beijing 102206, China*
[2]*Faculty of Engineering and Applied Sciences, University of Regina, Regina, Saskathewan S4S 0A2, Canada*
[3]*Department of Civil Engineering, McMaster University, Hamilton, Ontario, Canada L8S 4L7*

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ABSTRACT. Water quality management is essential for preserving valuable water resources and facilitating sustainable socio-economic development in watershed systems. However, it is challenging for decision makers to identify desired schemes for management of economic development and environmental protection due to complexities of rural systems. In this study, an inexact two-stage water quality management (ITWQM) model is developed for supporting economic and environmental management of a rural area in Heshui Watershed. In the modeling formulation, pollutant discharge and soil loss are allowed under a range of relaxed constraints in association with a variety of probabilities, such that the reliability of satisfying (or risk of violating) system constraints can be analyzed; besides, penalties are imposed when policies expressed as allowable pollutant discharge levels are not satisfied. Solutions in connection with regional sustainable development such as land use, water quality protection, crop cultivation, livestock husbandry, forest expansion, fishery and industrial production, have been obtained. The results can be used for generating decision alternatives and helping local managers to identify desired policies under various environmental, economic, and system-reliability conditions. Decisions at a lower risk level would lead to an increased reliability in fulfilling environmental requirements but with a reduced system benefit; conversely, a desire for increasing system benefit could result in a raised risk of violating environmental constraints.

Keywords: optimization, risk analysis, sustainable development, water quality, uncertainty

1. Introduction

Sustainable development has been widely recognized as an effective means for harmonizing human society and natural systems under multiple pressures of economic prosperity, eco-environmental protection, and human health (Huang et al., 2009). However, achieving a reasonable sustainability is difficult since many conflicting factors (e.g., social, economic and eco-environmental targets) have to be balanced due to the complexities of real-world systems. Particularly for many rural areas in developing countries, ecological destruction and environmental deterioration have become serious concerns as economy development is over-heated. For example, to meet the increasing food demands, the continuous expansion of crop, fruit, and vegetable production leads to more and more intensive use of pesticides. More than 500 formulations of pesticides are being used in our environment, and agriculture holds the largest single share of pesticide use. Because of their widespread use, pesticides leach into surface and groundwater, and are therefore present in drinking water and exert toxic effects on human health. On the other hand, in regional economic and environmental management, uncertainties might be attributed due to the randomness that are inherent in nature and due to the lack of sufficient data related to the chances of their occurrence and potential consequences. Uncertainties may exist in the related costs, impact factors and objectives, and be presented in fuzzy, probabilistic and/or interval formats; such uncertainties could further affect the related optimization processes and the generated decision schemes (Li et al., 2009). Consequently, a wide range of mathematical techniques were developed to examine economic, environmental and ecological impacts of various pollution control actions, and thus aid decision makers in formulating effective sustainable development policies under uncertainty (Chang et al., 2001; Karmakar and Mujumdar, 2007; Li et al., 2011; Deviney Jr et al., 2012; Graveline et al., 2012; Kisi et al., 2013; Xu and Qin, 2013).

Two-stage stochastic programming (TSP) is effective for problems where an analysis of policy scenarios is desired and when the right-hand-side coefficients are random with known probability distributions (Birge and Louveaux, 1988; Ruszczynski and Swietanowski, 1997). The fundamental idea be-

* Corresponding author. Tel.: +86 10 61773887; fax: +86 10 61773889.
E-mail address: yongping.li@iseis.org (Y. P. Li).

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hind TSP is the concept of recourse, which defines the ability to take corrective actions after a random event has taken place (Li and Huang, 2009). The TSP methods require decision makers to assign a cost to recourse activities that are taken to ensure feasibility of the second-stage problem. This means that, in TSP, infeasibilities in the second stage are allowed at a certain penalty (i.e. the second-stage decision is used to minimize penalty that may appear due to any infeasibility). For example, Huang and Loucks (2000) proposed an inexact two-stage stochastic programming (ITSP) technique, which was an extension of TSP by tackling uncertainties expressed as both probability distributions and intervals as well as accounting for economic penalties. Li et al. (2007) developed an inexact two-stage chance-constrained programming approach by introducing chance-constrained programming (CCP) into the ITSP framework to deal with policy options and examine violation risks under uncertainty; the developed method was successfully applied to municipal solid waste management problems, where interval solutions associated different risk levels of constraint violation were generated.

TSP can handle uncertainties expressed as probability distributions as well as account for economic penalties with recourse against any infeasibility; however, it can hardly deal with independent uncertainties of left-hand sides of constraints and coefficients of objective function. CCP does not require that all of the constraints be totally satisfied; instead, it can be satisfied in a proportion of cases with given probabilities (Loucks et al., 1981; Li and Huang, 2011). Both TSP and CCP require probabilistic specifications for uncertain parameters while, in many practical problems, the quality of information that can be obtained is mostly not satisfactory enough to be presented as probability distributions. In real-world problems, much information (e.g., social, economic, legal, environmental, water quantity / quality, resources, land availability, and planning implication) is often not of sufficient quality to be presented as probability distributions; instead, it is easier to describe such information as discrete intervals with knowing their lower and upper bounds. Interval-parameter programming (IPP) is an alternative for handling uncertainties in coefficients in left- and right-hand sides and objective function, which can tackle uncertainties that cannot be quantified as membership or distribution functions since interval numbers are acceptable as its uncertain inputs (Fan and Huang, 2012; Suo et al., 2013). Generally, although the uncertainty of water quality management received some discussion, little attention was paid to the incorporation of more complex uncertainties presented as stochastic and interval variables within the modeling framework to tackle pollution reduction problems of a rural region within a watershed system; furthermore, previous studies lacked linkage to economic consequences of violated environmental policies pre-regulated by authorities through taking recourse actions in order to correct any infeasibilities due to uncertainties.

Therefore, the objective of this study aims to develop an inexact two-stage water quality management (ITWQM) model for planning economic development activities and pollution control actions of Yongxin County in the Heshui River watershed, China. The county has encountered problems of serious conflicts among rapid economic development, ecological destruction and environmental deterioration. The ITWQM model is based on an inexact two-stage chance-constrained programming (ITCP) technique that can help examine the reliability of satisfying (or risk of violating) system constraints under uncertainty. The results obtained will be used for generating a range of decision alternatives under various system conditions, and thus helping the local managers to identify desired sustainable development strategies among water and land resources conservation, river-water quality protection, and regional economic development.

2. Methodology

This section is devoted to advancing an inexact two-stage chance-constrained programming (ITCP) method. It emphasizes on (i) how TSP, CCP and IPP techniques are incurporated within a general optimization framework, leading to such a ITCP method, (ii) how ITCP is useful for dealing with uncertainties presented as random variables, interval values, and their combinations, and (iii) how the ITCP model is transferred into deterministic form, and the solution is generated through such a hybrid approach. Firstly, when uncertainties are expressed as probability distributions while decisions need to be made periodically over time, the study problem can be formulated as a TSP model:

$$Max\ f = cx - E\left[Q\left(x,\ \omega\right)\right] \tag{1a}$$

subject to

$$Ax \le b \tag{1b}$$

$$x \le 0 \tag{1c}$$

In model (1), decision variables are divided into two subsets: those that must be determined before the realizations of random variables are disclosed (i.e. first-stage variable, x) and those (recourse variables) that are determined after the realized values of the random variables (ω) are observed (Li et al., 2014). The $Q\left(x,\ \omega\right)$ is the optimal value, for any given Ω , of the following nonlinear program:

$$Min\ \ q\left(y,\ \omega\right) \tag{2a}$$

subject to

$$W\left(\omega\right)y = h\left(\omega\right) - T\left(\omega\right)x \tag{2b}$$

$$y \ge 0 \tag{2c}$$

where y is the second-stage decision variables (i.e. recourse variables) that depend on the realization of the first-stage random vector; $q(y,\ \omega)$ denotes the second-stage cost function; $\{T(\omega),\ W(\omega),\ h(\omega)\,|\,\omega \in \Omega\}$ are model parameters with reasonable dimensions, and are functions of the random vector (ω). For given values of the first-stage variables (x), the second-stage problem can be decomposed into independent linear sub-problems, with one sub-problem for each realization of the uncertain parameters. Then, model (1) can be reformulated as:

$$\begin{aligned} Max\ f &= cx \\ &-E\left[\min_{y\ge 0}\left\{q(y,\ \omega)\,|\,T(\omega)x + W(\omega)y = h(\omega)\right\}\right] \end{aligned} \tag{3a}$$

subject to

$$Ax \le b \tag{3b}$$

$$x \ge 0 \tag{3c}$$

Let random vector ω possesses a discrete and finite distribution, with support $\Omega = \{\omega_1,\ \omega_2,\ ...,\ \omega_s\}$, and denote p_h as the probability of realization of scenario ω_h, with p_h > 0 and $\sum_{h=1}^{s} p_h$ = 1 (Birge and Louveaux, 1988; Huang and Loucks, 2000). Then, model (3) can be equivalently formulated as a linear program:

$$Max\ f = cx - \sum_{h=1}^{s} p_h q(y_h,\ \omega_h) \tag{4a}$$

subject to

$$Ax \le b \tag{4b}$$

$$T(\omega_h)x + W(\omega_h)y_{\omega_h} = h(\omega_h),\quad \omega_h \in \Omega \tag{4c}$$

$$x \ge 0 \tag{4d}$$

$$y_h \ge 0 \tag{4e}$$

The TSP model can effectively deal with uncertainties in the right-hand sides presented as probability distributions when coefficients in the objective function and left-hand sides are deterministic. To handle uncertainties (existing in both left- and right-hand sides of the constraints as well as coefficients of objective function) that may not be quantified as membership or distribution functions, the IPP technique is introduced into the TSP framework. Thus, we have:

$$Max\ f^{\pm} = c^{\pm}x^{\pm} - \sum_{h=1}^{s} p_h q(y_h^{\pm},\ \omega_h^{\pm}) \tag{5a}$$

subject to

$$A^{\pm}x^{\pm} \le b^{\pm} \tag{5b}$$

$$T(\omega_h^{\pm})x^{\pm} + W(\omega_h^{\pm})y_h^{\pm} = h(\omega_h^{\pm}),\quad \omega_h \in \Omega \tag{5c}$$

$$x^{\pm} \ge 0 \tag{5d}$$

$$y_h^{\pm} \ge 0 \tag{5e}$$

In real-world problems, randomness in other right-hand-side parameters also needs to be reflected, such that uncertainties can be expressed as a minimum requirement on the probability of satisfying the constraints. CCP is effecttive for solving problems with random right-hand sides by converting them into deterministic versions through: (a) fixing a certain level of probability γ_i ($\gamma_i \in [0,\ 1]$) for uncertain constraint i, and (b) imposing the condition that the constraint should be satisfied with at least a probability level of α_i ($\alpha_i = 1 - \gamma_i$). Equation (5b) can be converted into:

$$\begin{aligned} &\Pr[\{t\,|\,A_i^{\pm}(t)X^{\pm} \le b_i^{\pm}(t)\}] \ge \alpha_i,\ |\,A_i^{\pm}(t) \in A^{\pm}(t), \\ &i = 1, 2, \ldots, m \end{aligned} \tag{6a}$$

Constraint (6a) can be specified as follows:

$$A_i^{\pm}(t)X^{\pm} \le b_i^{\pm}(t)^{\gamma_i},\quad \forall i \tag{6b}$$

where $b_i^{\pm}(t)^{\gamma_i} = F_i^{-1}(\gamma_i)$, given the cumulative distribution function of $b_i^{\pm}$ [i.e. $F_i(b_i^{\pm})$] and the probability of violating constraint i (i.e. γ_i). Then, an inexact two-stage chance-constrained programming (ITCP) model can be formulated as:

$$Max\ f^{\pm} = c^{\pm}x^{\pm} - \sum_{h=1}^{s} p_h q(y_h^{\pm},\ \omega_h^{\pm}) \tag{7a}$$

subject to

$$A_i^{\pm}(t)X^{\pm} \le b_i^{\pm}(t)^{\gamma_i},\quad \forall i \tag{7b}$$

$$T(\omega_h^{\pm})x^{\pm} + W(\omega_h^{\pm})y_h^{\pm} = h(\omega_h^{\pm}),\quad \omega_h \in \Omega \tag{7c}$$

$$x^{\pm} \ge 0 \tag{7d}$$

$$y_h^{\pm} \ge 0 \tag{7e}$$

The ITCP model (under each γ_i level) can be transformed into two deterministic submodels that correspond to the lower and upper bounds of desired objective-function value, based on an interactive algorithm that is different from the best/worst case analysis (Huang, 1998). Interval solutions associated with varying levels of constraint-violation risk can then be obtained by solving the two submodels sequentially.

Submodel corresponding to upper-bound objective value (f^+) can be firstly formulated as follows (assume that $B^{\pm} > 0$ and $f^{\pm} > 0$):

$$Max\ f^+ = \sum_{j=1}^{k_1} c_j^+ x_j^+ + \sum_{j=k_1+1}^{n_1} c_j^+ x_j^- - (\sum_{j=1}^{k_2}\sum_{h=1}^{s} p_{jh} d_j^- y_{jh}^- + \sum_{j=k_2+1}^{n_2}\sum_{h=1}^{s} p_{jh} d_j^- y_{jh}^+) \quad (8a)$$

subject to

$$\sum_{j=1}^{k_1} |a_{ij}|^- \,\mathrm{Sign}(a_{ij}^-) x_j^+ + \sum_{j=k_1+1}^{n_1} |a_{ij}|^+ \,\mathrm{Sign}(a_{ij}^+) x_j^- \le (b_i^+)^{(\gamma_i)},\ \ i = 1,\ 2,\ \ldots,\ m_1 \quad (8b)$$

$$\sum_{j=1}^{k_1} |a_{rj}|^- \,\mathrm{Sign}(a_{rj}^-) x_j^+ + \sum_{j=k_1+1}^{n_1} |a_{rj}|^+ \,\mathrm{Sign}(a_{rj}^+) x_j^- + \sum_{j=1}^{k_2} |a'_{rj}|^+ \,\mathrm{Sign}(a'^+_{rj}) y_{jh}^- + \sum_{j=k_2+1}^{n_2} |a'_{rj}|^- \,\mathrm{Sign}(a'^-_{rj}) y_{jh}^+ \ \le w_h^+,\ \ r = 1,\ 2,\ \ldots,\ m_2;\ \forall h \quad (8c)$$

$$x_j^+ \ge 0,\ j = 1,\ 2,\ \cdots,\ k_1 \quad (8d)$$

$$x_j^- \ge 0,\ j = k_1+1,\ k_1+2,\ \cdots,\ n_1 \quad (8e)$$

$$y_{jh}^- \ge 0,\ \forall h;\ j = 1,\ 2,\ \cdots,\ k_2 \quad (8f)$$

$$y_{jh}^+ \ge 0,\ \forall h;\ j = k_2+1, k_2+2, \cdots, n_2 \quad (8g)$$

where $x_j^{\pm}$, j = 1, 2, ..., k_1, are interval variables with positive coefficients in the objective function; $x_j^{\pm}$, j = k_1 + 1, k_1 + 2, ..., n_1, are interval variables with negative coefficients; $y_{jh}^{\pm}$, j = 1, 2, ..., k_2 and h = 1, 2, …, v are random variables with positive coefficients in the objective function; $y_{jh}^{\pm}$, j = k_2 + 1, k_2 + 2, ..., n_2 and h = 1, 2, …, v, are random variables with negative coefficients. Solutions of $x_{j\,\mathrm{opt}}^+$ (j = 1, 2, ..., k_1), $x_{j\,\mathrm{opt}}^-$ (j = k_1 + 1, k_1 + 2, ..., n_1), $y_{jh\,\mathrm{opt}}^-$ (j = 1, 2, ..., k_2), and $y_{jh\,\mathrm{opt}}^+$ (j = k_2 + 1, k_2 + 2, ..., n_2) can be obtained through submodel (8). Based on the above solutions, the second submodel for f^- can be formulated as follows:

$$Max\ f^- = \sum_{j=1}^{k_1} c_j^- x_j^- + \sum_{j=k_1+1}^{n_1} c_j^- x_j^+ - (\sum_{j=1}^{k_2}\sum_{h=1}^{v} p_{jh} d_j^+ y_{jh}^+ + \sum_{j=k_2+1}^{n_2}\sum_{h=1}^{v} p_{jh} d_j^+ y_{jh}^-) \quad (9a)$$

subject to

$$\sum_{j=1}^{k_1} |a_{ij}|^+ \,\mathrm{Sign}(a_{ij}^+) x_j^- + \sum_{j=k_1+1}^{n_1} |a_{ij}|^- \,\mathrm{Sign}(a_{ij}^-) x_j^+ \le (b_i^-)^{(\gamma_i)},\ \ i = 1,\ 2,\ \ldots,\ m_1 \quad (9b)$$

$$\sum_{j=1}^{k_1} |a_{rj}|^+ \,\mathrm{Sign}(a_{rj}^+) x_j^- + \sum_{j=k_1+1}^{n_1} |a_{rj}|^- \,\mathrm{Sign}(a_{rj}^-) x_j^+ + \sum_{j=1}^{k_2} |a'_{rj}|^- \,\mathrm{Sign}(a'^-_{rj}) y_{jh}^+ + \sum_{j=k_2+1}^{n_2} |a'_{rj}|^+ \,\mathrm{Sign}(a'^+_{rj}) y_{jh}^- \le w_h^-,\ r = 1,\ 2,\ \ldots,\ m_2;\ \forall h \quad (9c)$$

$$0 \le x_j^- \le x_{j\,\mathrm{opt}}^+,\ j = 1,\ 2,\ \cdots,\ k_1 \quad (9d)$$

$$x_j^+ \ge x_{j\,\mathrm{opt}}^-,\ j = k_1+1,\ k_1+2,\ \cdots,\ n_1 \quad (9e)$$

$$y_{jh}^+ \ge y_{jh\,\mathrm{opt}}^-,\ \forall h;\ j = 1,\ 2,\ \cdots,\ k_2 \quad (9f)$$

$$0 \le y_{jh}^- \le y_{jh\,\mathrm{opt}}^+,\ \forall h;\ j = k_2+1,\ k_2+2,\ \cdots,\ n_2 \quad (9g)$$

Solutions of $x_{j\,\mathrm{opt}}^-$ (j = 1, 2, ..., k_1), $x_{j\,\mathrm{opt}}^+$ (j = k_1 + 1, k_1 + 2, ..., n_1), $y_{jh\,\mathrm{opt}}^+$ (j = 1, 2, ..., k_2), and $y_{jh\,\mathrm{opt}}^-$ (j = k_2 + 1, k_2 + 2, ..., n_2) can be obtained from solving submodel (9). Through integrating solutions of submodels (8) and (9), interval solution for the ITCP model under a set of γ_i (i = 1, 2, …, m_1) levels can be obtained.

3. Case Study

Yongxin County, located in the mountain-river-lake region (western part of Jiangxi Province, China), is selected as the study area (Figure 1). The study area is 65 km in width from east to west, and 56 km in length from north to south, with a total area of approximately 2,190 km^2. The county is located in a subtropical zone with a yearly average temperature of 18.2 °C, and frost-free period is approximately 280 days per year (Huang et al., 2006). Its elevation changes from 120 to over 1,000 m. The average annual precipitation is 1508.9 mm, with most of the rain fall occurring during April to June. The average annual evaporation is 1066.4 mm. The topography of the area consists of mountains with steep slopes and narrow canyons in the north and south, hilly land in the east and west, and a large flood plain in the centre (Huang et al., 2009). The study area lies in the middle reach of the Heshui Watershed. As a tributary of the Ganjiang River, the Heshui River has a total length of 225 km, with 77 km flowing within the borders of Yongxin County from west to east. There are several small tributaries that flow into the Heshui River. The county uses the Heshui River to provide resources for regional water supply, agricultural irrigation, fishery farming, industrial production, and navigation. Annual surface water yield in the study area is around 1.77 billion m^3 and the annual groundwater storage is about 286 million m^3.

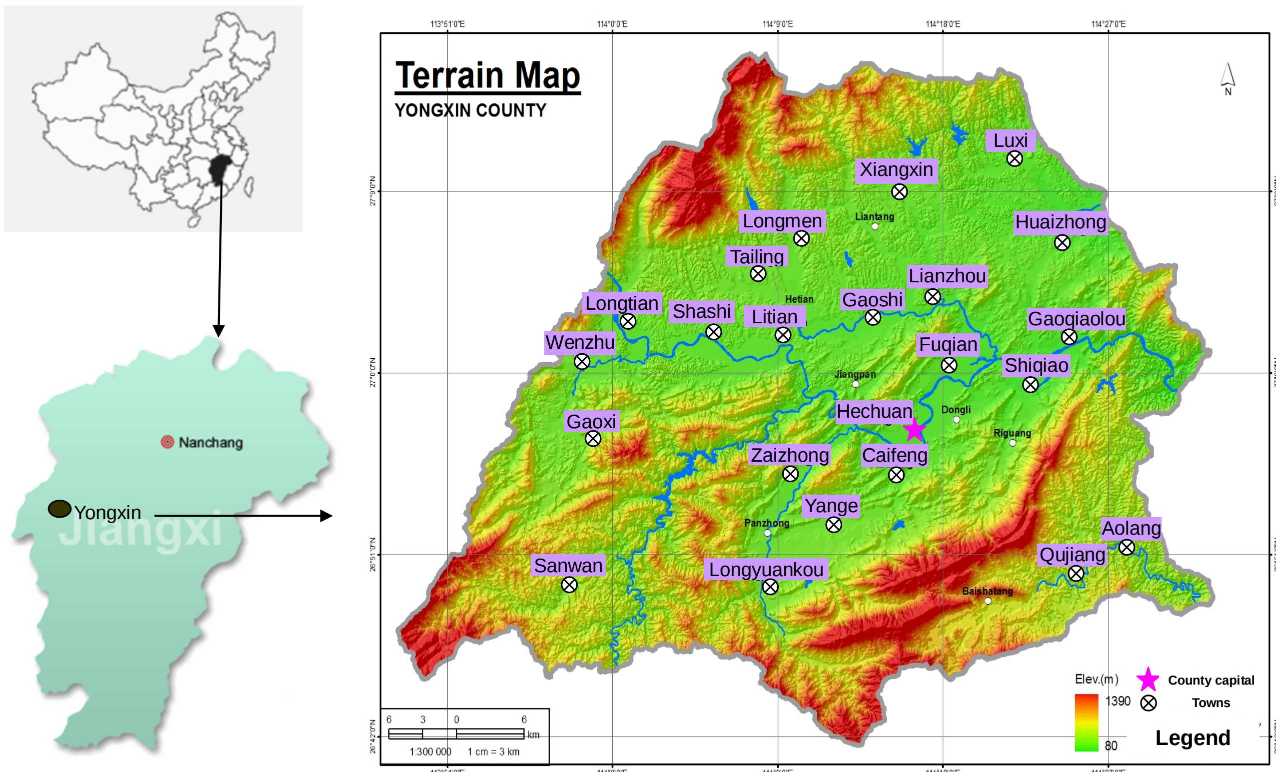

Figure 1. The study area (source: Huang et al. 2006).

Yongxin County consists of 23 townships, and its capital is located in the Town of Hechuan. The total population of Yongxin County reached 505,015 at the end of 2012, which is expected to grow at a rate of 7.0‰ per year in the future. There are a number of economic activities within the study area, including agricultural, industrial, fishery, livestock, and forestry production. These activities have been expanding yearly as the county develops economically, and thus there is a need to ensure that this economic growth does not cause damage to the environment of the area. In the county, rice, wheat, grain, rapeseeds and vegetables are the principal crops and main agricultural income sources; the yields of grain, oil, vegetables and cocoon were 284,200, 22,269, 83,517 and 856 tonne in 2009, respectively. The main types of livestock raised in the study area are hogs, cattle and poultry (e.g., chicken, duck, and goose). The total meat production in 2009 was 30,850 tonne, including 23,282 tonne of pork and 4,066 tonne of beef, respectively. The total area of forestry in the county is about 980 km^2, which was expanded by 29.4 km^2 in 2009. The total yield of aquatic products (e.g., fish and prawn) was 14,375 tonne in 2009. The second industrial sector in the county is mainly comprised of mining, manufacturing, construction, transportation and other industries. The area possesses more than 20 types of mineral deposits, and the mineral production was 315.0 thousand tonne in 2009. The output from tertiary industries, such as retail, wholesale, restaurants and tourism, was increased at an annual rate of about 9.5% from 2002 to 2009 (Yongxin Bureau of Statistics, 2010).

In recent years, the rapid urbanization and shift economic growth of the area have caused serious deterioration of eco-environment, erosion of soil, unnatural distribution of population, and shortage of water resources. In the study area, the treatment level of wastewater discharged from domestic activities and industrial operations is far from satisfactory. Although the treatment ratio of domestic sewage in the center townships reached 60% in 2010, wastewater generated in the large rural areas was barely treated. Seepage and runoff of pesticides and fertilizers from agricultural activities and discharge of wastewater from farmers and livestock are also affecting the quality of the surface water. For example, the cultivation rate is insufficient (lower than 20%); the duplicate planting rate is low, especially during the autumn and winter; most of the arable land is hardly protected and the nutrients in soils are lost signifycantly. Soil erosion is observed in a total of 434 km^2 of land in the study area, accounting for 19.9% of the total land area. An average of 1.70 million tonne of soil is lost per year, with the average soil erosion modulus being 3,956 tonne per km^2. Control of the serious erosion problem in Yongxin County is necessary for ensuring the continued success of agricultural production in the area and environmental sustainability.

Based on the ITCP technique, an inexact two-stage water quality management (ITWQM) model is formulated for planning economic and environmental sustainable development in the rural system. The objective is associated with a number of socio-economic and ecological factors such as economic return, environmental protection, and ecological sustainability, while the constraints are related to pollutant discharges, soil losses, resources availabilities, environmental requirements, and policy regulations. The decision variables include areas of crop farms, areas of fishery farms, areas of expanded forests, populations of livestock, and outputs of industries. The formulation of the ITWQM model is presented as follows:

$$
\begin{aligned}
Max\ f^{\pm} = & \sum_{i=1}^{I_a}\sum_{j=1}^{J} AG_{i,j}^{\pm}(TA_{i,j}^{-} + \Delta TA_{i,j}u_{i,j}) \\
& + \sum_{i=1}^{I_f}\sum_{j=1}^{J} FI_{i,j}^{\pm}(TF_{i,j}^{-} + \Delta TF_{i,j}v_{ij}) \\
& + \sum_{i=1}^{I_l}\sum_{j=1}^{J} LH_{i,j}^{\pm}(TL_{i,j}^{-} + \Delta TL_{i,j}w_{i,j}) \\
& + \sum_{i=1}^{I_i}\sum_{j=1}^{J} IB_{i,j}^{\pm}(TI_{i,j}^{-} + \Delta TI_{i,j}x_{i,j}) \\
& + \sum_{i=1}^{I_s}\sum_{j=1}^{J} WB_{i,j}^{\pm}(TW_{i,j}^{-} + \Delta TW_{i,j}y_{i,j}) \\
& - \sum_{i=1}^{I_a}\sum_{j=1}^{J}\sum_{k=2}^{K}\sum_{l=1}^{L} p_l' \cdot CA_{i,k}^{\pm} \cdot DA_{i,j,k,l}^{\pm} \\
& - (\sum_{i=1}^{I_f}\sum_{j=1}^{J}\sum_{l=1}^{L} p_l' \cdot CF_{i,k=1}^{\pm} \cdot DF_{i,j,k=1,l}^{\pm} \\
& + \sum_{i=1}^{I_f}\sum_{j=1}^{J}\sum_{k=5}^{K}\sum_{l=1}^{L} p_l' \cdot CF_{i,k}^{\pm} \cdot DF_{i,j,k,l}^{\pm}) \\
& - \sum_{i=1}^{I_l}\sum_{j=1}^{J}\sum_{l=1}^{L} p_l' \cdot CL_{i,k=1}^{\pm} \cdot DL_{i,j,k=1,l}^{\pm} \\
& - \sum_{i=1}^{I_i}\sum_{j=1}^{J}\sum_{l=1}^{L} p_l' \cdot CI_{i,k=1}^{\pm} \cdot DI_{i,j,k=1,l}^{\pm} \\
& - \sum_{i=1}^{I_s}\sum_{j=1}^{J}\sum_{l=1}^{L} p_l' \cdot CW_{i,k=2}^{\pm} \cdot DW_{i,j,k=2,l}^{\pm}
\end{aligned}
\tag{10a}
$$

subject to

(1) Pollutant losses from agricultural activities:

$$\sum_{i=1}^{I_a}(TA_{i,j}^{-} + \Delta TA_{i,j}u_{i,j} - DA_{i,j,k=2,l}^{\pm}) \cdot SL_i^{\pm} \le PSL_{j,l}^{\pm}\ ,\ \forall j,\ l \tag{10b$_1$}$$

$$\sum_{i=1}^{I_a}(TA_{i,j}^{-} + \Delta TA_{i,j}u_{i,j} - DA_{i,j,k=3,l}^{\pm}) \cdot SLN_i^{\pm} \le PAN_{j,l}^{\pm}\ ,\quad \forall j,\ l \tag{10b$_2$}$$

$$\sum_{i=1}^{I_a}(TA_{i,j}^{-} + \Delta TA_{i,j}u_{i,j} - DA_{i,j,k=4,l}^{\pm}) \cdot SLP_i^{\pm} \le PAP_{j,l}^{\pm}\ ,\quad \forall j,\ l \tag{10b$_3$}$$

$$\sum_{i=1}^{I_a}(TA_{i,j}^{-} + \Delta TA_{i,j}u_{i,j} - DA_{i,j,k=5,l}^{\pm}) \cdot RAN_i^{\pm} \le PRN_{j,l}^{\pm}\ ,\quad \forall j,\ l \tag{10b$_4$}$$

$$\sum_{i=1}^{I_a}(TA_{i,j}^{-} + \Delta TA_{i,j}u_{i,j} - DA_{i,j,k=6,l}^{\pm}) \cdot RAP_i^{\pm} \le PRP_{j,l}^{\pm}\ ,\quad \forall j,\ l \tag{10b$_5$}$$

(2) Pollutant losses from fishery farming activities:

$$\sum_{i=1}^{I_f}(TF_{i,j}^{-} + \Delta TF_{i,j}v_{i,j} - DF_{i,j,k=1,l}^{\pm}) \cdot COF_i^{\pm} \le PCF_{j,l}^{\pm}\ ,\quad \forall j,\ l \tag{10c$_1$}$$

$$\sum_{i=1}^{I_f}(TF_{i,j}^{-} + \Delta TF_{i,j}v_{i,j} - DF_{i,j,k=5,l}^{\pm}) \cdot FN_i^{\pm} \le PFN_{j,l}^{\pm}\ ,\quad \forall j,\ l \tag{10c$_2$}$$

$$\sum_{i=1}^{I_f}(TF_{i,j}^{-} + \Delta TF_{i,j}v_{i,j} - DF_{i,j,k=6,l}^{\pm}) \cdot FP_i^{\pm} \le PFP_{j,l}^{\pm}\ ,\quad \forall j,\ l \tag{10c$_3$}$$

(3) Pollutant losses from livestock husbandry activities:

$$\sum_{i=1}^{I_l}(TL_{i,j}^{-} + \Delta TL_{i,j}w_{i,j} - DL_{i,j,k=1,l}^{\pm}) \cdot COL_i^{\pm} \le PCL_{j,l}^{\pm}\ ,\quad \forall j,\ l \tag{10d}$$

(4) Pollutant losses from industrial activities:

$$\sum_{i=1}^{I_i}(TI_{i,j}^{-} + \Delta TI_{i,j}x_{i,j} - DI_{i,j,k=1,l}^{\pm}) \cdot COI_i^{\pm} \le PCI_{j,l}^{\pm}\ ,\quad \forall j,\ l \tag{10e}$$

(5) Pollutant losses from forestry activities:

$$\sum_{i=1}^{I_s}(TW_{i,j}^{-} + \Delta TW_{i,j}y_{i,j} - DW_{i,j,k=2,l}^{\pm}) \cdot WS_i^{\pm} \le PWS_{j,l}^{\pm}\ ,\quad \forall j,\ l \tag{10f}$$

(6) Total COD-discharge allowance:

Table 1. Distributional Information of Allowable Soil Loss (unit: 10^3 t)

	p_h level	0.01	0.05	0.10	0.15	0.20
Scenario 1 (strict water quality requirement):	zone 1	[49, 81]	[64, 96]	[73, 105]	[79, 111]	[82, 115]
	zone 2	[121, 189]	[136, 204]	[145, 213]	[151, 219]	[154, 223]
	zone 3	[77, 123]	[92, 138]	[101, 147]	[107, 153]	[110, 157]
	zone 4	[93, 147]	[108, 162]	[117, 171]	[123, 177]	[126, 181]
	zone 5	[185, 285]	[200, 300]	[209, 309]	[215, 315]	[218, 319]
Scenario 2 (moderate water quality requirement):	zone 1	[113, 177]	[128, 192]	[137, 201]	[143, 207]	[146, 211]
	zone 2	[257, 393]	[272, 408]	[281, 417]	[287, 423]	[290, 427]
	zone 3	[169, 261]	[184, 276]	[193, 285]	[199, 291]	[202, 295]
	zone 4	[201, 309]	[216, 162]	[225, 333]	[231, 339]	[234, 343]
	zone 5	[385, 585]	[400, 600]	[409, 609]	[415, 615]	[418, 619]
Scenario 3 (lenient water quality requirement):	zone 1	[177, 273]	[192, 288]	[201, 297]	[207, 303]	[210, 307]
	zone 2	[393, 597]	[408, 612]	[417, 621]	[423, 627]	[426, 631]
	zone 3	[261, 399]	[276, 414]	[285, 423]	[291, 429]	[294, 433]
	zone 4	[309, 471]	[324, 486]	[333, 495]	[339, 501]	[342, 505]
	zone 5	[585, 885]	[600, 900]	[609, 909]	[615, 915]	[618, 919]

Table 2. Distributional Information of Allowable COD Discharges (unit: tonne)

	p_h level	0.01	0.05	0.10	0.15	0.20
Scenario 1	zone 1	[1625, 2560]	[1790, 2607]	[1897, 2631]	[1962, 2652]	[1994, 115]
	zone 2	[506, 566]	[621, 673]	[716, 762]	[757, 797]	[761, 223]
	zone 3	[785, 866]	[949, 1025]	[1091, 1161]	[1182, 1249]	[1221, 157]
	zone 4	[242, 269]	[355, 378]	[448, 468]	[518, 535]	[573, 181]
	zone 5	[502, 562]	[623, 678]	[712, 752]	[788, 827]	[842, 877]
Scenario 2	zone 1	[2240, 3520]	[2405, 3567]	[2512, 3591]	[2577, 3612]	[2609, 3627]
	zone 2	[781, 861]	[896, 968]	[991, 1057]	[1032, 1092]	[1036, 1126]
	zone 3	[1153, 1261]	[1317, 1420]	[1459, 1556]	[1550, 1644]	[1589, 1677]
	zone 4	[429, 465]	[542, 574]	[635, 664]	[705, 731]	[760, 784]
	zone 5	[776, 856]	[897, 972]	[986, 1046]	[1062, 1121]	[1116, 1171]
Scenario 3	zone 1	[3520, 5440]	[3685, 5487]	[3792, 5511]	[3857, 5532]	[3889, 5547]
	zone 2	[1332, 1452]	[1447, 1559]	[1542, 1648]	[1583, 1683]	[1587, 1717]
	zone 3	[1890, 2052]	[2054, 2211]	[2196, 2347]	[2287, 2435]	[2326, 2468]
	zone 4	[804, 858]	[917, 967]	[1010, 1057]	[1080, 1124]	[1135, 1177]
	zone 5	[1324, 1444]	[1445, 1560]	[1534, 1634]	[1610, 1709]	[1664, 1759]

$$\Pr\left\{\begin{array}{l} \sum_{i=1}^{I_f}(TF_{i,j}^{-}+\Delta TF_{i,j}v_{i,j}-DF_{i,j,k=1,l}^{\pm})\cdot COF_i^{\pm} \\ +\sum_{i=1}^{I_l}(TL_{i,j}^{-}+\Delta TL_{i,j}w_{i,j}-DL_{i,j,k=1,l}^{\pm})\cdot COL_i^{\pm} \\ +\sum_{i=1}^{I_i}(TI_{i,j}^{-}+\Delta TI_{i,j}x_{i,j}-DI_{i,j,k=1,l}^{\pm})\cdot COI_i^{\pm}\le TCD_{j,l}^{\pm} \end{array}\right\} \ge 1\text{-}\,p_h,\ \forall j,\ l,\ h \tag{10g}$$

(7) Total soil loss allowance:

$$\Pr\left\{\begin{array}{l} \sum_{i=1}^{I_a}(TA_{i,j}^{-}+\Delta TA_{i,j}u_{i,j}-DA_{i,j,k=2,l}^{\pm})\cdot SL_i^{\pm} \\ +\sum_{i=1}^{I_s}(TW_{i,j}^{-}+\Delta TW_{i,j}y_{i,j}-DW_{i,j,k=2,l}^{\pm})\cdot WS_i^{\pm}\le TSL_{j,l}^{\pm} \end{array}\right\} \ge 1\text{-}\,p_h,\ \forall j,\ l,\ h \tag{10h}$$

(8) Total dissolved nitrogen loss allowance:

$$\sum_{i=1}^{I_a}(TA_{i,j}^{-}+\Delta TA_{i,j}u_{i,j}-DA_{i,j,k=5,l}^{\pm})\cdot RAN_i^{\pm} + \sum_{i=1}^{I_f}(TF_{i,j}^{-}+\Delta TF_{i,j}v_{i,j}-DF_{i,j,k=5,l}^{\pm})\cdot FN_i^{\pm}\le TNL_{j,l}^{\pm},\ \forall j,\ l \tag{10i}$$

(9) Total dissolved phosphorous loss allowance:

$$\sum_{i=1}^{I_a}(TA_{i,j}^{-}+\Delta TA_{i,j}u_{i,j}-DA_{i,j,k=6,l}^{\pm})\cdot RAP_i^{\pm} + \sum_{i=1}^{I_f}(TF_{i,j}^{-}+\Delta TF_{i,j}v_{i,j}-DF_{i,j,k=6,l}^{\pm})\cdot FP_i^{\pm}\le TPL_{j,l}^{\pm} \quad \forall j,\ l \tag{10j}$$

Table 3. Allowable Dissolved Nitrogen and Phosphorus Discharges (unit: t/yr)

	Scenario	p_i'	Allowable dissolved nitrogen discharge				
			Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Nitrogen discharge from agricultural activity:	1	0.2	[49.0, 56.0]	[101.8, 119.1]	[68.9, 80.6]	[80.9, 94.7]	[149.8, 175.3]
	2	0.6	[98.1, 112.1]	[203.6, 238.2]	[137.8, 161.2]	[161.7, 189.3]	[299.5, 350.5]
	3	0.2	[147.1, 168.1]	[305.4, 357.3]	[206.7, 241.8]	[242.5, 284.0]	[449.3, 525.8]
Phosphorus discharge from agricultural activity:	1	0.2	[5.3, 7.0]	[22.0, 25.9]	[11.7, 14.4]	[15.5, 18.6]	[36.9, 42.8]
	2	0.6	[10.5, 14.0]	[44.0, 51.8]	[23.4, 28.8]	[31.0, 37.2]	[73.9, 85.5]
	3	0.2	[21.0, 21.0]	[88.0, 77.7]	[46.9, 43.3]	[62.1, 55.8]	[147.9, 128.3]
Nitrogen discharge from fishery activity:	1	0.2	[5.5, 6.3]	[11.3, 13.3]	[7.7, 8.9]	[8.9, 10.5]	[16.6, 19.5]
	2	0.6	[10.9, 12.5]	[22.6, 26.7]	[15.3, 17.9]	[17.9, 21.3]	[33.3, 38.9]
	3	0.2	[16.4, 18.8]	[33.9, 39.7]	[23.0, 26.9]	[27.0, 31.6]	[49.9, 58.4]
Phosphorus discharge from agricultural activity:	1	0.2	[0.6, 0.8]	[2.5, 2.8]	[1.3, 1.6]	[1.7, 2.1]	[4.1, 4.7]
	2	0.6	[1.2, 1.6]	[4. 9, 5.7]	[2.6, 3.2]	[3.4, 4.1]	[8.2, 9.5]
	3	0.2	[2.3, 2.6]	[8.6, 9.8]	[4.8, 5.2]	[6.2, 6.9]	[14.3, 16.4]

(10) Technical constraints:

$$TA_{i,j}^{-} + \Delta TA_{i,j} u_{i,j} \geq DA_{i,j,k,l}^{\pm} \geq 0, \ \forall i, j, k, l \tag{10k$_1$}$$

$$TF_{i,j}^{-} + \Delta TF_{i,j} v_{i,j} \geq DF_{i,j,k,l}^{\pm} \geq 0, \ \forall i, j, k, l \tag{10k$_2$}$$

$$TL_{i,j}^{-} + \Delta TL_{i,j} w_{i,j} \geq DL_{i,j,k,l}^{\pm} \geq 0, \ \forall i, j, k, l \tag{10k$_3$}$$

$$TI_{i,j}^{-} + \Delta TI_{i,j} x_{i,j} \geq DI_{i,j,k,l}^{\pm} \geq 0, \ \forall i, j, k, l \tag{10k$_4$}$$

$$TW_{i,j}^{-} + \Delta TW_{i,j} y_{i,j} \geq DW_{i,j,k,l}^{\pm} \geq 0, \ \forall i, j, k, l \tag{10k$_5$}$$

$$0 \leq u_{ij}, v_{ij}, w_{ij}, x_{ij}, y_{ij} \leq 1, \ \forall i, j \tag{10k$_6$}$$

Table 4. Economic Data of Agricultural Activity (RMB¥ 10^6/km^2)

	Paddy farm	Dry farm	Fruit/vegetable
Net benefit from agricultural activity:			
zone 1	[1.33,1.80]	[0.69, 0.93]	[2.28, 3.08]
zone 2	[1.15, 1.55]	[0.64, 0.86]	[1.01, 1.36]
zone 3	[1.12, 1.51]	[0.58, 0.78]	[2.23, 3.02]
zone 4	[1.22, 1.65]	[0.61, 0.82]	[1.68, 2.27]
zone 5	[1.18,1.59]	[0.61, 0.82]	[1.91, 2.58]
Reduction of net benefit due to excess pollutant discharge:			
soil loss	[2.25, 3.94]	[1.50, 2.63]	[0.75, 1.69]
dissolved nitrogen	[0.83, 2.10]	[1.20, 2.44]	[0.60, 1.22]
dissolved phosphorus	[0.38, 0.94]	[0.94, 2.11]	[0.45, 1.13]

The detailed nomenclatures for the variables and parameters are provided in the Appendix. The study area consists of five subareas (i.e. zone 1 to zone 5), each of which has different industrial and agricultural activities. The quality of data collected cannot allow the parameters to be determined precisely. To closely reflect the real-world complexities and avoid losses of valuable information, all of the parameters are thus inputted with uncertain values. Tables 1 and 2 present the distributional information of allowable soil loss and COD discharge, and three scenarios related to different river water qualities are implemented. Under scenario 1, water quality regulation is aimed at controlling soil losses and mitigating pollutant discharges are implemented; this may lead to low pollutant emission and low soil loss. Scenario 2 targeted at achieving a balance between economic and environmental objectives, where moderate schemes on both pollution control and economic development would be expected. In scenario 3, environmental conservation is placed in a less important position than economic development, corresponding to a set of lenient environmental constraints. Table 3 lists the allowable dissolved nitrogen and phosphorus discharges, which are mainly from agricultural and fishery activities. Due to the excessive application of animal manure and commercial fertilizer in watershed system, unused nutrients are transported to the canal water via soil erosion and surface runoff. Table 4 presents the economic data related to agricultural activities, which are presented as intervals. The net benefit represents the profit gained from agricultural activity, while the cost coefficient represents the penalty associated with the violation of environmental constraints.

4. Results and Discussion

In this study, a set of probabilistic constraints on allowances of soil loss and COD discharge are considered, which can help examine the risks of river water-quality violation and generate desired regional economy development schemes under uncertainty. Variations in p_h levels correspond to the decision makers' preferences regarding the trade-off between the system benefit and the constraint-violation risk. Figure 2 presents the solution of net system benefit ($f^{\pm}$) under different p_h levels. Any change in p_h value would yield different system benefits, and the trend of $f^{\pm}$ variation along with the p_h level would demonstrate a tradeoff between economic objective and constraint-violation risk. Generally, an increased p_h level

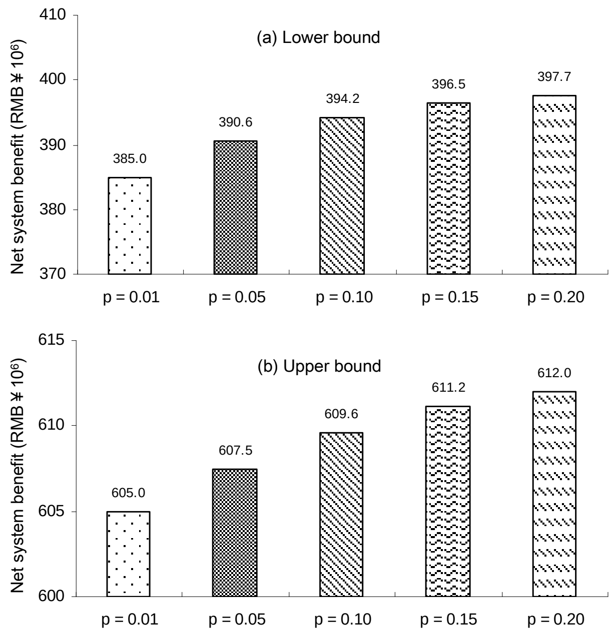

Figure 2. Net system benefits under p_h levels.

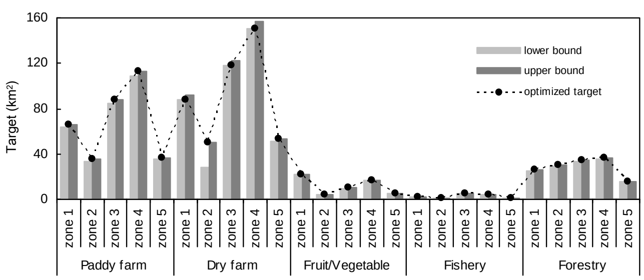

Figure 3. Optimized targets of farmland, fishery and forestry.

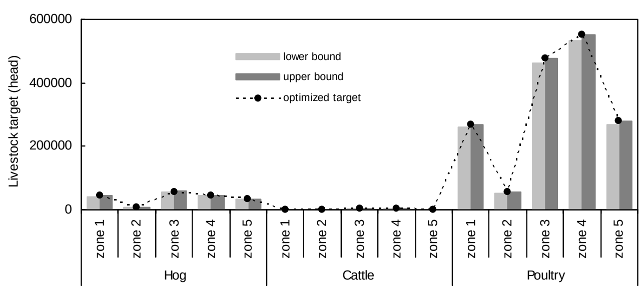

Figure 4. Optimized target of livestock production.

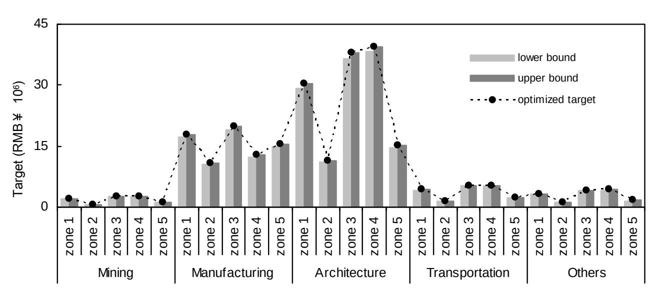

Figure 5. Optimized targets of various industries.

implies a raised risk of violating pollutant-discharge constraints, leading to a decreased strictness for the constraints and thus an increased $f^{\pm}$ value (from RMB¥ [385.0, 605.0] × 10^6 under p = 0.01 to RMB¥ [397.7, 612.0] × 10^6 under p = 0.20). Such increased benefits, however, would be associated with raised pollutant discharges and thus amplified constraint-violation risks. These demonstrate that the tradeoff between the system benefit and the system-failure risk must be analyzed. In addition, the system benefit includes incomes from five sectors such as agriculture, fishery, livestock, industry and forestry, and the detailed incomes of differrent economic activities under varied p_h levels are listed in Table 5. Results showed that agriculture and fishery are the major contributors to the local economy and income for each sector would vary with p_h level.

Through solving the ITWQM model, the optimized targets for various economic activities (i.e. agriculture, fishery, livestock, industry, and forestry) can obtained, as shown in Figures 3 to 5. In general, when the targeted values reach their lower bounds (e.g., dry farm in zone 1), the corresponding policy may result in less pollutant discharge and thus lower penalty (due to excess effluent discharge) but, at the same time, lower system benefit would be achieved. This may not be beneficial to booming the local economy development since the study area is one of the poorest rural regions of China. Conversely, the upper bounds of targets correspond to an optimistic strategy (e.g., paddy farm in zone 1). Under such a condition, a plan with aggressive economic development is generated, resulting a higher system benefit but, at the same time, a higher risk of penalty when the regulated environmental requirement is violated. Probabilistic surplus pollutant discharge would occur if the targets are pre-regulated too high; excess pollutant discharges would lead to economic penalties due to violating environmental requirements (as listed in Table 5). Enlarged cropping area and expanded livestock husbandry would lead to more economic penalties due to increased pollutant discharges and soil losses. Effective pollution control measures have to be adopted for the two sectors. Therefore, different policies in pre-regulating the economic activity are associated with different levels of benefit, penalty and system-failure risk.

Soil erosion has become a major environmental problem in the study area. High levels of forestry activities and the reclamation of hilly areas, wastelands and steep slopes have increased the rate of soil erosion in the area. This, along with the increase in paddy and vegetable farming, has added to the amounts of sediment found in the river. Figure 6 provides the results for soil losses under scenario 1. Results indicated that the amount of soil loss would increase when p_h level is raised, due to the amplified allowance for soil loss. For example, for agricultural activity in zone 1, the amount of soil loss would be [51.4, 68.9] × 10^3 tonne when p = 0.01; the amount of soil loss would increase to [80.5, 100.9] × 10^3 tonne when p = 0.20. The results also showed that the farmland is the main source of soil loss in the watershed. For example, when p = 0.01, the total amount of soil losses would be [341.5, 515.9] × 10^3 tonne, while the amount of soil loss discharged from

Table 5. Penalties and Incomes under Different p_h Levels (unit: RMB¥10^6)

	p_h level	0.01	0.05	0.10	0.15	0.20
Economic penalties due to excess discharge:	Agriculture	[594.7, 613.0]	[593.4, 610.2]	[592.3, 608.3]	[591.5, 607.0]	[591.1, 606.4]
	Fishery	[19.1, 31.0]	[18.4, 29.3]	[17.7, 28.3]	[17.3, 27.6]	[17.1, 27.4]
	Livestock	[454.6, 459.5]	[454.4, 458.8]	[454.2, 458.5]	[454.1, 458.3]	[453.9, 458.1]
	Industry	[220.1, 229.0]	[219.9, 228.6]	[219.7, 228.3]	[219.6, 228.1]	[219.6, 228.0]
	Forestry	[5.3, 17.7]	[5.2, 17.6]	[5.2, 17.6]	[5.1, 17.5]	[5.1, 17.5]
Incomes from various activities:	Agriculture	[198.3, 306.7]	[201.1, 308.0]	[203.0, 309.1]	[204.3, 309.0]	[204.9, 310.3]
	Fishery	[113.19, 171.8]	[114.9,172.5]	[114.9, 173.2]	[116.6, 173.6]	[116.8, 173.8]
	Livestock	[42.4, 72.6]	[43.0, 72.9]	[43.0, 73.0]	[43.5, 73.2]	[43.7, 73.3]
	Industry	[24.6, 33.5]	[25.0, 33.7]	[25.0, 33.9]	[25.5, 34.0]	[25.6, 34.0]
	Forestry	[6.5, 20.3]	[6.6, 20.4]	[6.6, 20.4]	[6.7, 20.5]	[6.7, 20.5]

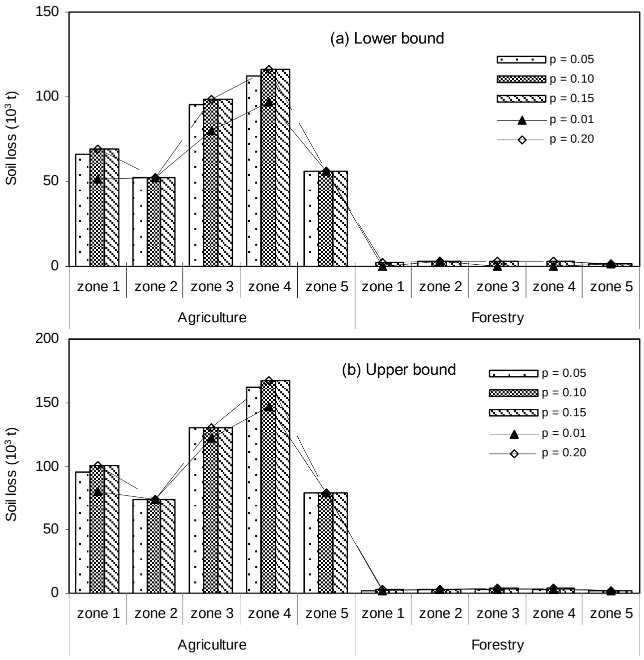

Figure 6. Results of soil loss under scenario 1.

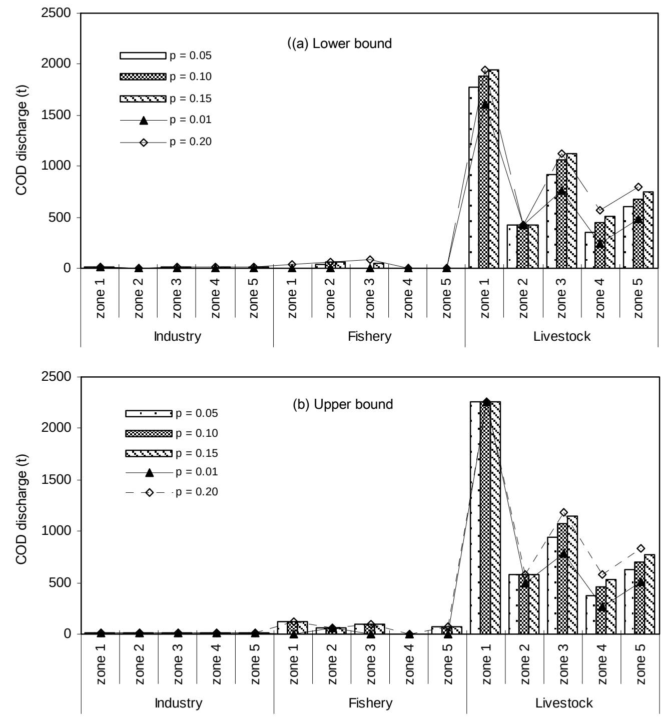

Figure 7. Results of COD discharge under scenario 1.

agriculture is [281.4, 502.0] × 10^3 tonne (occupying approximately [82.4, 97.3]% of the total soil losses). In general, agricultural activity is associated with nonpoint source pollution due to sediments from eroded or overgrazed lands, pesticides, nutrients, and other chemicals; the wash-off of effluents through runoff process resulted in serious environmental concerns to the downstream water quality in the study area. Excess soil loss could be controlled by abating extensive land uses for fruit / vegetable, paddy and dry farms. However, agriculture is the biggest contributor to the local economy in the rural area. The tradeoff between agricultural income and sediment pollution control would be of concern for the local authority in the future.

Figure 7 presents COD discharges under scenario1. The results indicate that (i) the amount of COD discharged from each source would be lifted up along with increasing p_h level, (ii) the livestock production (i.e. hogs, cattle and poultry) generates a significant amount of COD such that any consideration for COD reduction should focus on the related livestock husbandry, and (iii) the amount of COD discharged from industrial activities possesses an increasing tread since industry is promoted by the authority in the recent years to boost up the local economy income. Under scenario 1, the total amounts of COD would be [3541.2, 4578.3] tonne when p = 0.01 and [5088.3, 5821.7] tonne when p = 0.20, where the livestock contributed to 98.5% and 94.4% of the total COD, respectively. Wastewaters from livestock husbanddry are high in COD and nutrient levels. Unfortunately, most local farmers lack resources and capitals to treat these wastewaters, and thus lead to wastewaters discharged directly into the river. This has a high impact on the surface water quality of the area. Figure 8 presents COD discharges under scenario 3, which are all higher than the amounts of COD under scenario 1. Under scenario 3, the total amounts of COD would be [6847.9, 7904.7], [7232.9, 8573.3], [7547.9, 9031.1], [7891.3, 9236.9] and [8173.0, 9339.4] tonne under p_h levels of 0.01, 0.05, 0.10,

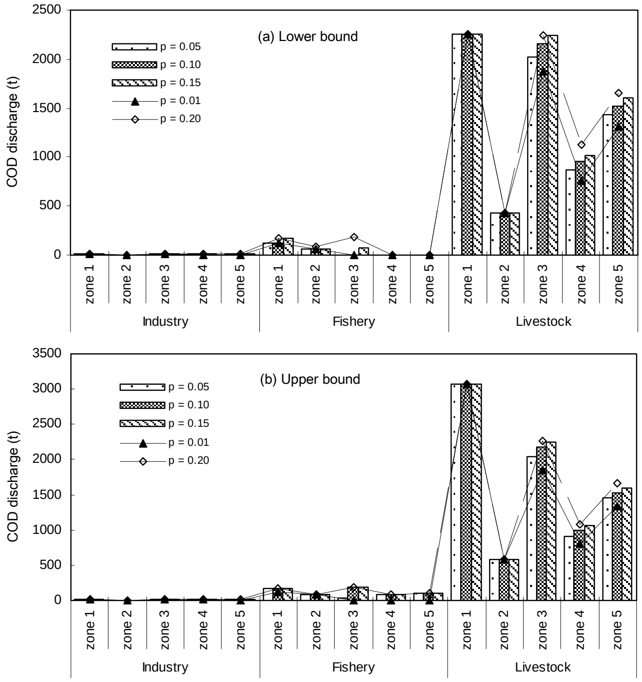

Figure 8. Results of COD discharge under scenario 3.

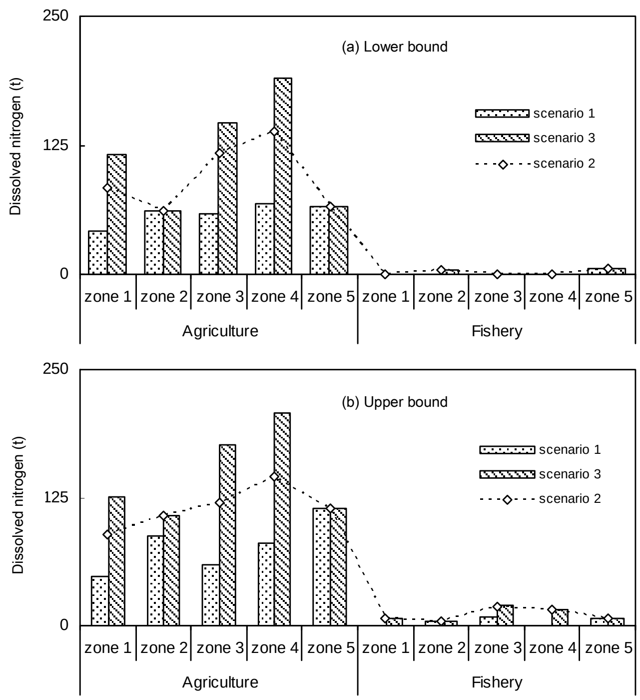

Figure 9. Results of dissolved nitrogen loss.

0.15 and 0.20, respectively. This is due to the fact that, under scenario 3, preferential policies towards the economic development, such as higher emission allowance and resources cap, were adopted for stimulating regional economic growth.

The river water quality in the study area has begun to deteriorate due to the increments in agricultural and industrial activities that have resulted in continuous increases of

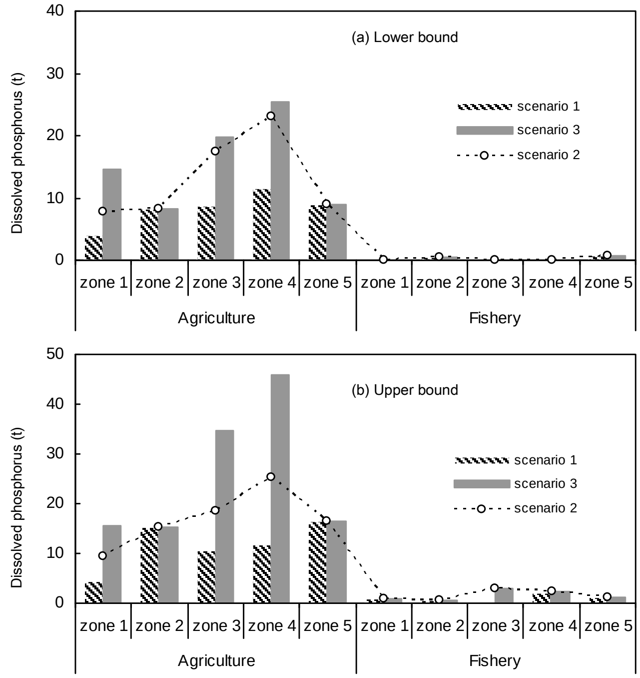

Figure 10. Results of dissolved phosphorus loss.

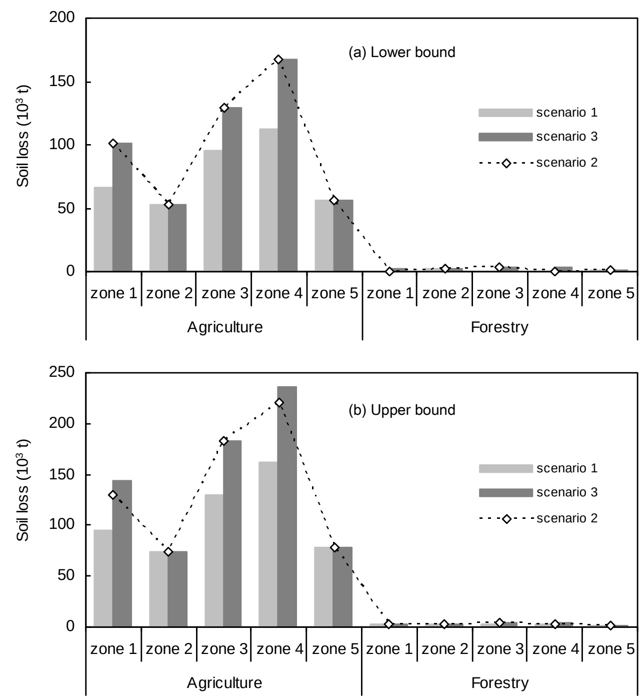

Figure 11. Results of soil loss (p = 0.05).

pollutant discharges. High nutrient discharges (especially in the forms of nitrides and phosphates) from agricultural lands have augmented the organic content of the surface water. Figures 9 and 10 present the results of dissolved nitrogen and phosphorous losses that mainly come from agricultural and fishery activities under different scenarios. Different scenarios correspond to different policies (priorities) for economic development and environmental protection. The total dissolved nitrogen losses would be [301.9, 410.1], [475.3, 629.5] and [587.6, 787.0] tonne under scenarios 1 to 3, respectively, implying an increasing trend; agriculture accounted for 96.6, 94.8 and 95.7% of the total dissolved nitrogen loss under the three scenarios, respectively. The total amounts of dissolved phosphorous losses would be [42.5, 63.1], [66.6, 92.8] and [78.3, 135.9] tonne under scenarios 1 to 3, respectively; dissolved phosphorous losses in the watershed can be attributed to agricultural activity (i.e. 94.8, 94.9 and 96.3% under the three scenarios, respectively). The amounts of soil losses also increased from scenario 1 to scenario 3, as shown in Figure 11. Farmland contributed to 98.4, 97.5 and 98.2% of total soil losses, respectively. The results demonstrated that (i) agricultural activities are responsible for pollutant emission and soil loss under all of the scenarios, (ii) aggressive economic development policy (i.e. scenario 3) would be associated with high profits, while paying a significant cost of environmental deterioration, and (iii) conservative development policy (i.e. scenario 1) would lead to reduced environmental risks, but might miss economic development opportunities.

5. Conclusions

An inexact two-stage chance-constrained programming (ITCP) method has been advanced to allow uncertainties presented as both probability distributions and discrete intervals to be effectively incorporated within the optimization framework. Besides, ITCP can help examine the reliability of satisfying (or risk of violating) system constraints under uncertainty. Based on the ITCP technique, an inexact two-stage water quality management (ITWQM) model has been formulated for supporting economic and environmental sustainable development of Yongxin County in the Heshui Watershed. Pollutant emissions generated by various point and non-point sources (i.e. agriculture, fishery, livestock, industry and forestry) are considered simultaneously; COD discharge and soil loss are allowed under a range of relaxed constraints in association with a variety of probabilities. Three scenarios with different economic and environmental objectives have been examined to investigate the effects of different policies on regional sustainable development decisions. Interval solutions for production activities and pollutant emissions under varied p_h levels are generated through solving a set of deterministic submodels subsequently.

The results indicate that agriculture is the main income source for the study area among all economic activities, while the extensive agricultural activities are also responsible for pollutant emission (nitrogen and phosphorous) and soil loss under all scenarios. Control of the serious erosion problem is necessary for ensuring the continued success of agricultural production in the area and environmental sustainability. The COD discharge is mainly derived from livestock husbandry activities (i.e. hog, cattle and poultry), and any consideration for COD reduction should focus on the related livestock activities in the future. Fishery farm accounts for a high percentage of nitrogen and phosphorous losses, and the second contribution to the overall net benefit. The amount of pollutant discharged from industry possesses an increasing tread since various industrial activities are promoted by the authority in order to boost up the local economy income. Summarily, the results obtained can be used to generate decision alternatives and help local managers to identify desired policies under various environmental, economic, and system-reliability conditions. Detailed schemes for economic development and environmental management can be designed based on modeling outputs. Decisions at a lower risk level (i.e. p_h level) would lead to an increased reliability in fulfilling environmental requirements but with a reduced system benefit; conversely, a strong desire for increasing system benefit could run into a raised risk of violating environmental constraints. Therefore, different policies in predefining the economic production would reflect a tradeoff between the system benefit and the constraint violation risk.

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