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A water quality management model considering impacts of water utilization and providing risk analysis under uncertainty: a case study of the Ankang section in Hanjiang River Basin, China

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ABSTRACT

In this study, an interval-parameter chanced-constrained full-infinite programming (ICFP) model based on Monte Carlo simulation is proposed for supporting water quality management under uncertainty (expressed as interval parameters, probability distribution, and functional intervals), and analyzing the reliability of satisfying (or the risk of violating) various constraints. The ICFP model was applied to investigate the utility of the model for managing industry development under water quality constraints in the Ankang section of the Hanjiang River Basin, which faces threats of point and nonpoint source pollution. The research area is one of the water sources of the South-to-North Water Diversion, which is a national strategic project aimed at mitigating the water shortage in north and northwest China. The results indicated that higher discharge amounts of chemical oxygen demand occur at the medicine manufacturing industry. Tradeoffs between economic benefits and system-failure risks were also examined. Alternative policy can be obtained from different combinations of decision variables within their lower and upper bounds, which are valuable for decision makers, who need to develop the desired regional economic plans while satisfying environmental requirements.

Keywords: Water quality management; Industry development; Probability distribution; Waste-load allocation; Uncertainty

1. Introduction

Large volumes of industrial and agricultural waste and inadequately treated sewage are discharged into natural water sources every year, leading to a reduction of clean drinking water supply and the compromising of aquatic ecosystems [1]. In recent years, some cities in China have faced the crisis of continuous deterioration of water quality because of the rapid development of the economy. In mid-March 2014, according to the data released by the Ministry of Environmental Protection, residential areas populated by a total of 2.5 billion people were located near to key polluting enterprises and transport routes; consequently, 2.8 billion people currently use unsafe drinking water. More seriously, the poor water environment leads to a reduction in agricultural productivity, economic loss, and a poor living environment which severely endangers human health. Although some beneficial actions have been adopted, it is difficult to fully understand and quantify the interactions between local industrial development and the water environment.

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This understanding is essential to facilitate well-informed decisions regarding placement of new industries and the adaptation of existing industrial production [2,3].

Over the past decade, much research has been conducted for developing reliable theoretical and decision-making models for improving the water environment [2,4–7]. Certain models have proven useful for aiding stakeholders in the decision-making process, such as the quality simulation along river system (QUASAR) model developed from the Bedford Ouse river water environmental management model [8], the Water Quality Analysis Simulation Program (WASP) model developed by the US Environmental Protection Agency [9,10], and the MIKE model developed by the Danish Hydraulic Institute [11]. These studies could, for example, include simulating variability in water quantity and quality fluxes for different spatial and temporal scales, which requires an accurate assessment of a number of features such as resident population, industry and commercial activities, surface cover, topography, and urban form.

Nevertheless, these previous studies inadequately addressed the variety of uncertainties existing in water quality management challenges. According to Refsgaard [11], these uncertainties originate from not only the water environment itself, but also from insufficient knowledge of the various physical and biochemical processes occurring in the water environment. In actual fact, many system components and their interrelationships are characterized by various uncertainties that might affect relevant decision-making based on optimization analyses [12]. For example, the volume and pollution content of wastewater flows vary with the industrial units, generated products, and product amounts, leading to temporal and spatial variations in pollutant loading among multiple point sources; nonpoint sources are difficult or impossible to trace to a source and enter the receiving water over an extensive area with sporadic time frames and are related to many uncertain factors [13,14]. These raise the question of how to effectively address such varied forms of uncertainty. Thus, it is significant to inject increasingly more momentum to water quality management, including considerations for the diversity of management activities, variation of system conditions, uncertainty of impact factors, dynamics of capacity expansion, as well as the associated environmental implications.

As a result, a number of stochastic programming approaches have been developed for tackling uncertainties in water quality management [15–17]. Among them, chance-constrained programming (CCP) can effectively represent the risk of violating system constraints under uncertainty, which is required to hold with at least some level of reliability [18]. According to Li et al. [19], CCP is an effective technique to analyze complex interrelationships among different system elements, and the solutions can provide comprehensive information on economic achievement as a function under the desired probability level of satisfying constraints, and from which the relationship between profitability and reliability can be quantified. Probability distributions of the right-hand side parameters are required in CCP, and a normal (Gaussian) distribution is often considered as an attractive alternative for many random variables. Generally, CCP is suitable for situations where uncertainties can be expressed as the probability distributions of the constraints' right-hand side [20]. Consequently, Huang [21] proposed an inexact-stochastic water management model and applied it to support the decision of water quality management within an agricultural system. Liu et al. [22] formulated an inexact chance-constrained linear programming model for water quality improvement. The model was applied to the Lake Qionghai watershed in China for water quality improvement with the goal of achieving a minimum total cost. Du et al. [23] proposed an inexact chance-constrained waste-load allocation model for water quality management of the Xiangxihe River by addressing uncertainties expressed as intervals and probability distributions as well as analyzing the reliability of satisfying (or the risk of violating) various constraints. However, this method could only solve the problems containing crisp-interval coefficients [a, b], the lower and upper bounds of which (i.e., a and b) were both deterministic and definitely known. For solving problems related to real-world energy systems planning, this definition was not suitable for all cases where the two bounds might be associated with the external impact factors, leading to functional intervals (i.e., lower and upper bounds of intervals are expressed as functions). For example, if N is expressed as a functional interval of [$15.25 \times (2 + a)$, $17.63 \times (1 + a)$]; N is a function of a, ranging between $15.25 \times (2 + a)$ and $17.63 \times (1 + a)$. The full-infinite programming (FIP) method was effective for dealing with uncertainties expressed as crisp intervals and functional intervals [24,25]; however, few applications to water quality management have been reported.

Therefore, the aim of the present study is to advance the interval-parameter chanced-constrained full-infinite programming (ICFP) model based on Monte Carlo simulations to identify optimal decision schemes for relevant industrial, municipal, and agricultural activities on the Ankang section of the Hanjiang River Basin, China. Hanjiang River, the largest tributary of the Yangtze River, has suffered increasingly severe degradation of water quality induced by multiple point and nonpoint sources. The research area is one of the water sources situated in the middle route of the South-to-North Water Diversion, which is a national strategic project aimed at mitigating the water shortage in north and northwest China. Increasing water demands in this region have directly affected the water quality in the Ankang section of the Hanjiang River Basin. By means of the Monte Carlo simulation method, the results from the ICFP model for water supply, scale of industrial production, planting schemes, livestock husbandry size, and manure/fertilizer application rate under various probability levels can be obtained and analyzed sequentially. These results can be useful to help local decision makers to formulate systematical and effective decision alternatives and gain insights into the tradeoff between system benefit and system-failure risk.

2. Study area

Ankang city (N31°42′–33°49′, E108°01′–110°01′) is located in the southeast of Shaanxi Province, with an area of 23.39×10^3 km^2 and a population of 3.1 million people in 2012. The location of Ankang in the Hanjiang River Basin is shown in Fig. 1. Ankang city consists of 10 districts, namely Hanbin, Xunyang, Shiquan, Hanyin, Pingli, Baihe, Ziyang, Langao, Ningshan, and Zhenping. The Hanjiang River crosses over the entire city from west to east, forming the

Fig. 1. Location of Ankang in Hanjiang River Basin.

natural landscape of "two mountains, one river". The city falls within the northern edge of the Northern Subtropical Monsoon Climate Zone and the vertical zonal climate is obvious. The tectonic position of Ankang falls within the southern part of the Qinling Mountains fold system and the northern edge of the Yangtze paraplatform.

Ankang city falls within the Hanjiang River catchment of the Yangtze River Basin, and is a key water source component of the middle route of the South-North Water Diversion Project. Although Ankang city is rich in water resources, the regional distribution of water is uneven and varies wildly. In addition, since 60%–70% of annual runoff occurs during the flood season, meeting the water requirements of the city's industry, agriculture, and residents is a challenge. In addition, drought and flood disasters are key obstacles restricting social and economic development. More seriously, the development of industrial and agricultural production has led to large volumes of wastewater. Agricultural water often being contaminated with pesticides and fertilizers, and along with domestic sewage, is discharged to the environment. According to statistics, approximately 516×10^6 m^3 of wastewater is discharged directly or indirectly into the Hanjiang River upstream of Ankang, whereas approximately 480.60×10^6 m^3 of domestic sewage is discharged into the river downstream of Ankang, with the volumes of wastewater discharged increasing year by year.

In December 2014, the trans-basin water diversion project was put into operation. As a result, deficits between the water supply and demand will also become apparent gradually. Achieving sustainable use of water will become more difficult (especially in the dry season), and the degradation of the aquatic ecology will become severe. Thus, the influence of the above problems on the sustainable development of the society and economy of the river basin cannot be ignored. Ankang is located upstream of the Hanjiang River Basin; therefore, the improper management of water quality will not only affect the development of the local economy (especially tourism), but also result in a serious threat to drinking water sources, even affecting the aquatic environment of Danjiangkou reservoir in the Hanjiang River Basin and the middle route of the South–North Water Diversion Project. Therefore, based on the existing planning arrangements, further strengthening of the management of water resources and the protection of the aquatic environment in the Hanjiang River Basin are critical. At the same time, to meet the water quality requirements of the middle route of the South–North Water Diversion Project, there should be coordination of the relationship between social and economic development and water quality protection, and effective controls should be implemented to halt the input of pollutants into the water body. Therefore, it is vitally necessary to conduct research on effective water management considering industrial development and population growth in the Hanjiang River Basin. The water quality of the water body could be ensured by controlling pollutants emitted to the environment by key polluting enterprises.

Management and planning are the process of making a decision on the basis of a desired future. However, future conditions are often unknown and complex, and coupled with the limitations of human cognitive ability, the management and planning process encompasses many uncertainties. Unless these uncertainties in the system are fully identified, effective and practical decision-making results cannot be achieved. Moreover, some problems and shortcomings of the previous water quality management system persist. First, research on the management of the water environment of Hanjiang River remains at the stage of assessing advanced internationally developed models, and most studies merely conduct simple applications of these models without due consideration of local conditions, which restricts the development of locally relevant management of the water environment. Second, despite the uncertainty and complexity associated with the water environment, the traditional method of research has been simplistic, and even neglected the complex relationship between internal and external drivers of the water environment; therefore, previous research has been unable to characterize the internal and external components of water environment management systems. Third, few previous studies have focused on both point and nonpoint source pollution in the river basin. Research on the water quality of the Ankang section of the Hanjiang River Basin has been inadequate, which has an effect on the scientific rigor and effectiveness of the management of the water environment of the upper reaches of the Hanjiang River Basin. Fig. 2 represents the water quality management system of the Ankang city section of the Hanjiang River.

3. Model formulation

The study area encompasses the Hanjiang River Basin, which stretches from Ningshan county to Baihe county, covering 340 km of river reach and containing a total of 20 monitoring stations. An interval-parameter chanced-constrained industry-development model was implemented to manage this study area. The research considered the majority of point and nonpoint source pollution affecting the Ankang section. Based on a field survey and relevant literature, biochemical oxygen demand and total nitrogen (TN) were selected as the water quality indicators to determine a water pollution control program. Eight kinds of major point sources along the river were selected in the study area, including toxic metal production enterprises, yam diosgenin production plants, the pharmaceutical and chemical industries, cement manufacturing, livestock breeding, domestic garbage landfills, county sewage treatment plants, and other sources of pollution. In addition, since nonpoint source pollution generally results from agricultural activities, agricultural planting areas in each district and some counties (Hanbin district and the counties of Hanyin, Shiquan, Ningshan, Ziyang, Langao, Pingli, Zhenping, Xunyang, and Baihe) were characterized. Both point and nonpoint source pollutants are generally discharged into rivers, resulting in the rivers' ability to accept and degrade pollutants being compromised and water quality problems emerging. To protect the water environment and water ecosystem in the Ankang area, improved management of pollutant discharge is urgently required. Policy makers are responsible for the reasonable distribution of pollution load for eight key point sources and 10 counties (mainly agricultural area). In addition, the model should address the uncertainty within the information available for the water environment of the Ankang section. Therefore, the ICFP model could be established for the Ankang section of the Hanjiang River as follows:

$$\begin{aligned}
\mathrm{MAX}\, f^{\pm} &= \sum_{i=1}^{8}\sum_{p=1}^{2} L_p^{\pm} \times \alpha_{ip}^{\pm} \times \mathrm{XG}_{ip}^{\pm} + \sum_{j=1}^{10}\sum_{p=1}^{2} L_p^{\pm} \times \beta_{jp}^{\pm} \\
&\times \mathrm{GS}_{jp}^{\pm} + \sum_{s=1}^{4} \mathrm{SC}_S^{\pm} \times \left(\chi_s^{\pm} - \delta_s^{\pm}\right) + \sum_{j=1}^{10}\sum_{k=1}^{6} \mathrm{ZGL}_{jk}^{\pm} \times \varepsilon_{jk}^{\pm} \\
&\times \mathrm{CM}_{jk}^{\pm} + \sum_{j=1}^{10}\sum_{k=7}^{12}\sum_{p=1}^{2} \mathrm{ZGL}_{jkp}^{\pm} \times \varepsilon_{jkp}^{\pm} \times \mathrm{CM}_{jkp}^{\pm} \\
&- \sum_{i=1}^{8}\sum_{j=1}^{8}\sum_{p=1}^{2} L_p^{\pm} \times \varphi_{ip}^{\pm} \times \mathrm{GS}_{jp}^{\pm} \times \left(1 - \mathrm{CWR}_{jp}^{\pm}\right) \\
&- \sum_{i=1}^{8}\sum_{p=1}^{2} L_p^{\pm} \times \phi_{ip}^{\pm} \times \mathrm{XG}_{ip}^{\pm} \times \mathrm{QFL}_{ip}^{\pm} \times \left(1 - \mathrm{QFB}_{ip}^{\pm}\right) \\
&- \sum_{j=1}^{10}\sum_{k=1}^{12}\sum_{p=1}^{4} \gamma_{jp}^{\pm} \times \mathrm{MR}_{jkp}^{\pm} - \sum_{j=1}^{10}\sum_{k=1}^{12}\sum_{p=1}^{2} \eta_{jp}^{\pm} \\
&\times \mathrm{HR}_{jkp}^{\pm}
\end{aligned} \tag{1-1}$$

Eq. (1-1) is the formulation of the proposed model through maximizing the benefit of industry development, water supply, aquaculture, and agricultural production, whereas the costs comprise wastewater treatment, fecal collection, and chemical fertilizers. The constraints of the ICFP model are associated with the local economy and environmental requirements as follows:

(1) Chemical oxygen demand (COD) emission constraints:

$$\begin{aligned}
&\mathrm{XG}_{ip}^{\pm} \times \mathrm{QFL}_{ip}^{\pm}\left(1 - \mathrm{QFB}_{ip}^{\pm}\right) \times \mathrm{QO}_{\mathrm{BOD},ip}^{\pm} \\
&\quad \times \left(1 - \mathrm{QW}_{\mathrm{BOD},ip}^{\pm}\right) \le \mathrm{QYL}_{\mathrm{BOD},ip}^{\pm}
\end{aligned} \tag{1-2a}$$

$$\begin{aligned}
&\mathrm{GS}_{jp}^{\pm} \times \mathrm{CWG}_{jp}^{\pm} \times \mathrm{CW}_{\mathrm{BOD},jp}^{\pm} \times \left(1 - \mathrm{CWR}_{jp}^{\pm}\right) \\
&\quad \times \left(1 - \mathrm{CB}_{\mathrm{BOD},jp}^{\pm}\right) \le \mathrm{CWL}_{\mathrm{BOD},jp}^{\pm}
\end{aligned} \tag{1-2b}$$

(2) Nitrogen emission constraints:

$$\begin{aligned}
&\sum_{k=1}^{6}\left(\mathrm{CNB}_{\mathrm{TN},j}^{\pm} \times \mathrm{CLL}_{kp}^{\pm} + \mathrm{CDJ}_{kp}^{\pm} \times \mathrm{DJN}_{\mathrm{TN},jkp}^{\pm}\right) \times \mathrm{CM}_{jkp}^{\pm} + \Delta 1 \\
&\times \left[\sum_{k=7}^{8}\left(\mathrm{CNB}_{\mathrm{TN},j}^{\pm} \times \mathrm{CLL}_{kp}^{\pm} + \mathrm{CDJ}_{kp}^{\pm} \times \mathrm{DJN}_{\mathrm{TN},jkp}^{\pm}\right) \times \mathrm{CM}_{jkp}^{\pm}\right] \\
&+ \Delta 2 \times \left[\sum_{k=9}^{12}\left(\mathrm{CNB}_{\mathrm{TN},j}^{\pm} \times \mathrm{CLL}_{kp}^{\pm} + \mathrm{CDJ}_{kp}^{\pm} \times \mathrm{DJN}_{\mathrm{TN},jkp}^{\pm}\right) \times \mathrm{CM}_{jkp}^{\pm}\right] \\
&\le \mathrm{CYN}_{\mathrm{TN},jp}^{\pm} \times \mathrm{SL}_{jp}^{\pm}
\end{aligned} \tag{1-2c}$$

$$\begin{aligned}
&(\mathrm{CSB}_p^{\pm} \times \sum_{s=1}^{4} \mathrm{SF}_s^{\pm} \times \mathrm{SC}_s^{\pm} \times \mathrm{FLB}_p^{\pm} \times \mathrm{ZNB}_{\mathrm{TN},M1}^{\pm} + L_p^{\pm} \times \mathrm{HF}_p^{\pm} \\
&\times \mathrm{VCE}_p^{\pm} \times \mathrm{FLB}_p^{\pm} \times \mathrm{ZNB}_{\mathrm{TN},M1}^{\pm} - \sum_{j=1}^{10}\sum_{k=1}^{6} \mathrm{MR}_{jkp}^{\pm} \times \mathrm{FLB}_p^{\pm} \\
&\times \mathrm{ZNB}_{\mathrm{TN},M1}^{\pm} - \Delta 1 \times \sum_{j=1}^{10}\sum_{k=7}^{8} \mathrm{MR}_{jkp}^{\pm} \times \mathrm{FLB}_p^{\pm} \times \mathrm{ZNB}_{\mathrm{TN},M1}^{\pm} \\
&- \Delta 2 \times \sum_{j=1}^{10}\sum_{k=9}^{12} \mathrm{MR}_{jkp}^{\pm} \times \mathrm{FLB}_p^{\pm} \times \mathrm{ZNB}_{\mathrm{TN},M1}^{\pm} + L_p^{\pm} \times \mathrm{VCE}_p^{\pm} \\
&\times \mathrm{DE}_p^{\pm} \times \mathrm{VFB}_p^{\pm} \times \mathrm{VWN}_{\mathrm{TN},p}^{\pm}) \le \mathrm{VYP}_{\mathrm{TN},p}^{\pm}
\end{aligned} \tag{1-2d}$$

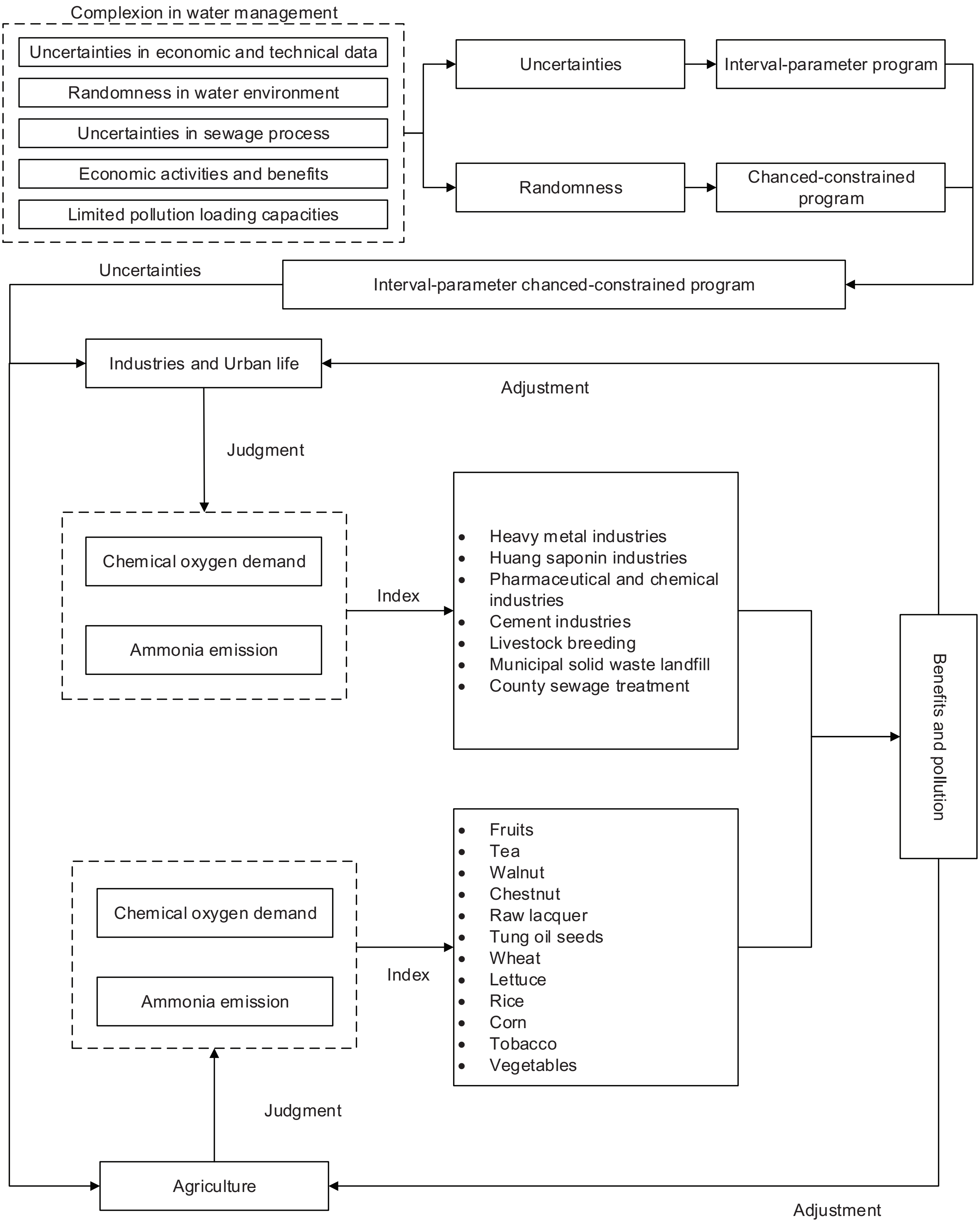

Fig. 2. Water quality management system in Ankang city section of Hanjiang River.

$$\begin{aligned}&\Big\{\sum_{j=1}^{10}\sum_{k=1}^{6}\left(\mathrm{CNB}_{\mathrm{TN},j}^{\pm}\times\mathrm{CLL}_{kp}^{\pm}+\mathrm{CDJ}_{kp}^{\pm}\times\mathrm{DJN}_{\mathrm{TN},jkp}^{\pm}\right)\times\mathrm{CM}_{jkp}^{\pm}\\&+\Delta1\times\left[\sum_{j=1}^{10}\sum_{k=7}^{8}\left(\mathrm{CNB}_{\mathrm{TN},j}^{\pm}\times\mathrm{CLL}_{kp}^{\pm}+\mathrm{CDJ}_{kp}^{\pm}\times\mathrm{DJN}_{\mathrm{TN},jkp}^{\pm}\right)\times\mathrm{CM}_{jkp}^{\pm}\right]\\&+\Delta2\times\left[\sum_{j=1}^{10}\sum_{k=9}^{12}\left(\mathrm{CNB}_{\mathrm{TN},j}^{\pm}\times\mathrm{CLL}_{kp}^{\pm}+\mathrm{CDJ}_{kp}^{\pm}\times\mathrm{DJN}_{\mathrm{TN},jkp}^{\pm}\right)\times\mathrm{CM}_{jkp}^{\pm}\right]\\&+\mathrm{CFB}_{jp}^{\pm}\times\sum_{s=1}^{4}\mathrm{SF}_{s}^{\pm}\times\mathrm{SC}_{s}^{\pm}\times\mathrm{FLB}_{p}^{\pm}\times\mathrm{ZNB}_{\mathrm{TN},M1}^{\pm}+L_{p}^{\pm}\times\mathrm{HF}_{p}^{\pm}\times\mathrm{VCE}_{p}^{\pm}\\&\times\mathrm{FLB}_{p}^{\pm}\times\mathrm{ZNB}_{\mathrm{TN},M1}^{\pm}-\sum_{j=1}^{10}\sum_{k=1}^{6}\mathrm{MR}_{jkp}^{\pm}\times\mathrm{FLB}_{p}^{\pm}\times\mathrm{ZNB}_{\mathrm{TN},M1}^{\pm}\\&-\Delta1\times\sum_{j=1}^{10}\sum_{k=7}^{8}\mathrm{MR}_{jkp}^{\pm}\times\mathrm{FLB}_{p}^{\pm}\times\mathrm{ZNB}_{\mathrm{TN},M1}^{\pm}\\&-\Delta2\times\sum_{j=1}^{10}\sum_{k=9}^{12}\mathrm{MR}_{jkp}^{\pm}\times\mathrm{FLB}_{p}^{\pm}\times\mathrm{ZNB}_{\mathrm{TN},M1}^{\pm}\Big\}\le\mathrm{AYN}_{TN,p}^{(q)}\end{aligned}\tag{1-2e}$$

(3) Soil loss constraints:

$$\begin{aligned}&\sum_{k=1}^{6}\mathrm{CLL}_{kp}^{\pm}\times\mathrm{CM}_{jkp}^{\pm}+\Delta1\times\sum_{k=7}^{8}\mathrm{CLL}_{kp}^{\pm}\times\mathrm{CM}_{jkp}^{\pm}\\&+\Delta2\times\sum_{k=9}^{12}\mathrm{CLL}_{kp}^{\pm}\times\mathrm{CM}_{jkp}^{\pm}\le\mathrm{HYT}_{p}^{\pm}\times\mathrm{SL}_{jp}^{\pm}\end{aligned}\tag{1-2f}$$

(4) Fertilizer and manure constraints:

$$\begin{aligned}&\left(1-\mathrm{MR}_{\mathrm{TN},p}^{\pm}\right)\times\mathrm{ENB}_{F1}^{\pm}\times\mathrm{HR}_{jkp}^{\pm}+\left(1-\mathrm{FNB}_{\mathrm{TN},p}^{\pm}\right)\\&\times\mathrm{ZNB}_{\mathrm{TN},M1}^{\pm}\times\mathrm{MR}_{jkp}^{\pm}-\mathrm{MR}_{\mathrm{TN},jkp}^{\pm}\times\mathrm{CM}_{jkp}^{\pm}\ge0\end{aligned}\tag{1-2g}$$

$$\mathrm{EPB}_{F2}^{\pm}\times\mathrm{HR}_{jkp}^{\pm}+\mathrm{FPB}_{\mathrm{TP},M2}^{\pm}\times\mathrm{MR}_{jkp}^{\pm}-\mathrm{CNX}_{\mathrm{TN},jkp}^{\pm}\times\mathrm{CM}_{jkp}^{\pm}\ge0\tag{1-2h}$$

$$\begin{aligned}&\sum_{k=1}^{6}\left(\mathrm{ENB}_{F1}^{\pm}\times\mathrm{HR}_{jkp}^{\pm}+\mathrm{ZNB}_{\mathrm{TN},M1}^{\pm}\times\mathrm{MR}_{jkp}^{\pm}-\mathrm{MR}_{\mathrm{TN},jkp}^{\pm}\times\mathrm{CM}_{jkp}^{\pm}\right)\\&+\Delta1\times\sum_{k=7}^{8}\left(\mathrm{ENB}_{F1}^{\pm}\times\mathrm{HR}_{jkp}^{\pm}+\mathrm{ZNB}_{\mathrm{TN},M1}^{\pm}\times\mathrm{MR}_{jkp}^{\pm}-\mathrm{MR}_{\mathrm{TN},jkp}^{\pm}\times\mathrm{CM}_{jkp}^{\pm}\right)\\&+\Delta2\times\sum_{k=9}^{12}\left(\mathrm{ENB}_{F1}^{\pm}\times\mathrm{HR}_{jkp}^{\pm}+\mathrm{ZNB}_{TN,M1}^{\pm}\times\mathrm{MR}_{jkp}^{\pm}-\mathrm{MR}_{\mathrm{TN},jkp}^{\pm}\times\mathrm{CM}_{jkp}^{\pm}\right)\\&\le\mathrm{CYN}_{\mathrm{TN},jp}^{\pm}\times\mathrm{SL}_{jp}^{\pm}\end{aligned}\tag{1-2i}$$

$$\begin{aligned}&\sum_{k=1}^{6}\left(\mathrm{EPB}_{F2}^{\pm}\times\mathrm{HR}_{jkp}^{\pm}+\mathrm{FPB}_{\mathrm{TP},M2}^{\pm}\times\mathrm{MR}_{jkp}^{\pm}-\mathrm{CNX}_{\mathrm{TN},jkp}^{\pm}\times\mathrm{CM}_{jkp}^{\pm}\right)\\&+\Delta1\times\sum_{k=7}^{8}\left(\mathrm{EPB}_{F2}^{\pm}\times\mathrm{HR}_{jkp}^{\pm}+\mathrm{FPB}_{\mathrm{TP},M2}^{\pm}\times\mathrm{MR}_{jkp}^{\pm}-\mathrm{CNX}_{\mathrm{TN},jkp}^{\pm}\times\mathrm{CM}_{jkp}^{\pm}\right)\\&+\Delta2\times\sum_{k=9}^{12}\left(\mathrm{EPB}_{F2}^{\pm}\times\mathrm{HR}_{jkp}^{\pm}+\mathrm{FPB}_{\mathrm{TP},M2}^{\pm}\times\mathrm{MR}_{jkp}^{\pm}-\mathrm{CNX}_{\mathrm{TN},jkp}^{\pm}\times\mathrm{CM}_{jkp}^{\pm}\right)\\&\le\mathrm{CHP}_{\mathrm{TN},jp}^{\pm}\times\mathrm{SL}_{jp}^{\pm}\end{aligned}\tag{1-2j}$$

$$\begin{aligned}&\mathrm{CSB}_{p}^{\pm}\times\sum_{s=1}^{4}\mathrm{SF}_{s}^{\pm}\times\mathrm{SC}_{s}^{\pm}+L_{p}^{\pm}\times\mathrm{HF}_{p}^{\pm}\times\mathrm{VCE}_{p}^{\pm}\\&-\sum_{j=1}^{10}\sum_{k=1}^{6}\mathrm{MR}_{jkp}^{\pm}-\Delta1\times\sum_{j=1}^{10}\sum_{k=7}^{8}\mathrm{MR}_{jkp}^{\pm}\\&-\Delta2\times\sum_{j=1}^{10}\sum_{k=9}^{12}\mathrm{MR}_{jkp}^{\pm}\ge0\end{aligned}\tag{1-2k}$$

(5) Energy and digestible protein requirement constraints:

$$\begin{aligned}&\sum_{j=1}^{10}\sum_{k=1}^{6}\mathrm{ZGL}_{jkp}^{\pm}\times\mathrm{CM}_{jkp}^{\pm}\times\mathrm{NES}_{p}^{\pm}+\sum_{j=1}^{10}\sum_{k=7}^{8}\mathrm{ZGL}_{jkp}^{\pm}\\&\times\mathrm{CM}_{jkp}^{\pm}\times\mathrm{NES}_{p}^{\pm}+\sum_{j=1}^{10}\sum_{k=9}^{12}\mathrm{ZGL}_{jkp}^{\pm}\times\mathrm{CM}_{jkp}^{\pm}\times\mathrm{NES}_{p}^{\pm}\\&-\sum_{S=1}^{4}\mathrm{DE}_{s}^{\pm}\times\mathrm{SC}_{s}^{\pm}-\sum_{p=1}^{2}\mathrm{HER}_{p}^{\pm}\times\mathrm{VCE}_{p}^{\pm}\ge0\end{aligned}\tag{1-2l}$$

$$\begin{aligned}&\sum_{j=1}^{10}\sum_{k=1}^{6}\mathrm{ZGL}_{jkp}^{\pm}\times\mathrm{CM}_{jkp}^{\pm}\times\mathrm{ZKD}_{p}^{\pm}+\sum_{j=1}^{10}\sum_{k=7}^{8}\mathrm{ZGL}_{jkp}^{\pm}\\&\times\mathrm{CM}_{jkp}^{\pm}\times\mathrm{ZKD}_{p}^{\pm}+\sum_{j=1}^{10}\sum_{k=9}^{12}\mathrm{ZGL}_{jkp}^{\pm}\times\mathrm{CM}_{jkp}^{\pm}\times\mathrm{ZKD}_{p}^{\pm}\\&-\sum_{s=1}^{4}\mathrm{DE}_{s}^{\pm}\times\mathrm{SC}_{s}^{\pm}-\sum_{p=1}^{2}\mathrm{HER}_{p}^{\pm}\times\mathrm{VCE}_{p}^{\pm}\ge0\end{aligned}\tag{1-2m}$$

(6) Planting area constraints:

$$0\le\mathrm{CM}_{j9p}^{\pm}\le\mu_{j2}^{\pm}\times\mathrm{SL}_{j2}^{\pm}\tag{1-2n}$$

(7) Technical and nonnegative constraints:

$$\Delta1\begin{cases}=1\text{if time period is in nonflood season}\\=0\text{if otherwise}\end{cases}\tag{1-2o}$$

$$\Delta2\begin{cases}=1\text{if time period is in nonflood season}\\=0\text{if otherwise}\end{cases}\tag{1-2p}$$

$$\begin{aligned}&\mathrm{XG}_{ip,\min}^{\pm}\le\mathrm{XG}_{ip}^{\pm}\le\mathrm{XG}_{ip,\max}^{\pm};\ \mathrm{ZQ}_{nk,\min}^{\pm}\le\mathrm{ZQ}_{nk}^{\pm}\le\mathrm{ZQ}_{nk,\max}^{\pm};\\&\mathrm{SC}_{s,\min}^{\pm}\le\mathrm{SC}_{s}^{\pm}\le\mathrm{SC}_{s,\max}^{\pm};\ \mathrm{CM}_{jkp,\min}^{\pm}\le\mathrm{CM}_{jkp}^{\pm}\le\mathrm{CM}_{jkp,\max}^{\pm}\end{aligned}$$

The binary variables were selected to identify the specific time period, and all the continuous decision variables were nonnegative in real-world applications. In addition, the detailed interpretations for the decision variables and relevant parameters are provided in Appendix. The developed ICFP model (i.e., Model (1)) can be solved through the interactive algorithm as illustrated in the methodology section. The detailed nomenclatures for the variables and parameters are provided in Appendix A.

According to the 2013 environmental pollution sources census of Ankang, 93 key pollution emission plants exist, including industries processing heavy metals, yellow ginger saponin plants, medicine and chemical industries, cement manufacturing enterprises, livestock and poultry enterprises, and sewage and garbage treatment industries. The key pollution factors are shown in Table 1. According to the existing planning results, by 2030, the average annual water diversions of the middle route of the South–North Water Diversion Project will be 13 billion m^3 (the redeployment of Hanjiang River Basin will be 12.05 billion m^3), the water supply in Hanjiang River Basin will be 21.1 billion m^3, and the water diversion to outside of the Hanjiang River Basin will be 13.691 billion m^3. The rate of water resource development and utilization is approximately 54%, which will increase, resulting in greater pressure on the Hanjiang River Basin water resources. In 2013, the Ankang city environmental monitoring station monitored and analyzed the surface water in the Ankang section of the Yangtze River. Twelve sections were monitored: six sections of the Hanjiang River and six sections, respectively, set in the six tributaries of Hanjiang River including the Yue, Xunyang, Ba, Dong, Shu, and Nanjiang rivers. Among them, two sections are controlled by the state, two sections are controlled by province, and eight sections are controlled by the local government. There were eight monitoring sections involving the Ankang section of the Hanjiang River, including six sections of the Hanjiang River and two set in Yue River and Xunyang River as primary tributaries of the Hanjiang River. Among these sections, four were provincially controlled and four were locally controlled. In 2013, the total water consumption of Ankang was 82.01×10^6 m^3. The industrial water and domestic water consumption were 25.23×10^6 m^3 (30.76%) and 56.78×10^6 m^3 (69.24%), respectively. Total wastewater emissions to all counties in Ankang are shown in Fig. 3.

Table 1
Emissions of key pollution factors

Counties	COD emissions (t)					TN emission (t)				
	Total	Industries	Agriculture	Urban life	Centralized management	Total	Industries	Agriculture	Urban life	Centralized management
Hanbin	11,721.62	2,286.00	3,038.72	5,573.00	823.90	1,650.39	177.65	474.79	927.33	70.62
Hanyin	2,530.64	364.34	340.73	1,710.57	115.00	400.53	19.88	139.37	231.38	9.90
Shiquan	2,211.00	110.21	753.58	1,234.79	112.42	329.42	4.39	145.87	169.52	9.64
Ningshan	843.92	181.8	37.22	578.70	46.20	110.08	4.50	17.83	83.79	3.96
Ziyang	3,236.64	161.14	988.13	2,029.62	57.75	458.88	2.47	177.22	274.24	4.95
Langao	2,396.61	233.86	924.33	1,140.05	98.37	259.87	6.76	86.55	158.16	8.40
Pingli	2,905.24	145.01	1,208.16	1,439.65	112.42	379.16	3.33	169.43	196.76	9.64
Zhenping	1,332.77	8.90	960.37	334.62	28.88	139.59	0.73	88.16	48.22	2.48
Xunyang	6,724.65	417.04	2,990.20	3,205.00	112.42	780.04	33.61	305.43	431.36	9.64
Baihe	1,926.99	242.9	577.69	1,075.60	30.80	239.45	2.49	85.38	148.94	2.64
Total	35,830.08	4,151.2	11,819.13	18,321.6	1,538.16	4,747.41	255.81	1,690.03	2,669.7	131.87

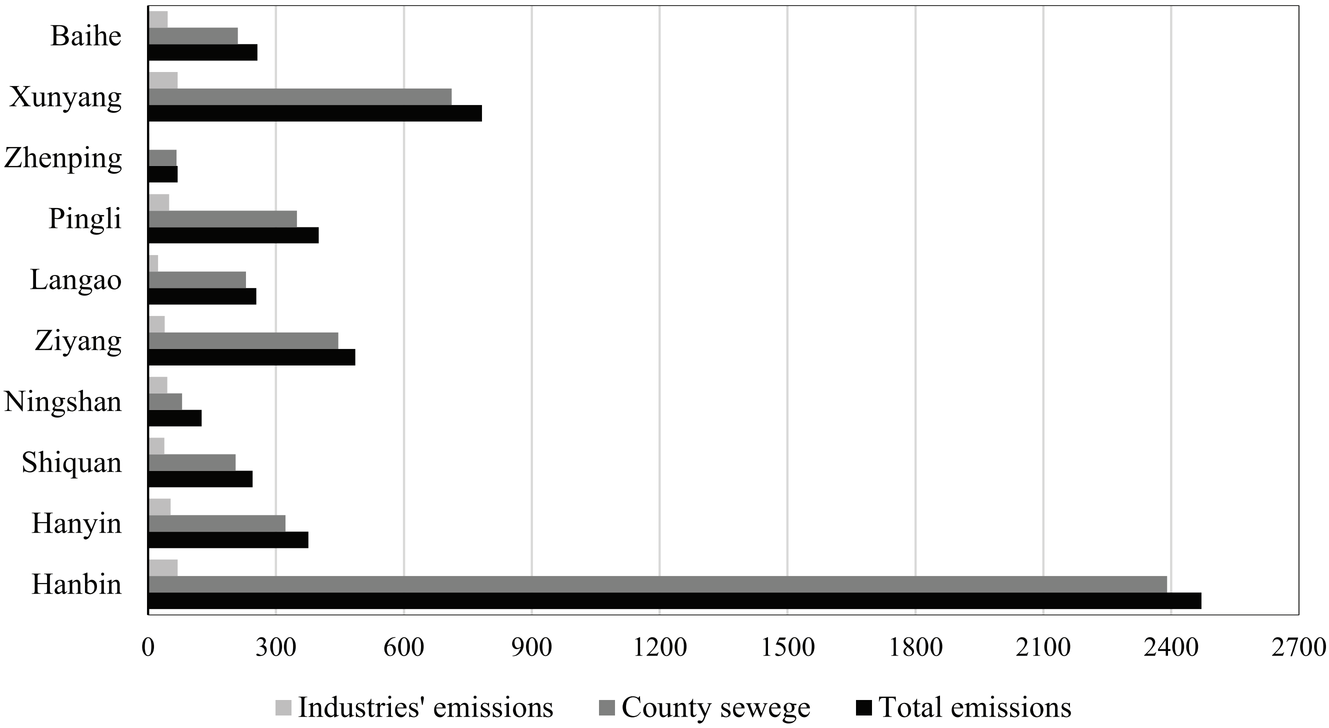

Fig. 3. Total wastewater emissions of counties in Ankang (10^5 t).

In the present study, the imprecise input parameters expressed as intervals were investigated according to field surveys, statistical data, government reports, and related literature. This interval value is generated based on the following facts: (a) product price per unit varied between \$647.2 and \$659.8 m^{-3} during the nonflood season, where \$647.2 m^{-3} is the minimum value and \$659.8 m^{-3} is the maximum value (Environmental Science Research and Design Institute of Zhejiang Province 2009); (b) the costs of products range from \$526.3 to \$532.2 m^{-3}. Therefore, the net benefit from the Gufu chemical plant could be obtained by using the minimum value of \$115.0 m^{-3} (i.e., 647.2–532.2) as its lower bound and the maximum value of \$133.5 m^{-3} (i.e., 659.8–526.3) as its upper bound. In addition, Table 2 lists the modeling parameters related to soil loss and runoff as well as dissolved nutrient concentrations. The soil erodibility parameters are closely related to soil types and the transformation of the international standard for soil grain-size analysis into the US standard is required for the Universal Soil Loss Equation [26]. The specific model solving processes are provided in Appendix B.

Table 2
Soil erosion and surface runoff parameters

Crops	Soil loss (t/ha)	Surface runoff (mm)	Phosphorus concentration (mg/L)
Upper			
Fruits	17.57	67.40	0.10
Tea	15.71	58.32	0.09
Walnut	16.83	65.25	0.13
Chestnut	17.10	67.43	0.12
Raw lacquer	16.96	66.40	0.10
Tung oil seeds	17.72	64.30	0.11
Wheat	18.00	37.09	0.07
Lettuce	21.03	46.70	0.27
Rice	33.80	185.60	0.14
Corn	32.55	179.77	0.12
Tobacco	32.50	168.92	0.12
Vegetables	10.76	170.90	0.45
Lower			
Fruits	22.60	96.95	0.14
Tea	18.11	84.50	0.13
Walnut	22.60	99.92	0.14
Chestnut	20.65	96.19	0.13
Raw lacquer	22.50	106.90	0.10
Tung oil seeds	22.66	95.30	0.14
Wheat	22.12	56.01	0.17
Lettuce	24.78	58.77	0.35
Rice	40.20	238.90	0.18
Corn	40.12	194.27	0.15
Tobacco	40.55	201.45	0.15
Vegetables	14.10	223.70	0.54

4. Results analysis

In the present study, the constraint of the allowable emission rate of TN was considered to be a series of probability constraints, which could effectively test the risk, and formed regional economic development plan expected under uncertain conditions. Fig. 4 gives the probability distribution of TN under different probabilities. Monte Carlo simulation, which produces an output for each run, was performed to randomly generate a large set of output results, thereby obtaining the corresponding cumulative probability distribution.

Table 3 lists the production scale of key polluting enterprises under different probabilities. Most of the decision variables are interval numbers, which also showed that the relevant decision was sensitive to uncertainty. For key polluting enterprises, the scale of production changed significantly with the probability level q which violated the constraints. For example, the scale of the cement industry would increase with the increase of probability. When q was 0.01, the scale of the cement production was [502.00, 512.30] × 10^9 kg; When q was 0.05, the scale of the cement production was [522.04, 536.04] × 10^9 kg; When q was 0.10, the scale of the cement production was [548.19, 559.88] × 10^9 kg; When q was 0.15, the scale of the cement production was [579.82, 599.31] × 10^9 kg. In the major polluting enterprises, the mineral processing wastewater from heavy metal production enterprises was all returned to factories for recycling use after precipitation. The smelting wastewater was recycled without discharge after precipitation, adsorption, filtration, and pH adjustment. The tailings wastewater was transported to the tailings reservoir where solid–liquid separation was conducted and the water was left for natural purification to take place, after which the purified water was sent back through the backwater device to the factories for recycling use without discharge. The key pollutants in the wastewater of heavy metal production enterprises included COD, and many kinds of heavy metals.

The results of water supply of key counties of Ankang under different probabilities are shown in Table 4. Urban

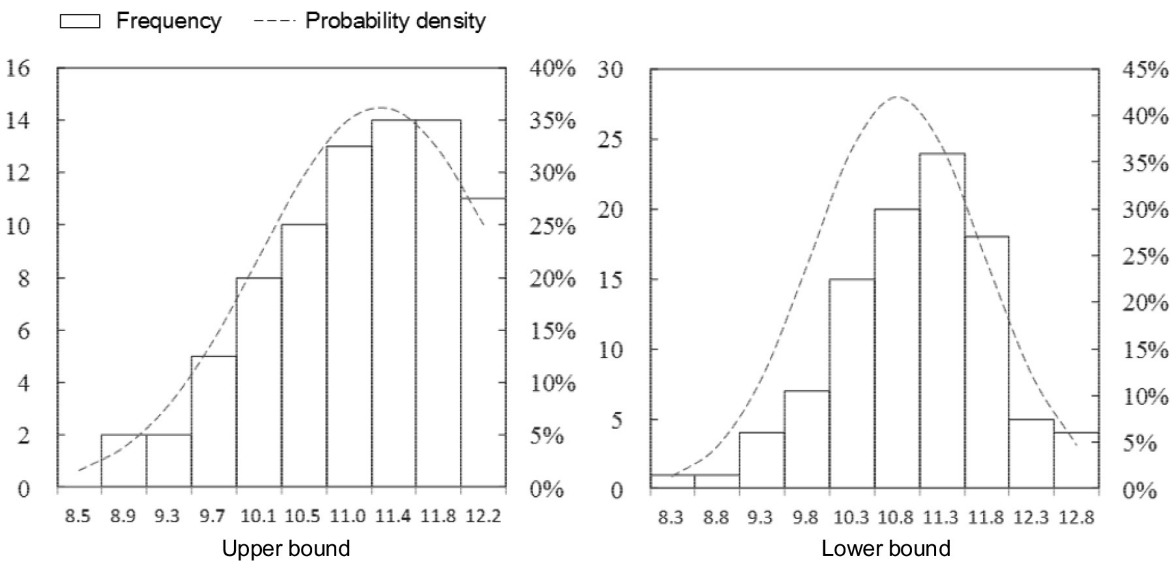

Fig. 4. Probability distribution of total nitrogen emission.

Table 3
Production scale of key polluting enterprises under different probabilities

Production scale	q = 0.01	q = 0.05	q = 0.1	q = 0.15
Heavy metal plants	[3.06, 4.12]	[3.73, 4.52]	[3.80, 5.14]	[3.95, 5.42]
Huang saponin plants	[0.25, 0.31]	0.43	[0.46, 0.55]	[0.56, 0.68]
Pharmaceutical and chemical plants	[23.12, 25.67]	26.90	[27.12, 28.71]	[29.12, 30.66]
Cement plants	[502.00, 512.30]	[522.04, 536.04]	[548.19, 559.88]	[579.82, 599.31]
Livestock breeding	0.42	[0.48, 0.67]	[0.55, 0.79]	[0.79, 0.83]
Municipal solid waste landfill	[56.22, 57.37]	[59.75, 61.33]	[63.24, 78.27]	[78.12, 82.84]
County sewage treatment plant	[4,927.60, 5,023.39]	[5,031.50, 5,234.30]	5,384.02	[5,565.80, 5,023.39]

Table 4
Water supply of key counties under different probabilities

Water supply	q = 0.01	q = 0.05	q = 0.1	q = 0.15
Hanbin	[648, 705]	[698, 723]	[732, 768]	[767, 804]
Hanyin	[155, 213]	[182, 243]	[195, 265]	[238, 285]
Shiquan	[312, 422]	[354, 495]	[366, 503]	[399, 503]
Ningshan	[745, 798]	[801, 823]	[811, 855]	[832, 856]
Ziyang	[343, 411]	[385, 452]	487	496
Langao	[401, 429]	[436, 480]	[465, 499]	[478, 521]
Pingli	[517, 549]	[546, 587]	[586, 605]	[599, 610]
Zhenping	[276, 317]	[301, 344]	[343, 376]	[301, 344]
Xunyang	[687, 701]	723	765	781
Baihe	[293, 308]	346	[351, 387]	387

water supply included domestic requirements and industrial water (cooling, washing, temperature adjusting, humidity adjusting, etc.). The quantity, quality, and pressure of water should be ensured in the process of water supply. At present, with the rapid increase of population and the development of urbanization and industry, the urban water consumption has soared, and addressing shortcomings in the water supply is becoming more and more urgent. The deficit between water supply and demand in many cities is prominent when lakes suffer pollution and water quality deterioration. Therefore, rational planning for urban water supply is urgent. The results of this model show that the urban water supply increased with the increase of probability; the trend was obvious and the deficits in the water supply quantity among different cities were relatively large. Compared with the other towns, Ningshan, Xunyang, and Hanbin would obtain more water supply. For example, when q was 0.01, the water supply of Ningshan was 7 457.98 × 10^6 m^3, when q was 0.05, the water supply quantity was 8 018.23 × 10^6 m^3, when q was 0.10, the water supply quantity was 8 118.55 × 10^6 m^3, and when q was 0.15, the water supply quantity was 8 328.56 × 10^6 m^3. When q was 0.01, the water supply of Hanbin was 6 487.05 × 10^6 m^3, when q was 0.05, the water supply quantity was 6 987.23 × 10^6 m^3, when q was 0.10, the water supply quantity was 7 327.68 × 10^6 m^3, and when q was 0.15, the water supply quantity was 7 678.04 × 10^6 m^3. When q was 0.01, the water supply of Xunyang was [687, 701] × 10^6 m^3, when q was 0.05, the water supply quantity was 723 × 10^6 m^3, when q was 0.10, the water supply quantity was 765 × 10^6 m^3, and when q was 0.15, the water supply quantity was 781 × 10^6 m^3. Such a large supply was due to the greater demand for water and higher economic benefits of water supply in these counties.

The calculation of the municipal wastewater emission of Ankang under the condition of q = 0.01 is shown in Table 5, including industrial wastewater, urban sewage, and wastewater treatment plant emissions. According to the calculation results, when q was 0.01, the city's wastewater emission was [5,480.6, 5,692.22] × 10^6 m^3, whereas emission of industrial wastewater stood at [432.94, 458.60] × 10^6 m^3, emission of urban sewage stood at [5,026.66, 5,120.26] × 10^6 m^3, and emission of the wastewater treatment plant stood at [22.60, 25.65] × 10^6 m^3. In planning years, counties with larger city wastewater emissions were Hanbin, Xunyang, Ziyang, and Pingli, the wastewater emissions of which accounted for [75.23%, 75.65%] of the total city wastewater emissions. At present, industrial enterprises in Ankang run a total of 86 sets of wastewater treatment facilities with a daily processing capacity of 38.50 × 10^3 m^3, 5.63 × 10^9 kg, 9.30 × 10^9 kg, and 120 × 10^3 kg of wastewater, COD, and ammonia nitrogen, respectively. There has been a gradual increase in the nitrogen content of the Hanjiang River and its tributaries in recent years, and the water quality of coastal cities and towns shows a trend of deterioration. A major reason for the deterioration in water quality was due to the delay in construction of the urban sewage system in Ankang and subsequent imperfect facilities.

The emissions of COD under different probabilities are shown in Table 6. COD is an important organic pollution parameter that could be quickly determined. The amount of reducing substances in water samples needed to be tested by a chemical method. According to the calculation results, when q was 0.01, the emission of COD was [35.80, 39.90] × 10^6 kg and the COD of urban living water was [1.70, 2.80] × 10^6 kg. Counties with larger COD emissions were Hanbin, Xunyang, Ziyang, and Pingli the COD emissions of the four counties accounted for [68.44%, 72.58%] of the city's emissions. Among them, the COD produced by domestic waste, agricultural emissions, industrial emissions, and centralized pollution control facilities accounted for 51%, 33%, 12%, and 4% of the total COD emissions, respectively. Furthermore, when the nitrogen substances in the surface water exceeded the standard, rapid microbial growth occurred, plankton thrived, and eutrophication

Table 5
Emission of wastewater in Ankang (q = 0.01)

Counties	Emission of wastewater			
	Total emission	Industries	Urban sewage	Sewage treatment
Hanbin	[2,470.96, 2,578.89]	[68.94, 73.65]	[2,390.25, 2,450.30]	[11.77, 12.45]
Hanyin	[376.28, 388.35]	[52.74, 55.64]	[321.89, 324.64]	[1.65, 1.78]
Shiquan	[245.22, 257.44]	[37.88, 42.10]	[205.73, 207.75]	1.72
Ningshan	139.36	[44.80, 46.70]	[80.00, 87.90]	[0.66, 0.94]
Ziyang	[485.68, 497.80]	[38.92, 41.30]	460.80	[0.83, 1.91]
Langao	[254.09, 267.88]	[23.35, 27.69]	[229.34, 234.62]	[1.41, 1.83]
Pingli	[400.15, 413.30]	[48.98, 50.22]	[349.57, 347.31]	[1.61, 1.92]
Zhenping	[69.31, 78.60]	[2.50, 3.08]	[66.40, 68.44]	[0.41, 0.56]
Xunyang	[782.91, 792.30]	[68.97, 70.23]	[712.34, 724.90]	1.80
Baihe	[256.64, 278.30]	[45.86, 47.99]	[210.34, 214.50]	0.74

Table 6
Emissions of COD and TN under different probabilities

Emissions amount	Lower bound	Upper bound
COD		
q = 0.01	35.83	42.66
q = 0.05	36.16	42.99
q = 0.10	36.52	43.34
q = 0.15	36.91	43.70
TN		
q = 0.01	4.75	5.12
q = 0.05	4.88	5.55
q = 0.10	5.43	6.25
q = 0.15	6.11	7.51

was inevitable. In the model results, when q was 0.01, the TN emission of the study area was [4.70, 54.20] × 10^6 kg, whereas the COD emission of urban sewage was [18.30, 20.30] × 10^6 kg, which was the maximum. The output ranking of TN was: domestic waste (sewage produced by residents' daily life) > agricultural emissions > industrial emissions > sewage treatment plant emissions. Industrial activity contributed 51% of TN emissions in the study area. Among them, TN emissions of Hanbin, Xunyang, Ziyang, and Hanyin was [3.30, 7.60] × 10^6 kg, which accounted for [70.21%, 76.49%] of the city's TN emissions.

5. Discussion

The objective of the proposed model is to minimize the system cost based on optimized water demands. As the actual value of each continuous variable varies within its lower and upper bounds, the net system cost would change correspondingly between f_{opt}^{-} and f_{opt}^{+}. The lower p corresponded to lower cost levels; this implied that the manager had an optimistic attitude, which might be associated with a higher system risk. Conversely, a plan with a higher recourse cost would have lower system risk. Thus, a decision with a higher cost would correspond to a lower risk of system failure. For instance, the system cost would be RenMinBi (RMB) ¥ [14.20, 16.70] × 10^9 when q = 0.01, RMB ¥ [14.4, 19.1] × 10^9 when q = 0.05, RMB ¥ [19.80, 23.10] × 10^{12} when q = 0.1, and RMB ¥ [22.30, 25.20] × 10^9 when q = 0.0, as shown in Fig. 5. Besides, the lower bounds f_{opt}^{-} imply that the manager has an optimistic attitude for estimating the system cost. Conversely, a plan with a higher system cost would better resist water pollution. Assuredly, according to the above analysis, environmental factors have impacts on the total system cost. Considering the environmental factors, the expected system costs would increase obviously. Therefore, the administration section should adopt more suitable measures to promote the water allocation and reduce the negative efforts of environmental pollution. This ensured that the management scenarios and plans be made with reasonable consideration of both system cost and risk.

Therefore, the impact of growing volumes of effluent discharged by industrial enterprises on the Ankang section of the Hanjiang River Basin should not be ignored, especially the pollution caused by rapid development of industries processing heavy metals. In the present study, the expansion of key polluting enterprises showed a positive correlation with the impact of the Hanjiang River water quality in the Ankang section. In particular, the city hosts many industries that process heavy metals, producing tailings containing lead, zinc, and mercury, which are often piled up along the river, resulting in runoff into the Hanjiang River with the seasonal flood and causing serious pollution. In addition, the wastewater of the mining field is discharged directly without treatment, resulting in higher turbidity of the Hanjiang River. In such a water quality emergency, if planners and decision makers, particularly the government, relaxed the constraints placed to protect the environment to stimulate higher output from highly polluting enterprises, regardless of the consequences, the effects on the water quality of Ankang would be dire. Further degradation of the water quality would not only endanger the catchment area of Beijing and Tianjin and affect the water supply quality of the middle line of the South–North Water Diversion Project, but also greatly set back the sustainable development of Ankang City, and lead to immeasurable consequences.

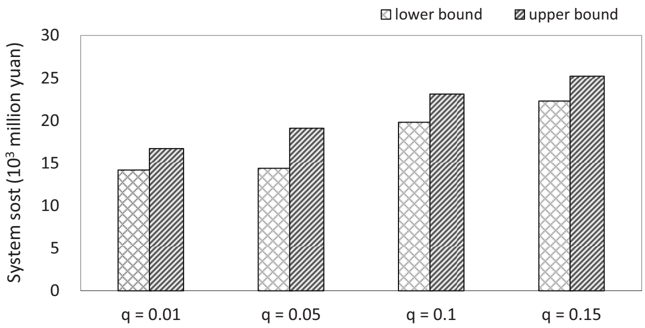

Fig. 5. System cost under different probabilities.

6. Conclusion

In this research, an ICFP model was developed, which could provide technical support for decision making in the process of reflecting and dealing with uncertain information. The pollutant allowable emission constraint (probability constraint) in the model met the requirements of the model at a certain probability level. The ICFP model was applied to the research of a water environment and industry development model in the Ankang section of the Hanjiang River under the condition of uncertainty. The results of different levels (q) could be obtained by solving the two submodels. The results show that in each q level, the production of key enterprises is the main economic source of the Ankang section of the Hanjiang River Basin. Moreover, the emission of nitrogen mainly originated from urban waste, and the contribution of key sewage companies to the point source of nitrogen was relatively large. Nonpoint source emissions of nitrogen mainly originated from the cultivation of crops. Finally, relationship between economic benefits and environmental risk (probability) was analyzed. The results showed that the conservative scheme (low income) could ensure the water quality standards, and the optimistic scheme (high yield) meant that the risk (probability) would increase. To sum up, system engineering was recommended for management of the water environment, involving a number of industries and infrastructure constructions, as well as communication and collaboration of multiple departments. An ICFP model developed in the present study could effectively coordinate and manage water environmental problems, including both point and nonpoint source pollution under uncertain conditions, and could provide a basis for planning in the production of various industries.

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References

[1] L.M. Surhone, M.T. Tennoe, S.F. Henssonow, UN World Water Development Report, Betascript Publishing, 2010. https://www.betascript-publishing.com/
[2] P.M. Bach, S. Staalesen, D.T. McCarthy, A, Deletic, Revisiting land use classification and spatial aggregation for modelling integrated urban water systems, Landscape Urban Plann., 143 (2015) 43–55.
[3] C. Mateus, D.D. Tullos, C.G. Surfleet, Hydrologic sensitivity to climate and land use changes in the Santiam River Basin, Oregon, J. Am. Water Resour. Assoc., 51 (2015) 400–420.
[4] X.S. Qin, G.H. Huang, B. Chen, B.Y. Zhang, An interval-parameter waste-load-allocation model for river water quality management under uncertainty, Environ. Manage., 43 (2009) 999–1012.
[5] F.A. Deviney Jr., D.E. Brown, K.C. Rice, Evaluation of Bayesian estimation of a hidden continuous-time Markov chain model with application to threshold violation in water-quality indicators, J. Environ. Inf., 19 (2012) 70–78.
[6] N. Barbalios, I. Ioannidou, P. Tzionas, S. Paraskeuopoulos, Behavioural adaptation towards efficient resource sharing under the lack of communication, J. Environ. Inf., 21 (2013) 119–135.
[7] Y.P. Li, G.H. Huang, H.Z. Li, A recourse-based interval fuzzy programming model for point-nonpoint source effluent trading under uncertainty, J. Am. Water Resour. Assoc., 50 (2014) 1191–1207.
[8] P.G. Whitehead, R.J. Williams, D.R. Lewis, Quality simulation along river systems (QUASAR): model theory and development, Sci. Total Environ., 194 (1997) 447–456.
[9] D.M. DiToro, J.J. Sifitzpatric, R.V. Thomann, Documentation for Water Quality Analysis Simulation Program (WASP) and Model Verification Program (MVP), Hydroscience Inc., US Environmental Protection Agency, Duluth, MN, 1983.
[10] M.B. Beck, Water quality modeling: a review of the analysis of uncertainty, Water Resour. Res., 23 (1987) 1393–1442.
[11] J.C. Refsgaard, Parameterization, calibration and validation of distributed hydrological models, J. Hydrol., 198 (1997) 69–97.
[12] Y.P. Li, G.H. Huang, S.L. Nie, Optimization of regional economic and environmental systems under fuzzy and random uncertainties, J. Environ. Manage., 92 (2011) 2010–2020.
[13] B.M. Vigon, W. Bruce, The status of nonpoint source pollution: its nature, extent and control, J. Am. Water Resour. Assoc., 21 (2007) 179–184.
[14] H. Li, Y.P. Li, G.H. Huang, Y.L. Xie, A simulation-based optimization approach for water quality management of Xiangxihe River under uncertainty, Environ. Eng. Sci., 29 (2012) 270–283.
[15] O. Fujiwara, S.K. Gnanendran, S. Ohgaki, Chance constrained model for river water quality management, J. Environ. Eng., 113 (1987) 1018–1031.
[16] A. Kampas, B. White, Probabilistic programming for nitrate pollution control: comparing different probabilistic constraint approximations, Eur. J. Oper. Res., 147 (2003) 217–228.
[17] D.Y. Miao, Y.P. Li, G.H. Huang, Z.F. Yang, Development of an optimization model for water resource systems planning, Eng. Appl. Artif. Intell., 26 (2013) 1061–1071.
[18] R.U. Bilsel, A. Ravindran, A multiobjective chance constrained programming model for supplier selection under uncertainty, Transp. Res., 45 (2011) 1284–1300.
[19] Y.P. Li, G.H. Huang, S.L. Nie, L. Liu, Inexact multistage stochastic integer programming for water resource management under uncertainty, J. Environ. Manage., 88 (2008) 93–107.
[20] Y.P. Li, G.H. Huang, Y.F. Huang, H.D. Zhou, A multistage fuzzy-stochastic programming model for supporting sustainable water-resources allocation and management, Environ. Model. Software, 24 (2009) 786–797.
[21] G.H. Huang, A hybrid inexact-stochastic water management model, Eur. J. Oper. Res., 107 (1998) 137–158.
[22] Y. Liu, H. Guo, F. Zhou, X. Qin, K. Huang, Y. Yu, Inexact chance-constrained linear programming model for optimal

water pollution management at the watershed scale, J. Water Resour. Plann. Manage., 134 (2008) 347–356.
[23] P. Du, Y.P. Li, G.H. Huang, Inexact chance-constrained waste-load allocation model for water quality management of Xiangxihe River, J. Environ. Eng., 139 (2013) 1178–1197.
[24] Y. Zhu, Y.P. Li, G.H. Huang, Y.R. Fan, S. Nie, A dynamic model to optimize municipal electric power systems by considering carbon emission trading under uncertainty, Energy, 88 (2015) 636–649.
[25] Y. Zhu, Y.P. Li, G.H. Huang, An optimization decision support approach for risk analysis of carbon emission trading in electric power systems, Environ. Model. Software, 67 (2015) 43–56.
[26] C.M. Davis, J.F. Fox, Sediment fingerprinting: review of the method and future improvements for allocating nonpoint source pollution, J. Environ. Eng., 135 (2014) 490–504.

Appendix A: Solution method

An interval full-infinite programming (IFIP) model can be formulated as follows [24]:

$$\text{Min } f^{\pm} = \sum_{j=1}^{k} c_j^{\pm}(\tau_i) x_j^{\pm} + \sum_{j=k+1}^{m} c_j^{\pm}(\tau_i) x_j^{\pm}, \quad \text{for all } \tau_i \in [\tau l, \tau u] \tag{A.1a}$$

subject to:

$$\sum_{j=1}^{n} a_{ij}^{\pm}(\tau_i) x_j^{\pm} \le b_i^{\pm}(\tau_i) \tag{A.1b}$$

$$x_j^{\pm} \ge 0 \tag{A.1c}$$

where $a_{ij}^{\pm}(\tau_i) \in \{R^{\pm}\}^{m\times n}$, $b_i^{\pm}(\tau_i) \in \{R^{\pm}\}^{m\times 1}$, $c_j^{\pm}(\tau_i) \in \{R^{\pm}\}^{1\times n}$, and $x_i^{\pm} \in \{R^{\pm}\}^{n\times 1}$; $R^{\pm}$ denotes a set of interval numbers; $a_{ij}^{\pm}(\tau_i)$, $b_i^{\pm}(\tau_i)$, and $c_j^{\pm}(\tau_i)$ are functional interval parameters. $c_j^{-}(\tau_i)$ and $c_j^{+}(\tau_i)(j = 1,\ 2,\ \ldots\ ,k)$ are positive for all τ_i values; $c_j^{-}(\tau_i)$ and $c_j^{+}(\tau_i)(j = k+1, k+2, \ldots, n)$ are negative functions for all τ_i values. Model (1) can be divided into the following two submodels, which ensures that stable and continuous solution intervals can be formed.

Submodel 2:

$$\text{Min } f^{+} = \sum_{j=1}^{k} c_j^{+}(\tau_i) x_j^{+} + \sum_{j=k+1}^{m} c_j^{+}(\tau_i) x_j^{-}, \quad \text{for all } \tau_i \in [\tau l, \tau u] \tag{A.2a}$$

subject to:

$$\sum_{j=1}^{k} \left|a_{ij}^{\pm}(\tau_i)\right|^{-} \text{Sign}\left[a_{ij}^{\pm}(\tau_i)\right] x_j^{+} + \sum_{j=k+1}^{n} \left|a_{ij}^{\pm}(\tau_i)\right|^{+} \text{Sign}\left[a_{ij}^{\pm}(\tau_i)\right] x_j^{-} \le b_i^{+}(\tau_i) \tag{A.2b}$$

$$x_j^{+} \ge 0, x_j^{-} \ge 0, \forall j \tag{A.2c}$$

Submodel 3:

$$\text{Min } f^{-} = \sum_{j=1}^{k} c_j^{-}(\tau_i) x_j^{-} + \sum_{j=k+1}^{m} c_j^{-}(\tau_i) x_j^{+}, \quad \text{for all } \tau_i \in [\tau l, \tau u] \tag{A.3a}$$

subject to:

$$\sum_{j=1}^{k} \left|a_{ij}^{\pm}(\tau_i)\right|^{+} \text{Sign}\left[a_{ij}^{\pm}(\tau_i)\right] x_j^{-} + \sum_{j=k+1}^{n} \left|a_{ij}^{\pm}(\tau_i)\right| \text{Sign}\left[a_{ij}^{\pm}(\tau_i)\right] x_j^{+} \le b_i^{-}(\tau_i) \tag{A.3b}$$

$$\mathrm{x}_j^{-} \le \mathrm{x}_{j\mathrm{opt}}^{+}, \quad j = 1, 2, \cdots, k \tag{A.3c}$$

$$x_j^{+} \ge x_{j\mathrm{opt}}^{-}, \quad j = k+1, k+2, \cdots, n \tag{A.3d}$$

$$x_j^{+} \ge 0, x_j^{-} \ge 0, \forall j \tag{A.3e}$$

where $x_{j\mathrm{opt}}^{+}$ and $x_{j\mathrm{opt}}^{-}$ are solutions of submodels (6) and (7), respectively; Sign(·) is defined as:

$$\text{Sign}\left[a_{ij}^{\pm}(\tau_i)\right] = \begin{cases} 1 & \left(a_{ij}^{\pm}(\tau_i) \ge 0 \text{ for all } \tau_i \in [\tau l, \tau u]\right) \\ -1 & \left(a_{ij}^{\pm}(\tau_i) \le 0 \text{ for all } \tau_i \in [\tau l, \tau u]\right) \end{cases} \tag{A.4}$$

The coefficients $a_{ij}^{\pm}(\tau_i)$, $b_i^{\pm}(\tau_i)$, and $c_j^{\pm}(\tau_i)$ in the constraints and objectives are functional intervals (instead of crisp intervals) in IFIP model. After IFIP being converted into two interval linear programming (ILP) submodels, the functional intervals can turn into traditional intervals. Thus, the IFIP can tackle the functional intervals effectively and efficiently. However, when some elements in $b_i^{\pm}(\tau_i)$ are expressed as probability distributions, the IFIP has difficulties for handling these uncertainties.

Chance-constrained programming (CCP) can effectively reflect the reliability of satisfying (or risk of violating) system constraints under uncertainty. It does not require that all of the constraints be totally satisfied; instead, the constraints can be satisfied in a proportion of cases with given probabilities [25]. When uncertainties of some elements in $b_i^{\pm}(\tau_i)$ are expressed as probability distributions, the CCP method can be used. In terms of uncertainties in $b_i^{\pm}(\tau_i)$, consider a general stochastic linear programming problem as follows:

$$\text{Min } f^{\pm} = c_j^{\pm}(\tau_i) x_j^{\pm} \tag{A.5a}$$

subject to:

$$a_{ij}^{\pm}(\tau_i) x_j^{\pm} \le b_i^{\pm}(\tau_i) \tag{A.5b}$$

$$x_j^{\pm} \ge 0 \tag{A.5c}$$

where $b_i(\tau_i)$ are sets with random elements defined on a probability space T, $t \in T$. The CCP approach solves this model by converting it to a deterministic version through: (i) fixing a certain level of probability $P_w \in [0,1]$ for each constraint, and (ii) imposing the condition that the constraint is satisfied with at least a probability of P_w. The feasible solution set is thus subject to the following constraints:

$$P_r\left[\left\{\tau \mid a_{ij}^{\pm}(\tau_i) x_j^{\pm} \le b_i^{\pm}(\tau_i)\right\}\right] \ge P_w \tag{A.5d}$$

$$a_{ij}^{\pm}(\tau_i) \in a^{\pm}(\tau_i), \quad b_i^{\pm}(\tau_i) \in b^{\pm}(\tau_i), \quad i = 1, 2, \cdots, m \tag{A.5e}$$

Constraint (A.5d) is generally nonlinear, and the set of feasible constraints is convex only for some particular cases. One of which is when the left-hand side coefficients $a_{ij}^{\pm}(\tau_i)$, are deterministic, and the right-hand side coefficients $b_i^{\pm}(\tau_i)$ are random, it leads to an equivalent linear constraint that has the same size and structure as a deterministic version. The only required information about the uncertainty is the p_w for the unconditional distribution of $b_i^{\pm}(\tau_i)$. Under this condition, constraint (A.5d) becomes linear:

$$a_{ij}^{\pm} x_j^{\pm} \le b_i^{\pm}(\tau)^{(P_w)}, \forall i \tag{A.5f}$$

where $b_i^{\pm}(\tau)^{(P_w)} = F_i^{-}(p_w)$, given the cumulative distribution function of $b_i^{\pm}(\tau_i)(\text{i.e.}, F_i(b_i))$, and the probability of satisfying constraint $w(p_w)$. If both a and b are uncertain, the set of feasible constraints may become more complicated.

One possible approach for better accounting for uncertainties in coefficients, and economic implications is to incorporate the CCP approach within the fuzzy linear programming framework. This leads to the following interval-parameter chanced-constrained full-infinite programming (ICFP) formulation:

$$\text{Min } f^{\pm} = \sum_{j=1}^{k} c_j^{\pm}(\tau_i)x_j^{\pm} + \sum_{j=k+1}^{n} c_j^{\pm}(\tau_i)x_j^{\pm}, \quad \text{for all } \tau_i \in [\tau l, \tau u] \tag{A.6a}$$

subject to:

$$\sum_{j=1}^{n} a_{ij}^{\pm}(\tau_i)x_j^{\pm} \le b_i^{(P_w)}(\tau_i), \quad i \in M, i \ne r \tag{A.6b}$$

$$\sum_{j=1}^{n} a_{ij}^{\pm}(\tau_r)x_j^{\pm} \le b_r^{\pm}(\tau_r), \quad i \in M, i \ne r \tag{A.6c}$$

$$x_j^{\pm} \ge 0 \tag{A.6d}$$

where $a_{ij}^{\pm}(\tau_i)$, $b_i^{\pm}(\tau_i)$ and $c_j^{\pm}(\tau_i)a_{ij}^{\pm}(\tau_i), b_i^{\pm}(\tau_i)$, $a_{ir}^{\pm}(\tau_r)$, $b_r^{\pm}(\tau_r)$ and $c_j^{\pm}(\tau_i)$ are functional interval parameters. $c_j^{-}(\tau_i)$ and $c_j^{+}(\tau_i)$ (j = 1, 2, …,k) are positive for all τ_i values; $c_j^{-}(\tau_i)$ and $c_j^{+}(\tau_i)$ (j = k + 1, k + 2, …,n) are negative functions for all τ_i values. Model (5) can be converted into two submodels.

Submodel 7:

$$\text{Min } f^{+} = \sum_{j=1}^{k} c_j^{+}(\tau_i)x_j^{+} + \sum_{j=k+1}^{n} c_j^{+}(\tau_i)x_j^{-}, \quad \text{for all } \tau_i \in [\tau l, \tau u] \tag{A.7a}$$

subject to:

$$\sum_{j=1}^{k} \left|a_{ij}^{\pm}(\tau_i)\right|^{-} \text{Sign}\left[a_{ij}^{\pm}(\tau_i)\right]x_j^{+} + \sum_{j=k+1}^{n} \left|a_{ij}^{\pm}(\tau_i)\right|^{+} \text{Sign}\left[a_{ij}^{\pm}(\tau_i)\right]x_j^{-} \le b_i^{(P_w)}(\tau_i), \forall i, i \ne r \tag{A.7b}$$

$$\sum_{j=1}^{k} \left|a_{ij}^{\pm}(\tau_i)\right|^{-} \text{Sign}\left[a_{ij}^{\pm}(\tau_i)\right]x_j^{+} + \sum_{j=k+1}^{n} \left|a_{ij}^{\pm}(\tau_i)\right|^{+} \text{Sign}\left[a_{ij}^{\pm}(\tau_i)\right]x_j^{-} \le b_i^{+}(\tau_i), \forall i, i \ne r \tag{A.7c}$$

$$x_j^{+} \ge 0, x_j^{-} \ge 0, \forall j \tag{A.7d}$$

Submodel 8:

$$\text{Min } f^{-} = \sum_{j=1}^{k} c_j^{-}(\tau_i)x_j^{-} + \sum_{j=k+1}^{n} c_j^{-}(\tau_i)x_j^{+}, \quad \text{for all } \tau_i \in [\tau l, \tau u] \tag{A.8a}$$

subject to:

$$\sum_{j=1}^{k} \left|a_{ij}^{\pm}(\tau_i)\right|^{+} \text{Sign}\left[a_{ij}^{\pm}(\tau_i)\right]x_j^{-} + \sum_{j=k+1}^{n} \left|a_{ij}^{\pm}(\tau_i)\right| \text{Sign}\left[a_{ij}^{\pm}(\tau_i)\right]x_j^{+} \le b_i^{(P_w)}(\tau_i), \forall i, i \ne r \tag{A.8b}$$

$$\sum_{j=1}^{k} \left|a_{ij}^{\pm}(\tau_i)\right|^{+} \text{Sign}\left[a_{ij}^{\pm}(\tau_i)\right]x_j^{-} + \sum_{j=k+1}^{n} \left|a_{ij}^{\pm}(\tau_i)\right| \text{Sign}\left[a_{ij}^{\pm}(\tau_i)\right]x_j^{+} \le b_i^{-}(\tau_i), \forall i, i \ne r \tag{A.8c}$$

$$x_j^{-} \le x_{j\text{opt}}^{+}, j = 1, 2, \cdots, k \tag{A.8d}$$

$$x_j^{+} \ge x_{j\text{opt}}^{-}, j = k+1, k+2, \cdots, n \tag{A.8e}$$

$$x_j^{+} \ge 0, x_j^{-} \ge 0, \forall j \tag{A.8f}$$

where $x_{j\text{opt}}^{+}$ and $x_{j\text{opt}}^{-}$ are solutions of submodels (7) and (8), respectively; Sign(·) is defined as:

$$\text{Sign}\left[a_{ij}^{\pm}(\tau_i)\right] = \begin{cases} 1 & \left(a_{ij}^{\pm}(\tau_i) \ge 0 \text{ for all } \tau_i \in [\tau l, \tau u]\right) \\ -1 & \left(a_{ij}^{\pm}(\tau_i) \le 0 \text{ for all } \tau_i \in [\tau l, \tau u]\right) \end{cases} \tag{A.9}$$

When some of the decision variables in Model (6) are integers, the model can help to tackle the facility expansion issue in energy systems. The upper and lower bounds of the optimal objective and decision variables can be obtained through solving the ICFMP model. When the upper and lower bounds of a functional interval maintain constants, the parameters of model can be converted to interval forms, making the model solvable. This shows the functional interval is a more general definition for interval uncertainty than the interval number. The significance of this definition is its capability in reflecting modeling uncertainties with more complexities and describing the real world conditions with more effectiveness. Consequently, ICFMP method inherits the advantages of IPP, CCP, and FIP, and allows uncertainties expressed as determinates, crisp interval values, probability distribution (in right-hand side) and functional intervals to be incorporated within a general optimization framework.

Appendix B: List of symbols

Subscripts

i	—	Major polluters; i = 1 heavy metal production plant, i = 2 yam diosgenin production plant, i = 3 pharmaceutical and chemical enterprises, i = 4 cement enterprises, i = 5 livestock farming, i = 6 landfill plant, i = 7 sewage treatment plants, i = 8 other pollution sources
j	—	Town; r = 1 Hanbin district; r = 2 Hanyin county, r = 3 Shiquan county, r = 4 Ningshan county, r = 5 Ziyang county, r = 6 Langao county, r = 7 Pingli county, r = 8 Zhenping county, r = 9 Xunyang county, r = 10 Baihe county
k	—	Key crop; k = 1 fruits, k = 2 tea, k = 3 walnut, k = 4 Chinese chestnut, k = 5 raw lacquer, k = 6 seeds of tung tree, k = 7 wheat, k = 8 oil plants, k = 9 rice, k = 10 corn, k = 11 flue-cured tobacco, k = 12 vegetables
p	—	Period; p = 1 nonflood season, p = 2 flood season
s	—	Livestock species; s = 1 pig, s = 2 cattle, s = 3 sheep, s = 4 poultry

Decision variables

$XG^{\pm}_{ip}$ — Production scale of major polluters i in period p, t/d
$GS^{\pm}_{jp}$ — Water supply of town j in period p, m^3/d
$SC^{\pm}_{s}$ — Number of breeding livestock s
$CM^{\pm}_{jkp}$ — Area of key crop k in period p, ha
$MR^{\pm}_{jkp}$ — Amount of manure of key crop k in period p, t
$HR^{\pm}_{jkp}$ — Amount of fertilizer of key crop k in period p, t

Model parameters

$l^{\pm}_{p}$ — Length of the period, d
$\alpha^{\pm}_{ip}$ — Production net income of major polluters i in period p, yuan/t
$\beta^{\pm}_{jp}$ — Net income of water supply for town j in period p, yuan/m^3
$\chi^{\pm}_{s}$ — Average income of livestock, yuan
$\delta^{\pm}_{s}$ — Average cost of livestock, yuan
$ZGL^{\pm}_{jkp}$ — Crop output in period p, t/ha
$\varepsilon^{\pm}_{jkp}$ — Average income of agricultural products in period p, yuan/t
$QFL^{\pm}_{ip}$ — Wastewater discharge for major polluters i in period p, m^3/t
$QFB^{\pm}_{ip}$ — Recycle rate of wastewater major polluters i in period p, %
$\varphi^{\pm}_{jp}$ — Cost of sewage treatment for town j in period p, yuan/m^3
$CWG^{\pm}_{jp}$ — Wastewater discharge rate for town j in period p, m^3/m^3
$\beta CWR^{\pm}_{jp}$ — Wastewater reuse rate for town j in period p, %
$\phi^{\pm}_{ip}$ — Cost of sewage treatment for major polluters i in period p, yuan/m^3
$\varphi^{\pm}_{jp}$ — Urban waste collection and treatment costs in period p, yuan/t
$\eta^{\pm}_{jp}$ — Fertilizer costs for town j in period p, yuan/t
$QO^{\pm}_{BOD,ip}$ — COD concentration in raw sewage for major polluters i in period p, kg/m^3
$QW^{\pm}_{BOD,ip}$ — Wastewater COD removal efficiency for major polluters i in period p, %
$QYL^{\pm}_{BOD,ip}$ — COD emissions permit for major polluters i in period p, kg/d
$CW^{\pm}_{BOD,jp}$ — Wastewater COD concentration for town j in period p, kg/m^3
$CB^{\pm}_{BOD,ip}$ — COD removal efficiency of wastewater treatment plants for town j in period p, %
$CWL^{\pm}_{BOD,ip}$ — Allowed COD emissions in sewage treatment plant for town j in period p, kg/d
$CNB^{\pm}_{IN,jp}$ — Nitrogen content in soil-growing areas for town j, %
$CLL^{\pm}_{kp}$ — Average amount of soil loss in period p, t/ha
$CDJ^{\pm}_{kp}$ — Surface runoff in growing areas for town j in period p, mm
$DJN^{\pm}_{TN,jkp}$ — Dissolved nitrogen content in surface runoff in period p, mg/L
$CYN^{\pm}_{TN,jp}$ — Allow nitrogen loss in growing areas for town j in period p, t/ha
$SL^{\pm}_{jp}$ — Available land area in growing areas for town j in period p, ha
$CSB^{\pm}_{p}$ — Proportion of manure in two periods, %
$SF^{\pm}_{s}$ — Amount of livestock manure, *t*
$HF^{\pm}_{p}$ — Human excrement generation, *t*
$VCE^{\pm}_{p}$ — Total rural population in the study
$FLB^{\pm}_{p}$ — Faces wastage rate in period p, %
$ZNB^{\pm}_{TN,M1}$ — Nitrogen content in feces, %
$DE^{\pm}_{p}$ — Per capita water consumption in period p, m^3/(person·d)
$VFB^{\pm}_{p}$ — Rural waste generation rate in period p, %
$VWN^{\pm}_{TN,p}$ — Rural water dissolved nitrogen content in period p, kg/m^3
$VYP^{\pm}_{TN,p}$ — Allowed nitrogen loss for rural life in period p
$CFB^{\pm}_{jp}$ — Proportion of produce feces for town j in period p, %
$CNB^{\pm}_{jp}$ — Proportion of rural population for town j in period p, %
$MR^{\pm}_{TN,p}$ — Proportion of nitrogen fertilizer volatilization or denitrification in period p, %
$AYN^{(P_i)}_{TN,p}$ — Allowed TN emissions in period p under probability level q
$HYT^{\pm}_{p}$ — Allowed soil loss in period p, t/ha
ENB_{F1} — Nitrogen content in the fertilizer, %
$FNB^{\pm}_{TN,p}$ — Proportion of nitrogen fertilizer volatilization or denitrification for feces in period p, %
$MR^{\pm}_{TN,jkp}$ — Nitrogen demand for growing areas in town j in period p, t/ha
$NES^{\pm}_{p}$ — Energy value for unit crop in period p, Mcal/kg
$DE^{\pm}_{s}$ — Energy value demands for livestock growth of livestock s, Mcal
$HER^{\pm}_{p}$ — Energy value demands for human life in period p, Mcal

$ZKD_p^{\pm}$	—	Digestible protein for crops in period p, %
$SKD_p^{\pm}$	—	Digestible protein for livestock growth in period p, kg
$KXD_p^{\pm}$	—	Digestible protein for human life in period p, kg
$\Delta 1$	—	Binary variables, identification of whether or not in nonflood season
$\Delta 2$	—	Binary variables, identification of whether or not in flood season
$XG_{ip,\min}^{\pm}, XG_{ip,\max}^{\pm}$	—	Production scale of major polluters i in period p, t/d
$ZQ_{nk,\min}^{\pm}, ZQ_{nk,\max}^{\pm}$	—	Scale of livestock farming for livestock s
$GS_{pj,\min}^{\pm}, GS_{pj,\max}^{\pm}$	—	Scale of water supply for town j in period p, m^3/d