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RESEARCH ARTICLE

Coupled planning of water resources and agricultural land-use based on an inexact-stochastic programming model

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Abstract Water resources are fundamental for support of regional development. Effective planning can facilitate sustainable management of water resources to balance socioeconomic development and water conservation. In this research, coupled planning of water resources and agricultural land use was undertaken through the development of an inexact-stochastic programming approach. Such an inexact modeling approach was the integration of interval linear programming and chance-constraint programming methods. It was employed to successfully tackle uncertainty in the form of interval numbers and probabilistic distributions existing in water resource systems. Then it was applied to a typical regional water resource system for demonstrating its applicability and validity through generating efficient system solutions. Based on the process of modeling formulation and result analysis, the developed model could be used for helping identify optimal water resource utilization patterns and the corresponding agricultural land-use schemes in three sub-regions. Furthermore, a number of decision alternatives were generated under multiple water-supply conditions, which could help decision makers identify desired management policies.

Keywords water resources management, regional water system, planning, scenario analysis, uncertainty

1 Introduction

Population growth and economic expansion have stimulated increasing demand for water resources, resulting in potential water shortage and water quality degradation in many regions across the world (Zhang et al., 2008). In this century, human beings will probably face a dilemma: whether to allow the water utilization level to continue to increase or to place a limit on it. Presently, to reduce the loss of industrial outputs resulting from water shortage, water resources originally used for agriculture must be diverted to industrial activities. This diversion will correspondingly reduce agricultural yields (Bao and Fang, 2007). Moreover, different types of crops may require varying irrigation methods and water quantities, causing a series of effects on water utilization. Obviously, unreasonable crop planting patterns can lead to many challenges in properly utilizing water resources, further affecting water allocations for agricultural and industrial sectors. Therefore, effective planning of water resources based on the consideration of agricultural land use is desired for regional sustainable development (Zhang et al., 2008).

Over the past years, a number of approaches have been applied for supporting the planning of water resource systems and agricultural land use (Abu-Taleb and Mareschal, 1995; Mainuddin et al., 1997; Reca et al., 2001; Carter et al., 2005; Chen et al., 2006; Sethi et al., 2006; Bao and Fang, 2007; Loukas et al., 2007; Mugabi et al., 2007; Castelletti et al., 2008; Zhang et al., 2008; Jiang et al., 2011; Mahmoud et al., 2011; Patterson and Adams, 2011; Younos, 2011; Pang et al., 2013). For example, Abu-Taleb and Mareschal (1995) employed a PROMETHEE V (i.e., preference ranking organization method for enrichment evaluations V) based multi-criteria analysis method to support water resources planning in the Middle East region. Mainuddin et al. (1997) formulated a monthly irrigation planning model for identifying optimal cropping patterns and the corresponding groundwater abstraction requirements in a groundwater development project. Reca et al. (2001) developed an economic optimization model for supporting hydrologic planning in agricultural irrigation systems. Carter et al. (2005) advanced a normative

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model to support land-use planning and evaluate the corresponding water management activities. They also discussed application of the model in the Province of Ontario, Canada. Chen et al. (2006) proposed a multi-criteria classification (MCC) method for planning water resource systems. Loukas et al. (2007) raised a modeling approach to evaluate sustainability of water resource management strategies in the Pinios River and the Lake Karla basins of Thessaly Region in Greece. Mugabi et al. (2007) proposed a strategic planning framework to assist water utilities in developing meaningful and useful utilization plans. Castelletti et al. (2008) developed an integrated and participatory planning (IPP) approach to facilitate effective planning of water resource systems. Zhang et al. (2008) developed a complex system dynamic (SD) model for integrated management of water resources in Tianjin, China. Mahmoud et al. (2011) discussed the application of a scenario development framework to help manage water resources in Verde River Watershed of Northern Arizona.

However, water resource planning is extremely complex due to the interactions of the many components of water systems, which involve a number of environmental, ecological, and human-related factors. Particularly, in a watershed that is mainly dependent on agricultural outputs, complexities are multiplied by the mixed features of natural variations and human interference. These complexities could become further intensified by interactions among relevant uncertain parameters and their economic implications. In order to formulate effective water resource planning systems, multiple uncertainties should be considered in the modeling efforts (Weng et al., 2010). Previously, a number of optimization techniques were proposed for tackling uncertainties and complexities, including interval linear programming (ILP), fuzzy linear programming (FLP), and stochastic linear programming (SLP) (Sutardi et al., 1995; Huang, 1996; Bender and Simonovic, 2000; Seifi and Hipel, 2001; Karmakar and Mujumdar, 2006; Qin et al., 2008; Fagan et al., 2010; Li et al., 2010; Weng et al., 2010; Tan et al., 2011; Lu et al., 2012). For example, Sutardi et al. (1995) proposed an integrated framework of stochastic dynamic programming (SDP) and fuzzy integer goal programming (FIGP) modeling techniques to handle problems of multi-objective and multi-criteria sequential decision making in water resource planning. Huang (1996) developed an interval parameter water quality management (IPWM) model and applied it to a case study of water pollution control within an agricultural system. Bender and Simonovic (2000) developed a fuzzy compromise approach for planning water resource systems. Seifi and Hipel (2001) presented an interior-point optimization algorithm for solving the problem of long-term reservoir operation planning with stochastic inflows. Karmakar and Mujumdar (2006) presented a modified grey fuzzy model for water-quality management within a river system. Li et al. (2010) developed an inexact two-stage water management (ITWM) model for planning agricultural irrigation in the Zhangweinan River Basin, China. Lu et al. (2012) proposed a strategic agricultural land-use planning approach in response to water-supplier variation under parameter uncertainty.

In fact, due to the characteristics of water resource systems and agricultural land use, inexact features are associated with economic factors (e.g., parameters related to cost and efficiency), natural processes (e.g., precipitation and climate change), and stream conditions (e.g., stream flow and water supply). Therefore, the aim of this study is to develop a coupled water resources and agricultural land-use planning model (CWR-ALUPM) for supporting the management of water resource and farmland uses. The model will be the integration of ILP and CCP approaches and will effectively deal with uncertainties existing in water resource systems that can be expressed as interval numbers and probabilistic distributions. In detail, this study can: (i) tackle multiple uncertainties existing in water systems of agricultural watersheds, (ii) identify desired patterns of crop planting, farmland use, and water resource allocation in agricultural, industrial, tourism, and municipal sectors, and (iii) generate a number of decision alternatives under various water supply conditions.

2 A coupled water resource and agricultural land-use planning model

Under pressure from rising populations, changing climatic conditions, and fluctuating droughts and floods, water resource managers are facing growing challenges. Particularly in an agricultural watershed, great concerns are rising on a wide range of water-related factors, such as land-use structure, natural precipitation process, water end-users, and produced wastewater. These factors are associated with social, economic, environmental, ecological, and institutional subsystems. There are strong interactions among related subsystems. For example, natural water resources (e.g., surface water and groundwater) are directly influencing the water demands of various end-users (e.g., agriculture, industry, service business, and municipality), which can correspondingly generate variations in farmland use and crop production, as well as industrial structure. In addition, wastewater, soil losses, and the transfer of pollutants in storm water runoff impact water systems. Therefore, it is desired to clarify the system structure and promote water resource systems planning for generating reliable and cost-effective water resource utilization schemes with a minimum of adverse eco-environmental impact and resource consumption.

2.1 Modeling formulation

In this research, a regional water system in an agricultural watershed has been thoroughly investigated where decision makers are in charge of designing crop planting and allocating water resources to multiple end-users within a multi-period horizon. In this typical system, the pumps, which are installed at the banks of drains and rivers, as well as pumping wells of groundwater, are used to lift the surface drainage water, river water, and groundwater. Such water resources are employed to satisfy the water demands of agricultural, industrial, tourism, and municipal sectors of three sub-regions. Also, three types of crops (e.g., corn, potato, and rice) are grown in these regions. In addition, metallurgical and food industries are involved in the industrial sector. During the monsoon season, a vast quantity of storm water erodes soil and pollutants (e.g., nitrogen and phosphorus) into waterways, depleting the landscape of nutrients. Various kinds of wastewater from other end-users can be sent to the centralized facility for safe treatment, and then be discharged to the natural surroundings (Fig. 1). In reality, owing to the lack of deterministic data, a large number of parameters have to be expressed as interval values. The flows of the surface drainage water, river water, and groundwater will be indicated as probabilistic distributions due to their random characteristics (Huang, 1996; Seifi and Hipel, 2001; Qin et al., 2008; Tan et al., 2011; Lu et al., 2012). The objective of this model is to maximize the system benefit, being equal to the benefits from crop planting and water consumptions of industrial, tourism, and municipal sectors, deducting the costs of water pumping and pollution controlling. Thus, the objective function and constraints of CWR-ALUPM can be formulated as the following:

$$\max f^{\pm} = f_{BC}^{\pm} + f_{BI}^{\pm} + f_{BT}^{\pm} + f_{BR}^{\pm} - f_{CW}^{\pm} - f_{CE}^{\pm}. \tag{1}$$

In detail, the objective function consists of:
(a) Benefit for agricultural irrigation

$$f_{BC}^{\pm} = \sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{t=1}^{3}(BA_{ijt}^{\pm}\cdot G_{ijt}^{\pm} - CA_{ijt}^{\pm})X_{ijt}^{\pm}, \tag{2}$$

(b) Water supply benefit for industry

$$f_{BI}^{\pm} = \sum_{k=1}^{2}\sum_{j=1}^{3}\sum_{t=1}^{3} BI_{kjt}^{\pm}\cdot DIY_{kjt}^{\pm}, \tag{3}$$

(c) Water supply benefit for tourism

$$f_{BT}^{\pm} = \sum_{j=1}^{3}\sum_{t=1}^{3} BT_{jt}^{\pm}\cdot DTY_{jt}^{\pm}, \tag{4}$$

(d) Water supply benefit for residents

$$f_{BR}^{\pm} = \sum_{j=1}^{3}\sum_{t=1}^{3} BR_{jt}^{\pm}\cdot DRY_{jt}^{\pm}, \tag{5}$$

(e) Cost for water pumping and delivery

$$f_{CW}^{\pm} = \sum_{j=1}^{3}\sum_{t=1}^{3}(CS_{jt}^{\pm}\cdot SZ_{jt}^{\pm} + CG_{jt}^{\pm}\cdot GZ_{jt}^{\pm} + CR_{jt}^{\pm}\cdot RZ_{jt}^{\pm}), \tag{6}$$

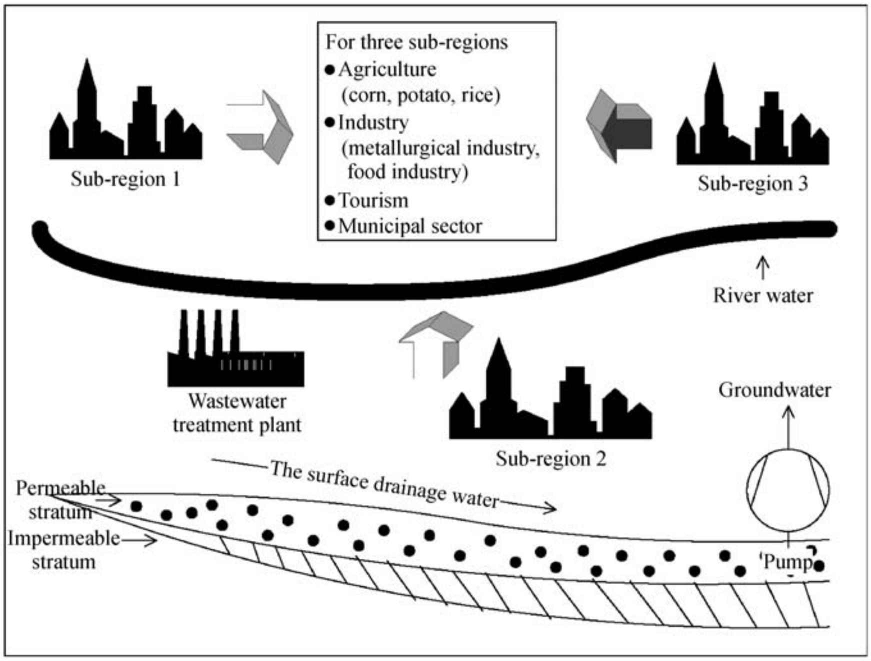

Fig. 1 The typical regional farmland use and water resources system.

and (f) Cost for wastewater treatment

$$f_{CE}^{\pm} = \sum_{k=1}^{2}\sum_{t=1}^{3}\left(CIW_{kt}^{\pm}\cdot\sum_{j=1}^{3}(PIW_{kjt}^{\pm}\cdot DIY_{kjt}^{\pm})\right) + \sum_{t=1}^{3}\left(CTW_{t}^{\pm}\cdot\sum_{j=1}^{3}(PTW_{jt}^{\pm}\cdot DTY_{jt}^{\pm})\right) + \sum_{t=1}^{3}\left(CRW_{t}^{\pm}\cdot\sum_{j=1}^{3}(PRW_{jt}^{\pm}\cdot DRY_{jt}^{\pm})\right). \quad (7)$$

The constraints include:

(1) Land resource availability constraints

(a) Maximum cultivated land area

$$\sum_{i=1}^{3} X_{ijt}^{\pm} \leqslant HA_{\max jt}, \quad \forall j,t, \quad (8)$$

(b) Minimum cultivated land area

$$\sum_{i=1}^{3} X_{ijt}^{\pm} \geqslant HA_{\min jt}, \quad \forall j,t. \quad (9)$$

(2) Water resource availability constraints

(a) Surface drainage water availability

$$\sum_{j=1}^{3} SZ_{jt}^{\pm} \leqslant SW_{t}^{\pm}, \quad \forall t, \quad (10)$$

(b) Groundwater availability

$$\sum_{j=1}^{3} GZ_{jt}^{\pm} \leqslant GW_{t}^{\pm}, \quad \forall t, \quad (11)$$

(c) River water availability

$$\sum_{j=1}^{3} RZ_{jt}^{\pm} \leqslant RW_{t}^{\pm}, \quad \forall t, \quad (12)$$

(d) Total water resource availability

$$\sum_{i=1}^{2}\sum_{j=1}^{3} DWA_{ijt}^{\pm}\cdot X_{ijt}^{\pm} + \sum_{k=1}^{2}\sum_{j=1}^{3} DIY_{kjt}^{\pm} + \sum_{j=1}^{3} DTY_{jt}^{\pm} + \sum_{j=1}^{3} DRY_{jt}^{\pm} \leqslant \sum_{j=1}^{3}(SZ_{jt}^{\pm} + GZ_{jt}^{\pm} + RZ_{jt}^{\pm}), \quad \forall t. \quad (13)$$

(3) Water supply constraints

(a) Water supply for agriculture

$$\sum_{i=1}^{2}\sum_{j=1}^{3} DWA_{ijt}^{\pm}\cdot X_{ijt}^{\pm} \leqslant TAW_{t}^{\pm}, \quad \forall t, \quad (14)$$

(b) Water supply for industry

$$TIW_{\min t}^{\pm} \leqslant \sum_{k=1}^{2}\sum_{j=1}^{3} DIY_{kjt}^{\pm} \leqslant TIW_{\max t}^{\pm}, \quad \forall t, \quad (15)$$

(c) Water supply for tourism

$$TTW_{\min t}^{\pm} \leqslant \sum_{j=1}^{3} DTY_{jt}^{\pm} \leqslant TTW_{\max t}^{\pm}, \quad \forall t, \quad (16)$$

(d) Water supply for municipal sector

$$TRW_{\min t}^{\pm} \leqslant \sum_{j=1}^{3} DRY_{jt}^{\pm} \leqslant TRW_{\max t}^{\pm}, \quad \forall t. \quad (17)$$

(4) Wastewater treatment capacity constraint

$$\sum_{k=1}^{2}\sum_{j=1}^{3} PIW_{kjt}^{\pm}\cdot DIY_{kjt}^{\pm} + \sum_{j=1}^{3} PTW_{jt}^{\pm}\cdot DTY_{jt}^{\pm} + \sum_{j=1}^{3} PRW_{jt}^{\pm}\cdot DRY_{jt}^{\pm} \leqslant WTC_{t}, \quad \forall t. \quad (18)$$

(5) Eco-environmental constraints

(a) Soil erosion control

$$\sum_{i=1}^{3}\sum_{j=1}^{3} SE_{ijt}^{\pm}\cdot X_{ijt}^{\pm} \leqslant TSE_{t}^{\pm}, \quad \forall t, \quad (19)$$

(b) Nitrogen discharge control

$$\left(\sum_{k=1}^{2}\sum_{j=1}^{3} PIN_{kjt}^{\pm}\cdot DIY_{kjt}^{\pm} + \sum_{j=1}^{3} PTN_{jt}^{\pm}\cdot DTY_{jt}^{\pm} + \sum_{j=1}^{3} PRN_{jt}^{\pm}\cdot DRY_{jt}^{\pm}\right)(1 - EN_{t}^{\pm}) + \sum_{i=1}^{3}\sum_{j=1}^{3} SN_{jt}^{\pm}\cdot X_{ijt}^{\pm} \leqslant TAN_{t}^{\pm}, \quad \forall t, \quad (20)$$

(c) Phosphorus discharge control

$$\left(\sum_{k=1}^{2}\sum_{j=1}^{3} PIP_{kjt}^{\pm}\cdot DIY_{kjt}^{\pm} + \sum_{j=1}^{3} PTP_{jt}^{\pm}\cdot DTY_{jt}^{\pm} + \sum_{j=1}^{3} PRP_{jt}^{\pm}\cdot DRY_{jt}^{\pm}\right)(1 - EP_{t}^{\pm}) + \sum_{i=1}^{3}\sum_{j=1}^{3} SP_{jt}^{\pm}\cdot X_{ijt}^{\pm} \leqslant TAP_{t}^{\pm}, \quad \forall t. \quad (21)$$

where f = the expected net system benefit (\$); t = time period, $t = 1, 2, 3$; i = the type of crop, $i = 1, 2, 3$ (where i = 1 for corn, 2 for potato, 3 for rice); j = sub-region, $j = 1, 2, 3$ (where j = 1 for sub-region 1, 2 for sub-region 2, 3 for sub-region 3); k = the type of industry, $k = 1, 2$ (where k = 1 for metallurgical industry, 2 for food industry); $BA_{ijt}^{\pm}$ = market price of crop i in sub-region j in period t (\$/kg); $G_{ijt}^{\pm}$ = yield of crop i in sub-region j in period t (kg/km^2); $CA_{ijt}^{\pm}$ = cost for cultivating crop i in sub-region j in period t (\$/km^2); $CS_{jt}^{\pm}$ = cost for pumping and delivering the surface drainage water in sub-region j in period t (\$/m^3); $CG_t^{\pm}$ = cost for pumping and delivering the ground water in sub-region j in period t (\$/m^3); $CR_{jt}^{\pm}$ = cost for pumping and delivering the river water in sub-region j in period t (\$/m^3); $BI_{kjt}^{\pm}$ = unit benefit of water allocated to industry k in sub-region j in period t (\$/m^3); $BT_{jt}^{\pm}$ = unit benefit of water allocated to tourism in sub-region j in period t (\$/m^3); $BR_{jt}^{\pm}$ = unit benefit of water allocated to the municipal sector in sub-region j in period t (\$/m^3); $CIW_{kt}^{\pm}$ = treatment cost of wastewater from industry k in period t (\$/tonne); $CTW_t^{\pm}$ = treatment cost of wastewater from tourism industry in period t (\$/tonne); $CRW_t^{\pm}$ = treatment cost of wastewater from municipal sector in period t (\$/tonne); $PIW_{kjt}^{\pm}$ = unit wastewater discharge by industry k in sub-region j in period t (tonne/m^3); $PTW_{jt}^{\pm}$ = unit wastewater discharge by tourism industry in sub-region j in period t (tonne/m^3); $PRW_{jt}^{\pm}$ = unit wastewater discharge by municipal sector in sub-region j in period t (tonne/m^3); $HA_{\max jt}$ = the maximum area allocated to crop i in sub-region j in period t (km^2); $HA_{\min jt}$ = the minimum area allocated to crop i in sub-region j in period t (km^2); $SW_t^{\pm}$ = the maximum allocated surface drainage water amount in sub-region j in period t (m^3); $GW_t^{\pm}$ = the maximum allocated groundwater amount in sub-region j in period t (m^3); $RW_t^{\pm}$ = the maximum allocated river water amount in sub-region j in period t (m^3); $DWA_{ijt}^{\pm}$ = the unit irrigation demand for crop i in sub-region j in period t (m^3/km^2); $TAW_t^{\pm}$ = the maximum water amount allocated to agriculture in period t (m^3); $TIW_{\max t}^{\pm}$ = the maximum water amount allocated to industry in period t (m^3); $TTW_{\max t}^{\pm}$ = the maximum water amount allocated to tourism in period t (m^3); $TRW_{\max t}^{\pm}$ = the maximum water amount allocated to municipal sector in period t (m^3); $TIW_{\min t}^{\pm}$ = the minimum water amount allocated to industry in period t (m^3); $TTW_{\min t}^{\pm}$ = the minimum water amount allocated to tourism in period t (m^3); $TRW_{\min t}^{\pm}$ = the minimum water amount allocated to residents in period t (m^3); WTC_t = total wastewater treatment capacity in period t (tonne); $SE_{ijt}^{\pm}$ = amount of soil lost from the land planted with crop i in sub-region j in period t (kg/km^2); $TSE_t^{\pm}$ = the allowed amount of soil lost in period t (kg); $SN_{jt}^{\pm}$ = nitrogen percent content of the soil in sub-region j in period t (%); $SP_{jt}^{\pm}$ = phosphorus percent content of the soil in sub-region j in period t (%); $PIN_{kjt}^{\pm}$ = unit nitrogen discharge by industry k in sub-region j in period t (tonne/m^3); $PIP_{kjt}^{\pm}$ = unit phosphor discharge by industry k in sub-region j in period t (tonne/m^3); $PTN_{jt}^{\pm}$ = unit nitrogen discharge by tourism industry in sub-region j in period t (tonne/m^3); $PTP_{jt}^{\pm}$ = unit phosphor discharge by tourism industry in sub-region j in period t (tonne/m^3); $PRN_{jt}^{\pm}$ = unit nitrogen discharge by municipal sector in sub-region j in period t (tonne/m^3); $PRP_{jt}^{\pm}$ = unit phosphor discharge by municipal sector in sub-region j in period t (tonne/m^3); $EN_t^{\pm}$ = nitrogen removal efficiency in period t (%); $EP_t^{\pm}$ = phosphor removal efficiency in period t (%); $TAN_t^{\pm}$ = the allowed amount of nitrogen discharge in period t (kg); $TAP_t^{\pm}$ = the allowed amount of phosphor discharge in period t (kg); $X_{ijt}^{\pm}$ = area allocated to crop i in sub-region j in period t (km^2); $DIY_{kjt}^{\pm}$ = water allocated to industry k in sub-region j in period t (m^3); $DTY_{jt}^{\pm}$ = water allocated to tourism in sub-region j in period t (m^3); $DRY_{jt}^{\pm}$ = water allocated to municipal sector in sub-region j in period t (m^3); $SZ_{jt}^{\pm}$ = allocated amount of surface drainage water in sub-region j in period t (m^3); $GZ_{jt}^{\pm}$ = allocated amount of groundwater in sub-region j in period t (m^3); $RZ_{jt}^{\pm}$ = allocated amount of river water in sub-region j in period t (m^3).

The purpose of the developed model is to pursue the best economic and environmental benefits within actual constraints of a regional water system. In terms of the total cultivated land area, it should be limited to the range of maximum and minimum available values. At the same time, the objective should be restrained by local natural conditions. Quantity limits have been set up on surface drainage water, groundwater, and river water, as well as the total water resource. Water supplies for agricultural, industrial, tourism, and municipal sectors also have corresponding ranges, which both ensure their normal operation and avoid the misuse of water resources. As for protecting local water quality, it is of great significance to control wastewater, soil, nitrogen, and phosphor discharges within acceptable levels. Overall, the model CWR-ALUPM of a regional water system in the agricultural watershed can be abstracted from the real world by formulating these objective function and relative constraints.

2.2 Solution method

In this study, ILP and CCP will be integrated into a general framework and then be employed for solving the coupled water resources and agricultural land-use planning model (CWR-ALUPM) for dealing with the uncertainties existing in the system (Huang et al., 1992, 1995a,b; Cai et al., 2007, 2009a, b, c; Tan et al., 2010; Dong et al., 2012). The modeling approach can be formulated as follows:

$$\max f^{\pm} = C^{\pm} \cdot X^{\pm}, \tag{22}$$

subject to

$$A^{\pm} X^{\pm} \leqslant B^{Pi^{\pm}}, \tag{23}$$

$$X^{\pm} \geqslant 0, \tag{24}$$

where $A^{\pm} \in \{\Re^{\pm}\}^{m\times n}$, $B^{\pm} \in \{\Re^{pi^{\pm}}\}^{m\times l}$, $C^{\pm} \in \{\Re^{\pm}\}^{l\times n}$, $X^{\pm} \in \{\Re^{\pm}\}^{n\times l}$, and $\Re^{\pm}$ denotes a set of interval numbers. Let x denote a closed and bounded set of real numbers. An interval number with known upper and lower bounds but with unknown distribution information is defined as an interval for x, $x^{\pm} = [x^{-}, x^{+}]$, where x^{-} and x^{+} represent the lower and upper bounds of $x^{\pm}$, respectively. When $x^{-} = x^{+}$, $x^{\pm}$ becomes a deterministic number, i.e., $x^{\pm} = x^{-} = x^{+}$. And P_i denotes a series of probability levels for parameters, which presents the violation levels of the related constraints.

According to the solution algorithm developed by Huang et al. (1992, 1995a, b), the model proposed above under different P_i values can be divided into two sub-models through a two-step method:

$$\max f^{+} = \sum_{j=1}^{k_1} c_j^{+} \cdot x_j^{+} + \sum_{j=k_1+1}^{n} c_j^{+} \cdot x_j^{-}, \tag{25}$$

subject to

$$\sum_{j=1}^{k_1} |a_{ij}|^{-} \operatorname{sign}(a_{ij}^{-}) x_j^{+} + \sum_{j=k_1+1}^{n} |a_{ij}|^{+} \operatorname{sign}(a_{ij}^{+}) x_j^{-} \leqslant b_i(t)^{(P_i)}, \quad \forall i, \tag{26}$$

$$x_j^{+} \geqslant 0, \quad \forall j, \tag{27}$$

and

$$\max f^{-} = \sum_{j=1}^{k_1} c_j^{-} \cdot x_j^{-} + \sum_{j=k_1+1}^{n} c_j^{-} \cdot x_j^{+}, \tag{28}$$

subject to

$$\sum_{j=1}^{k_1} |a_{ij}|^{+} \operatorname{sign}(a_{ij}^{+}) x_j^{-} + \sum_{j=k_1+1}^{n} |a_{ij}|^{-} \operatorname{sign}(a_{ij}^{-}) x_j^{+} \leqslant b_i(t)^{(P_i)}, \quad \forall i, \tag{29}$$

$$x_j^{\pm} \geqslant 0, \forall j, \tag{30}$$

$$x_j^{-} \leqslant (x_j^{+})_{opt}, \quad j = 1,2,...,k, \tag{31}$$

$$x_j^{+} \geqslant (x_j^{-})_{opt}, \quad j = k+1, k+2,...,n. \tag{32}$$

When the objective function is to be maximized, the sub-model corresponding to the upper bound of objective function values f^{+} is firstly formulated, and then the lower bound sub-model corresponding to f^{-} can be obtained based on the solutions of the first sub-model. Through solving the two sub-models (3) and (4), we can gain the solutions as follows: $(x_j)_{opt} = [(x_j^{-})_{opt}, (x_j^{+})_{opt}]$, and $f_{opt} = [f_{opt}^{-}, f_{opt}^{+}]$.

Tables 1 to 3 provide crop yields, benefits of industrial, tourism, and municipal sectors, and maximum available water resources, respectively. Through solving the model above, a series of interval decisions related to water resource utilization, farmland use, and eco-environmental protection schemes are generated.

3 Result analysis

Table 4 shows solutions of the planting areas of various crops in the three sub-regions, which vary on the basis of crop yields and prices, as well as local agricultural policies in periods 1 to 3. For example, for sub-region 1, there is [6.44, 10.63] km^2 area being planted with corn in period 1, and then the planted area decreases to zero in periods 2 and 3; potato is planted in periods 2 and 3, with the planting areas of 4.47 and [7, 9.29] km^2; the total cropping areas are [67.81, 72], 65, and [56.71, 59] km^2 in the three periods, respectively. Due to the favorable environment for agriculture, sub-region 2 can plant 5.21, 20.97, and 38.57 km^2 of potato, 64.97, 56.03, and 40.01 km^2 of rice, with the total areas of 88, 77, and 78.58 km^2 in periods 1, 2, and 3, contributing a large portion of the regional agriculture. Compared with the first two sub-regions, sub-region 3 can satisfy the corn demand in periods 1 and 2 with the planting areas of 66 and [37.17, 42.15] km^2, and relatively less cropping areas of potato and rice, 0, 5.49, and 0.53 km^2 for potato, and 0, 11.36, and 39.47 km^2 for rice in the three periods. And the total areas show the tendency to ascend from 66 km^2 in period 1, [54.02, 59] km^2 in period 2, and 40 km^2 in period 3. Overall, sub-region 2 is the biggest commercial production base of agriculture.

Table 5 indicates the irrigation requirements of various crops in the three periods. In the study region, [13.42, 13.68] and [5.44, 6.05] × 10^6 m^3 are used for irrigating corn in periods 1 and 2, and no water resource needs be transported to cornfields while no corn is planted in period 3. The irrigation requirements for potato planting are 0.80, 4.71, and 6.90 × 10^6 m^3 in the three periods. For rice planting, 60.39, 60.95, and 61.45 × 10^6 m^3 are assigned to ensure rice production. Total water requirements for

Table 1 Crop yields (tonne/km^2)

Sub-region	Crop	Period		
		$t = 1$	$t = 2$	$t = 3$
1	Corn	[645, 650]	[655, 660]	[665, 670]
	Potato	[2950, 3000]	[3050, 3100]	[3150, 3200]
	Rice	[845, 850]	[855, 860]	[865, 870]
2	Corn	[65, 660]	[665, 670]	[675, 680]
	Potato	[3150, 3200]	[3250, 3300]	[3350, 3400]
	Rice	[855, 860]	[865, 870]	[875, 880]
3	Corn	[635, 640]	[645, 650]	[655, 660]
	Potato	[2850, 2900]	[2950, 3000]	[3050, 3100]
	Rice	[835, 840]	[845, 850]	[855, 860]

Table 2 Benefits of water supply for industrial, tourism, and municipal sectors (\$/m^3)

Sub-region	Industry type	Period		
		$t = 1$	$t = 2$	$t = 3$
1	Metallurgical industry	[0.745, 0.754]	[0.769, 0.778]	[0.786, 0.795]
	Food industry	[0.706, 0.715]	[0.724, 0.732]	[0.737, 0.745]
2	Metallurgical industry	[0.713, 0.725]	[0.735, 0.743]	[0.754, 0.768]
	Food industry	[0.680, 0.689]	[0.694, 0.705]	[0.711, 0.720]
3	Metallurgical industry	[0.769, 0.778]	[0.790, 0.798]	[0.827, 0.835]
	Food industry	[0.740, 0.748]	[0.761, 0.770]	[0.784, 0.795]
1	Tourism	[0.866, 0.875]	0.896	0.918
2		[0.840, 0.847]	0.860	0.873
3		[0.814, 0.815]	[0.820, 0.828]	[0.829, 0.840]
1	Resident	[0.573, 0.584]	[0.609, 0.618]	[0.628, 0.635]
2		[0.573, 0.585]	[0.609, 0.619]	[0.628, 0.636]
3		[0.573, 0.586]	[0.609, 0.620]	[0.628, 0.637]

Table 3 Maximum available water resource under different significance level ($\times 10^4$ m^3)

Period	Significance level			
	$P_i = 0.01$	$P_i = 0.05$	$P_i = 0.10$	$P_i = 0.15$
Maximum available surface drainage water amount				
$t = 1$	[2587, 2678]	[2742.22, 2838.68]	[2871.57, 2972.58]	[3000.92, 3106.48]
$t = 2$	[2496, 2564]	[2645.76, 2717.84]	[2770.56, 2846.04]	[2895.36, 2974.24]
$t = 3$	[2415, 2504]	[2559.90, 2654.24]	[2680.65, 2779.44]	[2801.40, 2904.64]
Maximum available groundwater amount				
$t = 1$	[4275, 4356]	[4488.75, 4573.80]	[4617, 4704.48]	[4809.38, 4900.50]
$t = 2$	[3984, 4056]	[4183.20, 4258.80]	[4302.72, 4380.48]	[4482, 4563]
$t = 3$	[3485, 3567]	[3659.25, 3745.35]	[3763.80, 3852.36]	[3920.63, 4012.88]
Maximum available river water amount				
$t = 1$	[11855, 12146]	[12566.30, 12874.76]	[13040.50, 13482.06]	[13751.80, 14089.36]
$t = 2$	[11446, 11814]	[12132.76, 12522.84]	[12590.60, 13113.54]	[13277.36, 13704.24]
$t = 3$	[11187, 11535]	[11858.22, 12227.10]	[12305.70, 12803.85]	[12976.92, 13380.60]

Table 4 Cropping areas (km^2)

Sub-region	Crop	Period		
		t = 1	*t* = 2	*t* = 3
1	Corn	[6.44, 10.63]	0	0
	Potato	0	4.47	[7, 9.29]
	Rice	61.37	60.53	49.71
	Total	[67.81, 72]	65	[56.71, 59]
2	Corn	17.82	0	0
	Potato	5.21	20.97	38.57
	Rice	64.97	56.03	40.01
	Total	88	77	78.58
3	Corn	66	[37.17, 42.15]	0
	Potato	0	5.49	0.53
	Rice	0	11.36	39.47
	Total	66	[54.02, 59]	40

Table 5 Irrigation requirements for different corps ($\times 10^6$ m^3)

Crop	Period		
	t = 1	*t* = 2	*t* = 3
Corn	[13.42, 13.68]	[5.44, 6.05]	0
Potato	0.80	4.71	6.90
Rice	60.39	60.95	61.45
Total	[74.61, 74.87]	[71.10, 71.71]	68.35

irrigation can reach to [74.61, 74.87], [71.10, 71.71], and 68.35 × 10^6 m^3 in periods 1, 2, and 3, which presents a downtrend due to the improvement of water-saving irrigation technology. These solutions show that the preferred crop is rice in this region.

In this study region, industries mainly include metallurgy and food. Under comprehensive consideration of industry features, water resource availability, and pollution limitations, the water resource quantities allocated to the two industries of three sub-regions in the three periods are presented in Fig. 2 (lower bound). It is shown that in sub-regions 1 and 3, food industry is placed in the prime spot, [2.87, 2.95], [3, 3.13], and [3.10, 3.17] × 10^6 m^3 for sub-region 1, and [5.36, 5.50], [5.60, 5.84], and [5.78, 5.92] × 10^6 m^3 for sub-region 3 in the three periods. The metallurgical industry in sub-region 1 needs [0.96, 0.98], [1.00, 1.04], and [1.03, 1.06] × 10^6 m^3 of water, and [4.21, 4.32], [4.40, 4.59], and [4.54, 4.65] × 10^6 m^3 are required for sub-region 3, respectively. Sub-region 2 needs to attach weight to the metallurgical industry, which requires [3.25, 3.34], [3.40, 3.55], and [3.51, 3.60] × 10^6 m^3 of water, and [2.49, 2.56], [2.60, 2.71], and [2.68, 2.75] × 10^6 m^3 for food industry in periods 1, 2, and 3, respectively. This figure also indicates that the water resource requirements of the two industries increase period by period to meet the development of industry, and sub-region 3 is the major industry base in this region.

Table 6 lists the water requirements for the tourism and municipal sectors in three sub-regions in periods 1, 2, and 3. For tourism, restrained by natural conditions, sub-region 1 is the scenic-tourist site of this region, requiring [1.75, 8], [2.93, 10.48], and [6.20, 15.67] × 10^6 m^3 of water resources. The other two sub-regions do not qualify for the development of tourism. For the municipal sector, water is a necessity for supporting the daily life of local residents. In sub-region 1, [14.47, 14.89], [16.23, 16.94], and [17.37, 17.83] × 10^6 m^3 of water resources are needed; sub-region 2 requires [11.26, 11.84], [12.17, 12.74], and [12.41, 12.95] × 10^6 m^3; [9.36, 9.78], [10.14, 10.74], and [11.26,

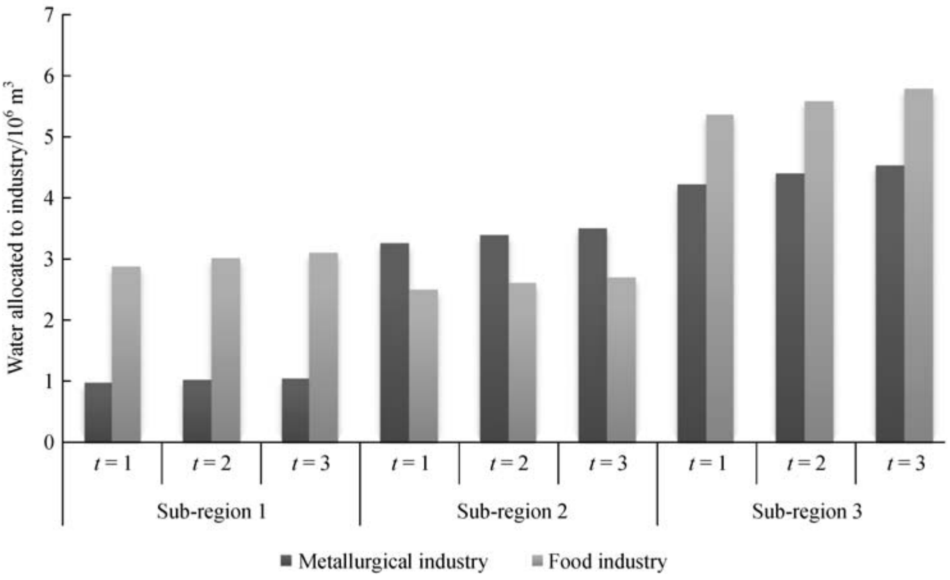

Fig. 2 The water resource allocated to industry under a lower bound.

Table 6 Water requirements for tourism and municipal sectors ($\times 10^6$ m^3)

Sub-region	Industry type	Period		
		$t = 1$	$t = 2$	$t = 3$
1	Tourism	[1.75, 8]	[2.93, 10.48]	[6.20, 15.67]
	Municipal	[14.47, 14.89]	[16.23, 16.94]	[17.37, 17.83]
2	Tourism	0	0	0
	Municipal	[11.26, 11.84]	[12.17, 12.74]	[12.41, 12.95]
3	Tourism	0	0	0
	Municipal	[9.36, 9.78]	[10.14, 10.74]	[11.26, 11.89]

11.89] × 10^6 m^3 are allocated to sub-region 3 for residents in the three periods, respectively. As shown in this table, sub-region 1 is the biggest water consumer for the municipal sector.

As shown in Table 7, the soil erosion caused by the cropping varies among different types of crops. For instance, the soil erosion from potato planting increases from [2.29, 2.32] and [13.04, 13.26] to [20.30, 20.88] × 10^6 tonnes in periods 1, 2, and 3, while [4.05, 4.24], [4.03, 4.22], and [3.92, 4.10] × 10^6 tonnes are eroded from rice fields according to the crop features and planting areas. For environmental pollution, a total amount of [18.12, 18.75], [18.64, 19.29], and [19.15, 19.71] × 10^6 tonnes of wastewater are discharged into the surroundings, with an upward trend each period. Additionally, this region produces [1.50, 1.51], [1.30, 1.32], and [1.08, 1.09] × 10^6 tonnes of nitrogen and [0.41, 0.42], 0.36, and [0.29, 0.30] × 10^6 tonnes of phosphor in periods 1, 2, and 3, respectively, both presenting a downward tendency.

Generally, different P_i values represent different violation levels. In this model, four P_i values are considered, including 0.01, 0.05, 0.10, and 0.15. Higher P_i values lead to a higher probability of constraint violation and then bigger allocation amounts of the three kinds of water resources (e.g., surface drainage water, river water, and groundwater). As show in Fig. 3, the surface drainage water can be only allocated to sub-region 2 and the allocation amount in period 1 increases from [24.58, 27.25], [26.05, 27.25], and [26.42, 27.35] to [28.51, 29.82] × 10^6 m^3 under the four violation levels, which presents an upward trend. In period 3, [22.94, 25.48], [24.32, 25.48], [24.66, 25.57], and [26.61, 27.88] × 10^6 m^3 of surface drainage water are needed when the violation levels are 0.01, 0.05, 0.10, and 0.15. Figure 4 shows the groundwater allocation solutions under the lower bound, which means that most of the groundwater is sent to sub-region 3. Specifically, in period 1, 31.64, 33.22, 33.24, and 35.59 × 10^6 m^3 are pumped to sub-region 3 under the four violation levels. In addition, as the available groundwater quantity increases slightly, 1.04, 1.09, 0.63, and 1.16 × 10^6 m^3 are allocated to sub-region 1 under the lower bound, respectively. From periods 1 to 3, the consumptions of surface drainage water and groundwater decrease gradually to protect water resources.

Table 7 Solutions of pollution controlling actions

	Period		
	$t = 1$	$t = 2$	$t = 3$
Erosion (10^6 tonnes)			
Corn	19.94	7.62	0
Potato	[2.29, 2.32]	[13.04, 13.26]	[20.30, 20.88]
Rice	[4.05, 4.24]	[4.03, 4.22]	[3.92, 4.10]
Wastewater (10^6 tonnes)			
	[18.12, 18.75]	[18.64, 19.29]	[19.15, 19.71]
Total nitrogen (10^6 tonnes)			
	[1.50, 1.51]	[1.30, 1.32]	[1.08, 1.09]
Total phosphor (10^6 tonnes)			
	[0.41, 0.42]	0.36	[0.29, 0.30]

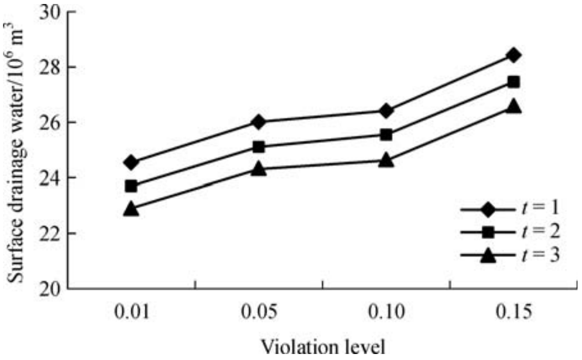

Fig. 3 The surface drainage water resource allocated to sub-region 2 under a lower bound.

Table 8 shows the river water resource allocation solutions, which illustrate more volume allocated to three sub-regions under higher P_i values. Particularly, under the violation levels of 0.01, 0.05, 0.10, and 0.15, the river water allocated to sub-region 1 increases from [61.95, 65.76], [65.08, 69.12], [65.32, 69.11], and [71.76, 76.17] × 10^6 m^3 in period 1 to [63.49, 67.74], [66.37, 70.87], [66.58, 70.87], and [80, 84.93] × 10^6 m^3 in period 3, becoming the biggest consumer. While sub-region 3 can obtain 16.09, 17.68, 17.88, and 16.02 × 10^6 m^3 in period 3 under the four violation levels as the smallest consumer according to the their river water pumping costs and availability. Besides that, these solutions also indicate that the deterministic allocations are not sensitive to system uncertainty, mainly due to the strict limitation of related constraints for sub-region 3.

In this model, higher P_i values lead to a higher probability of constraint violations, and generate a higher system benefit. In contrast, lower probability of constraint violations corresponding to lower P_i values can generate less system benefit. As shown in Fig. 5, the system benefit

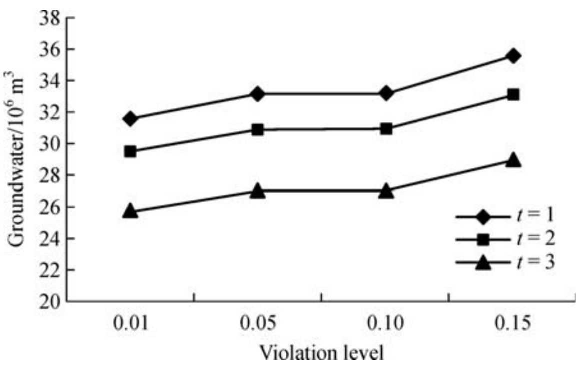

Fig. 4 The groundwater resource allocated to sub-region 3 under a lower bound.

Table 8 Available water resource allocation in the river ($\times 10^6$ m^3)

Sub-region	Period	Significance level			
		$P_i = 0.01$	$P_i = 0.05$	$P_i = 0.10$	$P_i = 0.15$
1	$t = 1$	[61.95, 65.76]	[65.08, 69.12]	[65.32, 69.11]	[71.76, 76.17]
	$t = 2$	[62.14, 66.59]	[65.14, 69.86]	[65.37, 69.86]	[73.08, 78.25]
	$t = 3$	[63.49, 67.74]	[66.37, 70.87]	[66.58, 70.87]	[80, 84.93]
2	$t = 1$	26.34	27.99	27.86	29.89
	$t = 2$	23.75	25.33	25.20	26.38
	$t = 3$	19.99	21.49	21.37	19.47
3	$t = 1$	17.22	18.77	18.97	20.75
	$t = 2$	15.98	17.51	17.71	18.72
	$t = 3$	16.09	17.68	17.88	16.02

increases from \$[270.49, 307.84], [271.86, 308.97], and [271.93, 309.05], to [272.37, 309.42] × 10^6 when the P_i value successively increases from 0.01, 0.05, 0.10, to 0.15. It is noteworthy that most solutions are intervals, which means that the corresponding decision variables are sensitive to the interval inputs. In comparison, deterministic solutions for the relevant decision variables will not be influenced by the uncertain parameters existing in the model.

4 Conclusions

In this research, a coupled water resources and agricultural land-use planning model (CWR-ALUPM) was developed for supporting the management of crops and water resource at a regional scale. In this model, interval linear programming (ILP) and chance-constraint programming (CCP) approaches were integrated into a general framework to tackle uncertainties and complexities expressed as intervals and probabilistic distributions. Then the developed model was applied to a typical regional water resource system in an agricultural watershed. The obtained solutions could help decision makers: (i) manage agricultural land uses to identify desired crop planting areas, (ii) allocate the available water resource to practical socio-economic activities of different sub-regions for achieving sustainable development, and (iii) determine optimal schemes under different constraint violations corresponding to various water resource supply conditions, balancing tradeoffs between social economy development and water resource protection. In addition, this proposed model can be entirely introduced into real-world cases based on the investigations of actual local situations.

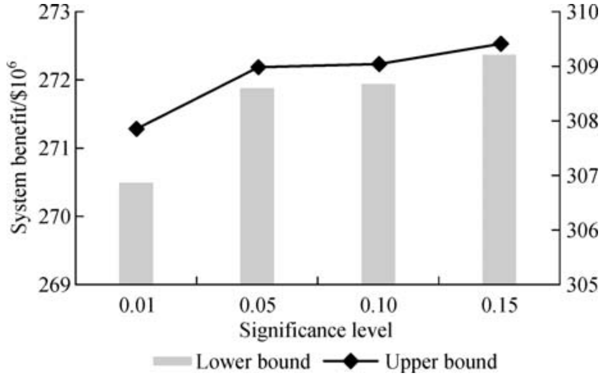

Fig. 5 The system benefit.

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