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Water Resources and Farmland Management in the Songhua River Watershed under Interval and Fuzzy Uncertainties

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Abstract The Songhua River Watershed (SHRW) in Northeastern China has been challenged by water scarcity, water contamination, and soil erosion for decades. These problems will remain or even worsen in the following decades, threatening regional eco-environmental quality and socio-economic development. Mitigation of these problems through integrated water resources and farmland management (WRFM) is desired but is challenged by multiple system complexities, e.g. interrelations of diverse system components. To fill this gap, an interval fuzzy water resources and farmland programming (IFWRFP) approach is developed in this study for eliminating the potential problems in the SHRW, leading to increased reliability of the decision support process. A series of systematic WRFM measures are proposed for enabling harmonious development of ecological environment and social economy in the SHRW. For instance, planting should always be the priority due to the major contribution of agriculture to the regional economy. As the primary commercial crop, rice cultivation should be allocated the most irrigation water, followed by corn, potato and soybean. Potato yield should be increased to compensate for reduced productivity of the other crops since 2019. It is also revealed that economic benefits are proportional to water environmental pollution in the SHRW. Therefore, decision-makers should adopt the most reasonable suggested schemes after fully balancing the trade-off of environment and economy. Most importantly, a variety of

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supporting policies are required for enabling sufficient implementation of these measures across the SHRW. For instance, individual farmers can be encouraged to follow the overall crop cultivation plan by the alteration of subsidiaries, taxes, and prices on crop-related activities. The modeling solutions show that the IFWRFP approach can systematically optimize allocations of water resources and cultivation patterns and thus potentially eliminate the problems of water scarcity, water contamination, and soil erosion in the SHRW.

Keywords Water resources · Soil erosion · Farmland · Interval fuzzy · Songhua River watershed

1 Introduction

As the largest river in Northeastern China and the seventh largest in China, the Songhua River has been the main freshwater source for many users such as agriculture, industries, households, and tourism in the provinces of Inner Mongolia, Jilin, and Heilongjiang. It is also significant for the conservation of wetlands and ecosystems (Liu et al. 2007a; Tan et al. 2010). However, a large amount of contaminants generated from extensive human activities and soil erosion were emitted into this river in the past decades. Ineffective allocation of water resources and farmland further aggravated the conflict among water users and exacerbated the problem of water pollution. Human and ecological health and socio-economic development were severely threatened by deteriorating water quality, decreasing water availability, and myopic water resources management schemes (Wang et al. 2012; Liu et al. 2007c; Wang et al. 2013). Meanwhile, the Songhua River Watershed (SHRW) is a huge and open system. It consists of numerous components (e.g., resources availability, distribution, and policy), processes (e.g., utilization technology, hydrologic process, and contaminant transportation), and external factors (e.g., social, economy, and natural conditions), which are dynamically interrelated with each other. It is a challenging task for decision makers such as local governments and stakeholders to identify a reasonable scheme of water resources and farmland allocations based on experiences. Lack of such a scheme leads to unreasonable water resources and land use, further worsens the situation of contamination and soil erosion (White and Fennessy 2005). A reliable and robust management scheme that can promote socio-economic development without harming eco-environmental quality under multiple system complexities is much desired for coordinating interests of various stakeholders and mitigating potential problems in the SHRW (Brabec et al. 2002; Mitchell 2005; Cho 2016).

Previously, a few of studies were conducted to support water resources and farmland management (WRFM) in the SHRW (Zhang et al. 2007; Shen et al. 2007; Liu et al. 2007a, 2007b; Li et al. 2008; Yu et al. 2009; Yang et al. 2010; Jin et al. 2010; Li et al. 2010; Zhang et al. 2010; Yan et al. 2012; Yang et al. 2015; Yu et al. 2016). For instance, Liu et al. (2007a) and Li et al. (2008) proposed potential measures for controlling organic pollution and non-point-source pollution, respectively, based on qualitative analyses. The effects of several alternative management measures were investigated by Jin et al. (2010) for water-quality improvement in the mainstream of the SHRW based on the construction of a water quality simulation model. In fact, the main problem of WRFM in the SHRW is the lack of systemic analysis and management of the WRFM system, and coordination of WRFM measures as well (Li et al. 2010). Thus, only focusing on the water quality management is largely insufficient to overcome this challenge. Recently, the management of water resources systems have been conducted in a few studies. For example, Yan et al. (2012) used a multi-objective programming model to provide several suggestions on water resources allocation in the Harbin region within the SHRW. Yu et al. (2016) developed a deterministic linear programming model for optimizing the distributions of total water pollutant emissions in the SHRW.

However, the literature review as stated above shows that no study was dedicatedly conducted to guide the integrated management of water allocation, water quality, soil erosion, and farmland use for achieving harmonious development of ecological environment and social economy in the SHRW. Furthermore, this task is challenged by the existence of dual uncertainties in water-related activities (e.g., water resources collection, distribution, usage, as well as wastewater treatment) in the SHRW-WRFM system, challenging the feasibility and effectiveness of existing alternative WRFM methods (e.g., Tong and Chen 2002; Richter et al. 2003; Hajkowicz and Collins 2007; Singh 2014; Albert et al. 2016; Dyckman 2016; Huo et al. 2016; Quitian and Rodríguez 2016; Turner et al. 2016; Serrao-Neumann et al. 2017). Specifically, deterministic estimations of WRFM system component properties such as water demand may be hardly achievable due to diversity and interactions of these components, ineffectiveness of estimation techniques, insufficiency of data monitoring, or other causes. It is a common practice for the SHRW-WRFM system that these non-deterministic estimations are performed as a series of interval-valued ranges with lower and upper boundaries. Meanwhile, another type of non-deterministic estimations in WRFM under uncertainties is fuzziness which mainly represents subjective estimations of related decision makers for some uncertain system component properties (e.g. the maximum surface water or groundwater allocation amounts to diverse end-users, and the allowed amount of soil loss or pollutants discharges). The aforementioned complexities in the SHRW-WRFM problem could hardly be effectively resolved by existing WRFM methods, especially the ones focusing on the SHRW. A reliable WRFM approach that can incorporate water allocation, water quality, soil erosion, farmland use, and economic development into the decision support process under coexistence of interval and fuzzy uncertainties is desired for the governments and the related stakeholders in the SHRW.

Therefore, the objective of this study is to propose an interval fuzzy water resources and farmland programming (IFWRFP) model for optimization of the WRFM scheme in the SHRW. Fuzzy linear programming and interval linear programming are combined into IFWRFP to deal with the fuzzy and interval uncertainties in the SHRW-WRFM system, respectively. IFWRFP can provide scientific support for WRFM in the SHRW under the consideration of water scarcity, water contamination, farmland use, and soil erosion. The objective can be further specified as i) identification of the influencing factors, structure, components and their interactions within the SHRW-WRFM system based on collection and analysis of a large amount of related data; ii) parameterization of multi-uncertainties in the SHRW-WRFM system as interval numbers and fuzzy sets; iii) construction of an IFWRFP model according to the practical problems existing in the SHRW; and iv) provision of decision support, especially allocation plans of water resources and farmland usage.

2 SHRW-WRFM Systems Analyses

2.1 System Identification

The Songhua River Watershed (SHRW) is the largest watershed in Northeastern China and covers a very large area across three provinces. This watershed is a coupled human-natural system involving complicated interactions among multi-dimensional human activities and natural processes at a broad range of spatial and temporal scales (Cai et al. 2013). The comprehensive system identification across natural and administrative boundaries is conducted to support the subsequent modeling studies, e.g. parameterization, model construction, scheme optimization, and management practices, aiming to address a series of potential water resource issues that might happen in this watershed.

As the first step of this process, the boundary of a general system of WRFM in a watershed is identified in accordance with expert experiences. Accordingly, a variety of relevant observation datasets, governmental reports, academic publications, statistical yearbooks, and many other data are extensively collected. Based on a systematic analysis of these data, the system boundary of WRFM in the SHRW is specified and the components, structure, complexities and potential problems in this system are sufficiently identified. In the latter process, the focus is to identify WRFM activities, their influential factors (e.g. water availabilities) and various impacts (e.g. water quality), the interrelationships among all system components, the related complexities in system optimization, and the consequences of unreasonable WRFM strategies in the SHRW. The result of SHRW-WRFM system identification is summarized in the following sub-sections: (2) to (5).

2.2 System Components

The Songhua River has two sources. One is the Nenjiang River originating from the middle part of Yilehuli Mountain in Greater Khingan, forming a vast plain area called Songnen plain. As the other source, the Second Songhua River originates from Changbai Mountain, joins the mainstream of Songhua River together with Nenjiang River, and then flows into the Heilongjiang River (Fig. 1) (He et al. 2011). The total length of the

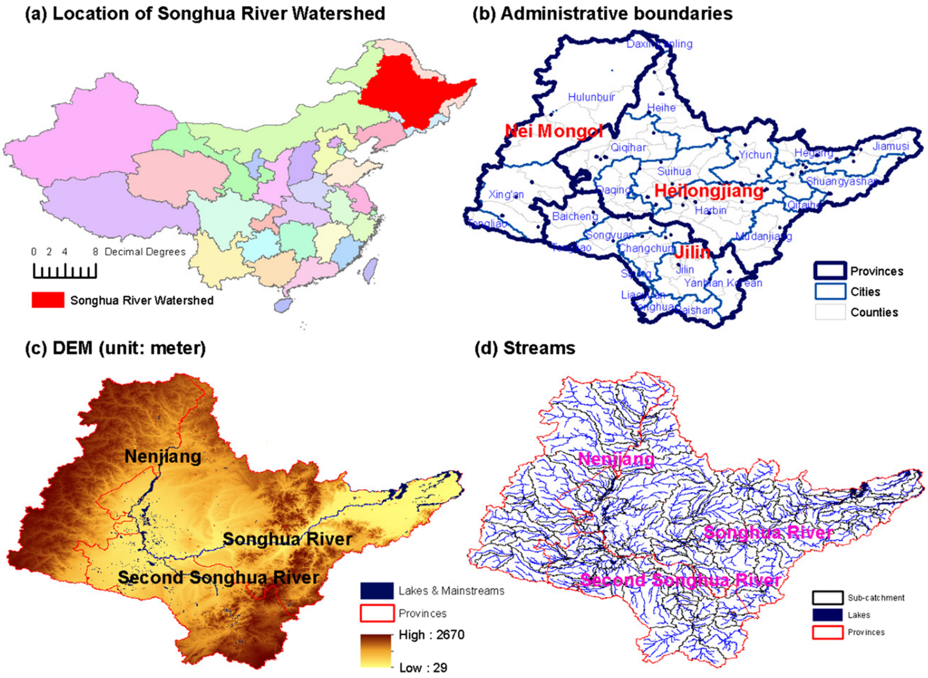

Fig. 1 Songhua River Watershed

Songhua River reaches to 2308 km and the SHRW covers a large area of 0.55 million km^2 following the Yangtze and Yellow River (Lei et al. 2008). The Songhua River mainly crosses the provinces of Inner Mongolia, Jilin, and Heilongjiang which account for around 28%, 24%, and 48% of the total watershed area. The annual average available water quantity of Songhua River is 88.0 billion m^3, including 73.5 billion m^3 of surface water, 11.7 billion m^3 of groundwater, and others (e.g., precipitation to be collected, and gray water to be reused) (Yang et al. 2010; Wang et al. 2012). Given the superior natural conditions (e.g., fertile soil, favorable climate and terrain, and abundant water resources), the SHRW is a significant industrial and agricultural base in China. Specifically, the industrial sectors in the SHRW consumed totally 6.04 billion m^3 of water in 2013. Besides, the SHRW is one of three major regions covered by black soil land worldwide. Due to the high fertility of black soil, this watershed is one of the most important commodity grain bases (Miao et al. 2011) that are suitable for growing corns, soybeans, potato, and rice on a large scale (Liu et al. 2007a). In 2008, the cultivated area was 138.9 billion m^2; the effective irrigated area was only 28.6 billion m^2, producing 53.2 million tons of grains.

In recent decades, the increasing pressure on water resources in the SHRW mainly originates from the unreasonable industrial structure, extensive economic growth, and ineffective related technologies (Yang et al. 2009). In addition, as one of the highest concentrations of wetland, the SHRW is more susceptible to external disturbances due to rare precipitation and reduced evaporation. So far, the water body and wetland have been heavily polluted by contaminants from domestic and industrial wastewaters and agricultural nonpoint pollutants, e.g. total nitrogen and phosphorus (Zhang et al. 2012; Xu et al. 2014). Specifically, municipalities or some cities along the river, e.g. Harbin and Jilin, produce 58 to 68% of the total COD and ammonia nitrogen discharge amounts in the river (He et al. 2011). Low effective utilization of chemical fertilizers and pesticides aggravate surface and groundwater contaminations. The annual consumption of chemical fertilizers is 2.04 million tonnes, with the average amount of 0.05 kg/m^2 (Zhao et al. 2014). In order to meet increasing food requirements, subsequent excessive reclamation leads to severe soil erosion in the SHRW for a long period. Soil erosion has further reduced the soil nutrient and depth and sacrificed a part of cultivated areas. In 2013, the area of soil erosion reached to 71.47 billion m^2 (Miao et al. 2011). In the past decades, continuous efforts were conducted to improve water quality, especially constructing many wastewater treatment plants. However, existing facilities cannot satisfy the current requirements because of increasing wastewaters generated from industrial and domestic usages and possibly discharged into the river directly. The polluted water body further endanger human and ecosystem health and worsen the water shortage situation.

2.3 System Structure

The WRFM system consists of the subsystems of economy, society, as well as environment, which all have a mutual influence on each other. Within this structure, the analysis is based upon examination of the water flow processes which could cause serious conflicts between system benefits and environmental pollution. Specifically, the Songhua River has been the major water source for many purposes, such as agricultural, industrial, and domestic uses, in northeast China for centuries. Socio-economic development and population booming have caused abundant water consumption and water quality pollution and further threatened human and environmental health. Meanwhile, both economic policies and eco-environmental regulations made by governments for guiding the behaviors of water utilization can indirectly influence water environmental quality in the watershed. Conversely, ecosystem degradation in the form of water pollution and soil erosion caused by human activities substantially restrains socio-economic development throughout the watershed (Fig. 3 in the Appendix).

2.4 System Complexities

An analysis of the WRFM system is helpful for distinguishing the conflicts between social and environmental interests. Resolving these conflicts by scientific management is the goal of an optimization procedure. However, the WRFM system is really complex, involving interactions of related socio-economic and eco-environmental components. Thus, these complicated and varied interactions may lead to a series of obstacles for quantitative analysis of the system. Besides, planning focuses on the future. The length of planning period is related to risk and uncertainty, and the validity of planning models decreases when the length increases. More importantly, the model's data are mainly based on forecasting models (e.g., stream flow rates and water demands), manual monitoring (e.g., eco-environmental quality), and governmental reports (e.g., socio-economic policies). However, various errors may exist in the forecasting process, resulting in the uncertainty of predicted values. In a monitoring process, inevitable subjectivity in empirical estimation affects data reliability directly. Policies and regulations are inherently risky in guiding the development of economy and society in the future decades. The complex features of the WRFM system, inaccurate estimation processes, and data unavailability may result in interval fuzzy uncertainty which has to be taken into account in the modeling process (Cheng et al. 2017a, 2017b).

2.5 Problems

A plenty of eco-environmental problems such as water ecological crisis, water-quality deterioration, and soil erosion have been existing in the SHRW. For instance, increasing nitrogen and phosphor pollutants generated from the point and non-point sources pollution greatly threaten water quality. Moreover, unreasonable water resources and farmland management may reduce the availability of water and farmland resources in the following decades. This may result in a series of severe consequences to eco-environment health and socio-economic development in the watershed. In order to protect water environment and ecosystem health under socio-economic development, it is desired to propose a scientific approach to support WRFM in the SHRW under the aforementioned complexities. To achieve this, an interval fuzzy water resources and farmland programming (IFWRFP) approach is developed based on a comprehensive analysis of the SHRW-WRFM system as stated above. The related details and results of this approach, including a few of scientific suggestions on WRFM in the SHRW, are presented in the following sections.

3 IFWRFP Method Development

3.1 System Parameterization

To quantify the WRFM system in the SHRW, an IFWRFP model is constructed through an effective parameterization method according to the results of the aforementioned system identification. The parameterization method can be abstracted as a few of interrelated procedures. The potential WRFM activities such as alternative water allocation and irrigation patterns are parameterized as decision variables that are to be optimized by IFWRFP. The preference of the decision maker of the WRFM system in the SHRW is translated as the objective function of the IFWRFP model. A variety of resources/technical limitations or mass balancing relationships in WRFM that may contradict with each other are expressed as constraints of the IFWRFP model.

It is a common practice in modeling studies that the reliability of a constructed model is validated through a comparison between modeling results and observations. Model validation is especially desired when the system under study is of significant heterogeneity in time, space, or other dimensions that may lead to invalidity of the model (Huang 1998; Cheng et al. 2015b). In this study, the IFWRFP model is built to simulate the WRFM system in the SHRW at coarse temporal and spatial resolutions and at a medium planning-period length. Under these conditions, the SHRW-WRFM system which is mainly composed of simple mass-balance relationships among a series of WRFM activities and the corresponding influencing factors would hardly significantly change in the planning period in comparison with historical or current status. As for the influencing factors such as water availabilities and demands that may still gradually change even at coarse temporal or spatial resolutions, their status in every sub-planning period is reasonably obtained through trend analysis. Meanwhile, the existing studies in evaluating the future status of the coefficients in the SHRW-IFWRFP model, and governmental programs involving high-reliability datasets are referred in this study to ensure the credibility of the settings of coefficient values. Moreover, interval fuzzy uncertainty analysis is incorporated into the framework of IFWRFP; this technique can effectively enhance the adaptation of the IFWRFP model in simulating WRFM systems under uncertainties to a large extent.

In reality, the SHRW flows across three provinces, leading to the spatial heterogeneity and dynamical correlations of these provinces or local communities in multiple aspects such as water quality, water availability, soil erosion, economic development, and other related connections. As a particular example, upstream water pollution substantially affects downstream ecosystem quality and economic benefits. If we want to enable scientific WRFM at finer spatial, temporal and systematic resolutions such as 1 km, 1 day and 1 sectoral element, a high-resolution optimization model should be constructed accordingly. This would require an integrated river system simulation model at the corresponding fine temporal and spatial resolutions that can reproduce these multi-dimensional correlations across the SHRW. Model construction would highly rely on high-quality datasets in weather, hydrology, hydraulics, ecosystem, environment, geology, society, and some other aspects. For the SHRW, these datasets are not available, meaning that high-resolution WRFM is not achievable. Meanwhile, it is the expectation of local governors in the SHRW that WRFM is enabled at the watershed scale. Namely, water resources allocation, water quality control, soil erosion mitigation, and cultivation alteration can be scientifically optimized from the perspective of the entire watershed.

Under such a condition, there are at least two options for the research community that is expected to provide reliable decision support for local development. Option #1 is still to build a high-resolution WRFM model based on generation of high-resolution datasets through an artificial distortion of original low-resolution data observations. The obtained modeling results are hardly reliable. Option #2 is this study in which an optimization model is constructed according to the quality and resolution of available data. There is not an artificial distortion of available original information and can enable systematic optimization of the WRFM problem through IFWRFP, although the constructed IFWRFP model cannot reflect the complicated features of the hybrid socio-economic, environmental, chemical, physical, and ecological process in the SHRW at fine resolutions. In consideration of the limitation of current data availabilities, therefore, the SHRW is taken as an entire system in the IFWRFP model while these spatial correlations and heterogeneity cannot be considered.

3.2 Modeling Formulations

According to the results of system parameterization, the IFWRFP model is constructed. In this model, the decision variables corresponding to the alternative WRFM measures consist of cultivation areas for crops; water allocation amounts to end users include planting, metallurgy, food industries, tourism, and households; and the allocation amounts of surface water and groundwater to three provinces, i.e. Inner Mongolia, Jilin, and Heilongjiang. It is a common conclusion for almost all WRFM problems that these measures are associated with complicated tradeoffs among WRFM system elements (e.g. crops and industries) in multiple dimensions such as planning objectives and temporal and spatial units. For instance, an increase in the amount of surface water allocated to one sector in one province and one period may lead to a decrease in the cultivation area of one water-intensive crop in another province and another period.

Under the existence of these tradeoffs, the objective function of the IFWRFP model is to maximize the net economic benefit represented as the linear sum of the difference between the benefit and the cost from every WRFM activity. The other potential objectives such as water quality control and soil erosion control are reflected in the constraints. This is because local governments have promulgated regulations in pollutant emission and soil erosion. The governors of the WRFM system in the SHRW only expect the highest net economic benefit while ensuring these regulations are not violated. The supply and demand of water and farmland resources are expected to be balanced over the SHRW. Wastewater treatment capacities are integrated into this model. Proper control of water pollution (e.g., nitrogen and phosphor discharge) and soil erosion, suitable for maintaining environmental requirements, is performed for the water bodies. In the IFWRFP model, the length of the planning period is 15 years and is further divided into three periods. The system parameters and variables are expressed as intervals due to the existence of interval uncertainty in the SHRW-WRFM system; meanwhile, the fuzziness of interrelationships in the objective function and the constraints involving interval-valued coefficients is expressed as fuzzy membership functions. The detailed IFWRFP model, explanations of the parameters, the solution algorithm, and some of the related system inputs are displayed in the Appendix A.

4 Results Analysis and Discussion

The ranges of optimal WRFM schemes in the SHRW are presented in this section. These ranges are useful to generate multiple decision alternatives for decision makers under system-component diversity and uncertainty. The upper and lower bounds of net system benefits correspond to two extreme WRFM schemes concerning the trade-off between environmental conservation and economic development. A series of implications as stated below are revealed from multi-dimensional comparisons of the optimal WRFM schemes.

4.1 Optimal Cultivation Schemes

Table 1 illustrates cultivated areas of four crops in three provinces in periods 1 to 3. Heilongjiang owns the largest crop cultivation area, followed by the Inner Mongolia and Jilin province. Rice is the main commercial crop (40% of total cultivated area), followed by corn (39.59%) and potato (12.37%), and then soybean (8.04%). Besides, the corn, soybean and rice productions should decrease slowly in periods 2 and 3. This is because of their reduced planting areas limited by the usage of water and fertilizer. Conversely, the yield for potato should increase in period 2 to supplement grain productivity. The Inner Mongolia and Jilin province follow the similar crop-planting tendency with Heilongjiang province that the cultivation areas of crops should decrease from rice, corn, potato, to soybean. It is implied that, in comparison with the spatial and temporal dissimilarity of WRFP schemes among three provinces, the differences of water demands, fertilizer usage, and other related factors among crops pose significant impacts on WRF management practices in the SHRW.

4.2 Optimal Irrigation Schemes

As shown in Table 1, the allocated water for irrigations in Inner Mongolia, mainly depending on surface water. There is a continuous decreasing trend over three periods, partly resulting from nearly a 57% decrement of corn irrigation requirement in period 3. For soybean planting, [1267.62, 2257.96], [1287.41, 2226.35], and [1210.17, 2193.28] million m^3 of surface water are provided to ensure steady economic benefits in periods 1 to 3, respectively. Owing to low unit water demands and limited planting areas, potatoes need only [2052.69, 2565.86], [2023.95, 2529.94], and [4603.38, 5754.23] million m^3 of surface water in periods 1 to 3, respectively, due to large cultivation areas. In period 3, the water demand is almost double of that of the last two periods. Overall, planting rice consumes the most surface water resources; the allocation of surface water decreases slightly in period 3 if the irrigation technologies are improved in terms of efficiencies in the future.

The water demand in Jilin province is lower than that in any other province. Specifically, as the second largest crop, [2799.09, 3732.12], [2717.96, 3623.94], and [1119.71, 1492.95] million m^3 of surface water are delivered for corn planting in periods 1 to 3, respectively, decreasing sharply in period 3. Soybean planting requires the minimum amount of water resources due to low cultivation areas. Potato consumes [1573.68, 1967.1], [1532.61, 1915.76], and [3403.74, 4254.68] million m^3 of surface water in periods 1 to 3, respectively, growing almost by 122% in period 3. Rice is still the largest water consumer, presenting a similar variation trend with those of Inner Mongolia.

Table 1 Cultivated area (km^2) and water allocated to irrigations (million m^3) in the Inner Mongolia, Jilin, and Heilongjiang provinces

	Province	Crop	Period		
			t = 1	$t = 2$	$t = 3$
Cultivated area	Inner Mongolia	Corn	[23,564.10, 23,564.10]	[23,184.90, 23,184.90]	[9969.45, 9969.45]
		Soybean	[9054.45, 10,263.45]	[9195.75, 10,119.75]	[8644.05, 9969.45]
		Potato	[10,263.45, 10,263.45]	[10,119.75, 10,119.75]	[23,016.90, 23,016.90]
		Rice	[28,588, 29,394]	[28,333.60, 28,949.60]	[27,753.60, 28,637.20]
	Jilin	Corn	[18,660.60, 18,660.60]	[18,119.70, 18,119.70]	[7464.75, 7464.75]
		Soybean	[6681, 7868.40]	[6300.45, 7663.05]	[6616.95, 7464.75]
		Potato	[7868.40, 7868.40]	[7663.05, 7663.05]	[17,018.70, 17,018.70]
		Rice	[22,140, 22,931.60]	[21,388.80, 22,297.20]	[20,733.60, 21,298.80]
	Heilongjiang	Corn	[46,830, 46,830]	[12,681.75, 12,681.75]	[11,186.25, 11,186.25]
		Soybean	[9512.10, 14,637.90]	[8193.05, 12,681.75]	[7448.35, 11,186.25]
		Potato	[14,637.90, 14,637.90]	[41,749.60, 42,883.50]	[37,269.20, 40,552.50]
		Rice	[47,320, 50,737.20]	[41,749.60, 45,498]	[37,269.20, 41,950]
Water allocated to irrigations	Inner Mongolia	Corn	[3534.62, 4712.82]	[3477.74, 4636.98]	[1495.42, 1993.89]
		Soybean	[1267.62, 2257.96]	[1287.41, 2226.35]	[1210.17, 2193.28]
		Potato	[2052.69, 2565.86]	[2023.95, 2529.94]	[4603.38, 5754.23]
		Rice	[10,291.68, 14,697]	[10,200.1, 14,474.8]	[9991.3, 14,317.54]
	Jilin	Corn	[2799.09, 3732.12]	[2717.96, 3623.94]	[1119.71, 1492.95]
		Soybean	[935.34, 1731.05]	[882.06, 1685.87]	[926.37, 1642.25]
		Potato	[1573.68, 1967.10]	[1532.61, 1915.76]	[3403.74, 4254.68]
		Rice	[7970.40, 11,465.80]	[7699.97, 11,148.60]	[7464.10, 10,649.40]
	Heilongjiang	Corn	[7024.50, 9366]	[1902.26, 2536.35]	[1677.94, 2237.25]
		Soybean	[1331.69, 3220.34]	[1147.03, 2789.99]	[1042.77, 2460.98]
		Potato	[2927.58, 3659.48]	[8349.92, 10,720.88]	[7453.84, 10,138.13]
		Rice	[17,035.20, 25,368.60]	[15,029.86, 22,749]	[13,416.91, 20,975]

Heilongjiang is the leading crop producer, which means a high requirement of water resources for irrigating. As illustrated in Table 1, the surface water allocated to corn planting drops suddenly in period 2 mainly caused by decreased demand and yield. The drought-resistant plant soybean only requires the minimal surface water. For potato planting, [2927.58, 3659.48], [8349.92, 10,720.88], and [7453.84, 10,138.13] million m^3 of surface water are supplied, almost triple since period 2. Comparatively, the surface water provided to rice reaches to about 1.5 times and twice water usage of rice planting in Inner Mongolia and Jilin. All of these water supply outcomes have particularly revealed the variations of various crop irrigation distributions in three provinces (or autonomous region), and also the changing trend in three periods.

An implication in the optimal irrigation schemes over the SHRW is that the optimal crop irrigation plans closely rely on cultivation schemes. Another one is that surface water dominates water-resource allocation in the SHRW due to its low cost, high availability, and easy access compared with groundwater.

4.3 Optimal Water Allocation Schemes

Table 2 shows the amounts of water allocated to various end-users in Inner Mongolia, Jilin, and Heilongjiang provinces in the three periods. For example, planting is the most primary surface water consumer. Owing to environmental and economic restrictions, no groundwater is utilized for irrigating. The allocated amount of surface water to Metallurgy increases gradually from [2243.06, 2281.85] and [2306.15, 2338.9] to [2383.66, 2434.79] million m^3 in periods 1 to 3, while groundwater quantity being [277.23, 282.03], [285.03, 289.08], and [294.61, 300.93] million m^3, accounting for a small part. Similarly, the major water source for the food industry is surface water. Groundwater is mainly delivered to tourism and household users. Overall, these five end-users can be sorted as planting, household, food industry tourism, and metallurgy according to their surface water consumptions, which account for 60.04, 12.62, 11.55, 7.93, and 7.85% of the total amount in period 1, almost the same ranking in the subsequent two periods. Obviously, it requires more than half distributions for irrigation in Inner Mongolia.

For Jilin province, obviously, planting consumes [13,278.51, 18,896.07], [12,832.6, 18,374.17], and [12,913.92, 18,039.28] million m^3 of surface water in periods 1 to 3, respectively, and no groundwater supply. Meanwhile, [2522.19, 2560.6], [2646.66, 2670.7], and [2710, 2740.14] million $m^3$of surface water are allocated to metallurgy in three periods, while food industry utilizes [3709.1, 3765.58], [3892.15, 3927.5], and [3985.29, 4029.62] million m^3 of surface water. Besides, only [311.73, 316.48] and [458.43, 465.41] million m^3 of groundwater are supplied for metallurgy and food industry respectively in period 1. In comparison, water resources for tourism purpose are less than Inner Mongolia and Heilongjiang provinces. Household has always been the most primary user of groundwater. Same with Inner Mongolia, planting, household, and food industry occupy the top three surface water consumers, but after them, metallurgy and tourism are the fourth and fifth ones, sharing the percentage of 53.26, 14.48, 12.99, 8.83, and 4.51%. Besides, the household and tourism are first two consumers of groundwater, based on its natural and economic characteristics.

Heilongjiang is a large province of agriculture and industry, requiring more water than other two provinces. Specifically, the allocated amount of surface water for

Table 2 Water allocated to end-users in the Inner Mongolia, Jilin, and Heilongjiang provinces (million m^3)

Province	End-user	Period					
		t = 1		t = 2		t = 3	
		Surface water	Groundwater	Surface water	Groundwater	Surface water	Groundwater
Inner Mongolia	Planting	[17,146.61, 24,233.64]	0	[16,989.20, 23,868.07]	0	[17,300.27, 24,258.94]	0
	Metallurgy	[2243.06, 2281.85]	[277.23, 282.03]	[2306.15, 2338.90]	[285.03, 289.08]	[2383.66, 2434.79]	[294.61, 300.93]
	Food industry	[3298.62, 3355.67]	[407.69, 414.75]	[3391.40, 3439.56]	[419.16, 425.11]	[3505.39, 3580.58]	[433.25, 442.54]
	Tourism	[2265.64, 2265.64]	[2147.24, 2385.91]	[2299.09, 2560.77]	[2038.82, 2311.04]	[2270.14, 2659.47]	[2013.14, 2358.40]
	Household	[3604.06, 3644.15]	[3196.06, 3231.60]	[3678.92, 3742.54]	[3262.44, 3318.86]	[3779.33, 3813.65]	[3351.48, 3381.92]
Jilin	Planting	[13,278.51, 18,896.07]	0	[12,832.6, 18,374.17]	0	[12,913.92, 18,039.28]	0
	Metallurgy	[2522.19, 2560.6]	[311.73, 316.48]	[2646.66, 2670.7]	[327.12, 330.09]	[2710, 2740.14]	[334.94, 338.67]
	Food industry	[3709.1, 3765.58]	[458.43, 465.41]	[3892.15, 3927.5]	[481.05, 485.42]	[3985.29, 4029.62]	[492.56, 498.04]
	Tourism	[1287.5, 1358.12]	[1141.75, 1204.37]	[1250.55, 1392.51]	[1108.98, 1234.87]	[1253.45, 1421.28]	[1111.55, 1260.38]
	Household	[4135.07, 4181.06]	[3666.95, 3707.74]	[4213.07, 4277.23]	[3736.12, 3793.01]	[4275.34, 4367.05]	[3791.34, 3872.67]
Heilongjiang	Planting	[28,318.97, 41,614.42]	0	[26,429.07, 38,796.22]	0	[23,591.46, 35,811.36]	0
	Metallurgy	[3280.30, 3350.66]	[405.43, 414.13]	[3382.33, 3447.83]	[418.04, 426.14]	[3473.80, 3537.48]	[429.35, 437.22]
	Food industry	[4823.97, 4927.45]	[596.22, 609.01]	[4974.01, 5070.34]	[614.76, 626.67]	[5108.53, 5202.17]	[631.39, 642.97]
	Tourism	[10,719.04, 11,781.59]	[9505.56, 10,447.83]	[10,503.69, 12,003.47]	[9314.6, 10,644.59]	[10,412.27, 12,225.04]	[9233.52, 10,841.08]
	Household	[5718.36, 5793.67]	[5070.99, 5137.79]	[5873.19, 5938.51]	[5208.30, 5266.23]	[5996.88, 6051.35]	[5317.99, 5366.29]

irrigating reaches to [28,318.97, 41,614.42], [26,429.07, 38,796.22], and [23,591.46, 35,811.36] million m^3 in periods 1 to 3, respectively, almost the twice the consumptions of Jilin province. Metallurgy is the smallest water consumer in Heilongjiang province. Tourism is the second biggest user of water resources and the largest consumer of groundwater, and the consumption gradually declines in periods 2 and 3. Household utilizes ground water after tourism users. Different from Inner Mongolia and Jilin provinces, tourism, and household seize the second and third consumers of surface water with the percentage of 20.28 and 10.82%, replacing food industry and metallurgy. Invariably, almost half of the surface water (53.57%) is used for irrigation in this major agricultural province. For groundwater, tourism and household are the two primary consumers.

4.4 Pollution Control

As shown in Fig. 2, Heilongjiang province contributes most to pollutants emission, discharging [134.00, 158.29] × 10^4 tons of pollutants in period 1, almost twice of those in Inner Mongolia and Jilin. In the same period, total nitrogen and phosphor reach to [167.13, 190.57] and [90.69, 108.27] × 10^4 tons, respectively, decreasing

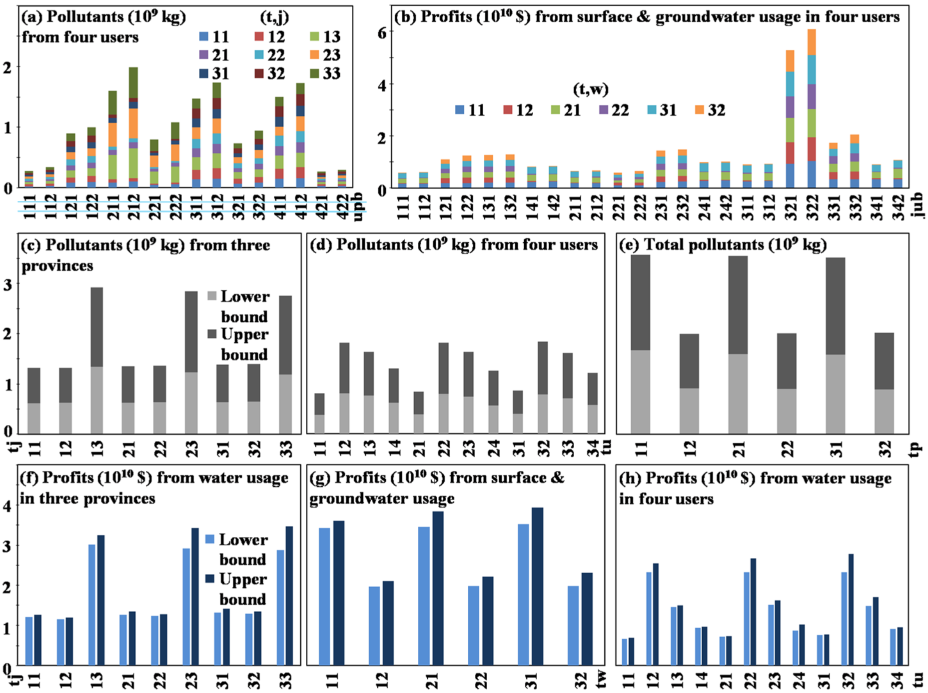

Fig. 2 Pollutants and profits from water usage in four users excluding crops cultivation (t = 1 for period 2014-2018, 2 for period 2019 to 2023, and 3 for period 2024 to 2028; j = 1 for Inner Mongolia, 2 for Jilin, and 3 for Heilongjiang; w = 1 for surface water, and 2 for groundwater; u = 1 for metallurgy, 2 for food industries, 3 for tourism, and 4 for households; b = 1 for lower bound, and 2 for upper bound; p = 1 for nitrogen, and 2 for phosphor)

slightly period by period. Additional attentions should be paid on taking more strict regulations and more efficient measures, especially in Heilongjiang province. Besides, positive associations were found between pollutions discharge and profits generation. To be specific, tourism is the biggest pollution source, discharging, followed by household, food industry, and metallurgy. The discharge amount of metallurgy increases slightly with periods, others get reduced. Consequently, targeted measures should be formulated based on the specific features of various water users. Through the optimized WRFM scheme, the total discharge amounts of nitrogen and phosphor in the SHRW are [27.45, 27.85] and [2.68, 2.70], [26.23, 26.74] and [2.51, 2.55], and [25.16, 25.58] and [2.41, 2.45] $\times 10^5$ tone in periods 1 to 3, respectively. If the current WRFM scheme would be applied in the entire future planning period, the discharge amounts increase by approximately [53.43%, 56.71%] and [65.15%, 73.02%] for nitrogen and phosphor, respectively. It is implied that the IFWRFP approach is very effective at water quality control.

4.5 Economic Benefits

Figure 2 illustrates the profits from water usage of four users (i.e., metallurgy, tourism, household, and food industry,) excluding crops cultivation in three provinces (i.e., Inner Mongolia, Jilin, and Heilongjiang) in periods 1, 2, and 3. Obviously, tourism in Heilongjiang is the most profitable consumer of water resources. Conversely, the metallurgy in Inner Mongolia generates the least amount of profits. As the highest profit among three periods, a total of \$ [35.12, 39.34] billion of is made from surface water resources in period 3. Comparably, profit from groundwater uses is the least in period 1 due to higher costs and less utilization. Moreover, Inner Mongolia, Jilin and Heilongjiang provinces create \$ [12.10, 12.58], [11.55, 11.95], and [30.22, 32.58] billion profit in period 1, respectively, which increase gradually with a period. Among them, Heilongjiang province is the biggest beneficiary, followed by Inner Mongolia and Jilin. Finally, the total benefit in period 3 decreases from tourism, through domestic sectors and food production, to metallurgy industries.

4.6 Overall Suggestions

This study can provide decision makers with specific management suggestions supported by scientific results, which can effectively control water pollution and soil erosion. For instance, it reveals the surface water resources are utilized in similar forms in three provinces. In particular, planting should always be the priority based on the foundational position of the agricultural economy in future 13 years. Compared with the other two provinces, in Heilongjiang, tourism possesses the second largest water consumer instead of domestic sectors. Based on economic and environmental considerations, household and tourism are the first two consumers of groundwater. Furthermore, the optimal management schemes of irrigations in three provinces advise that rice cultivation requires the most irrigation water, which should be the primary commercial crop, followed by corn, potato, and soybean in three provinces. Besides, potato yield should be increased to compensate for the other three grains productivity reduction since 2019. Profits of the optimal management schemes suggest that economic benefits are proportional to water environmental pollution. For example, Heilongjiang could benefit the most and also discharge the most pollutants in total.

Therefore, decision makers should formulate the water and farmland related policies based on most reasonable suggested schemes after fully balancing the trade-off of environment and economy. If not, they will pursue economic benefits at the expense of water environment contamination, or excessively chase environment conservation and neglect economic development accordingly. The optimal WRFM schemes obtained from the IFWRFP approach are only a series of general suggestions on how to promote regional economic development without damaging eco-environmental quality. To enable sufficiently implementing these schemes over the SHRW, there should be a variety of supporting measures that local governors can use. For instance, individual farmers can be encouraged to follow the overall crop cultivation plan by the alteration of subsidiaries, taxes, and prices on crop-related activities.

5 Conclusions

Nowadays, with the socio-economic development in SHRW, more water resources are consumed. Meanwhile, water misuse and pollution and unscientific policies have worsened water shortage and eco-environmental degradation. These consequences will inevitably limit future development and threaten ecosystem and human health if no proper system management can be conducted. Therefore, in this study, an interval fuzzy water resources and farmland programming method (IFWRFP), was developed for managing the water-related activities in the SHRW.

This study helped: (1) systematically identify the complexities associated with natural and social characteristics of the SHRW; (2) identify the optimal patterns of water and farmland resources allocation for implementing eco-environmental pollution control within planning periods; (3) tackle uncertainties expressed as intervals and fuzzy sets, and generate a series of interval solutions that could provide a range of decision alternatives for decision makers, not just one definite scheme under all system conditions and decision-maker preferences, reflecting the conflicts between socio-economy and eco-environment; and (4) successfully direct the formulation of regulation, control water pollution and enhance economic and eco-environmental benefits in the SHRW.

A series of suggestions were proposed for enabling harmonious development of ecological environment and social economy in the SHRW. For instance, planting should always be the priority based on the foundational position of the agricultural economy in future 13 years. Rice cultivation requires the most irrigation water, which should be the primary commercial crop, followed by corn, potato, and soybean in three provinces. Economic benefits are proportional to water environmental pollution. The modeling results show that the IFWRFP approach can systematically optimize allocations of water resources and cultivation patterns and thus potentially eliminate the problems of water scarcity, water contamination, and soil erosion in the SHRW.

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Compliance with Ethical Standards

Conflict of Interest None

Appendix A

IFWRFP model

Based on the aforementioned analyses, the objective function of the IFWRFP model is formulated as follows:

$$\begin{aligned}\text{Max } f^{\pm} \cong & \sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{t=1}^{3} \mathrm{EP}_{\mathrm{ijt}}^{\pm} \cdot \mathrm{YP}_{\mathrm{ijt}}^{\pm} \cdot P_{ijt}^{\pm} \\ & + \sum_{k=1}^{2}\sum_{j=1}^{3}\sum_{t=1}^{3} \mathrm{EI}_{\mathrm{kjt}}^{\pm} \cdot AI_{kjt}^{\pm} + \sum_{j=1}^{3}\sum_{t=1}^{3} \mathrm{ET}_{\mathrm{jt}}^{\pm} \cdot AT_{jt}^{\pm} + \sum_{j=1}^{3}\sum_{t=1}^{3} \mathrm{ER}_{\mathrm{jt}}^{\pm} \cdot AR_{jt}^{\pm} \\ & - \sum_{j=1}^{3}\sum_{t=1}^{3} \left(\mathrm{KR}_{\mathrm{jt}}^{\pm} \cdot HR_{jt}^{\pm} + \mathrm{KG}_{\mathrm{jt}}^{\pm} \cdot HG_{jt}^{\pm} \right) \\ & - \sum_{k=1}^{2}\sum_{t=1}^{3} \left(\mathrm{KWI}_{\mathrm{kt}}^{\pm} \cdot \sum_{j=1}^{3} \left(\mathrm{RI}_{\mathrm{kjt}}^{\pm} \cdot AI_{kjt}^{\pm} \right) \right) \\ & - \sum_{t=1}^{3} \left(\mathrm{KWT}_{\mathrm{t}}^{\pm} \cdot \sum_{j=1}^{3} \left(\mathrm{RT}_{\mathrm{jt}}^{\pm} \cdot AT_{jt}^{\pm} \right) \right) \\ & - \sum_{t=1}^{3} \left(\mathrm{KWR}_{\mathrm{t}}^{\pm} \cdot \sum_{j=1}^{3} \left(\mathrm{RR}_{\mathrm{jt}}^{\pm} \cdot AR_{jt}^{\pm} \right) \right) \end{aligned} \tag{1}$$

Constraints of the IFWRFP model consist of the following inequalities.

1) Songhua River Watershed farmland availability

(a) Maximum cultivation areas

$$\sum_{i=1}^{3} P_{ijt}^{\pm} \le \mathrm{MAXA}_{\mathrm{jt}}, \quad \forall j, t \tag{2}$$

(b) Minimum cultivation areas

$$\sum_{i=1}^{3} P_{ijt}^{\pm} \ge \sim\mathrm{MINA}_{\mathrm{jt}}, \quad \forall j, t \tag{3}$$

2) Songhua River Watershed water resources availability

(a) Surface water availability

$$\sum_{j=1}^{3} HR_{jt}^{\pm} \le \mathrm{MAXR}_{\mathrm{t}}^{\pm}, \quad \forall t \tag{4}$$

(b) Groundwater availability

$$\sum_{j=1}^{3} HG_{jt}^{\pm} \le \mathrm{MAXG}_{\mathrm{t}}^{\pm}, \quad \forall t \tag{5}$$

(c) Total water resources availability

$$\sum_{i=1}^{2}\sum_{j=1}^{3} \mathrm{RDP}_{\mathrm{ijt}}^{\pm} \cdot P_{ijt}^{\pm} + \sum_{k=1}^{2}\sum_{j=1}^{3} AI_{kjt}^{\pm} + \sum_{j=1}^{3} AT_{jt}^{\pm} + \sum_{j=1}^{3} AR_{jt}^{\pm} \le \sum_{j=1}^{3}\left(HR_{jt}^{\pm} + HG_{jt}^{\pm}\right), \quad \forall t \tag{6}$$

3) Songhua River Watershed water supply constraints

(a) Water supply for agriculture

$$\sum_{i=1}^{2}\sum_{j=1}^{3} \mathrm{RDP}_{\mathrm{ijt}}^{\pm} \cdot P_{ijt}^{\pm} \le \mathrm{MAXWP}_{\mathrm{t}}^{\pm}, \quad \forall t \tag{7}$$

(b) Water supply for industry

$$\sum_{j=1}^{3} AT_{jt}^{\pm} \le \mathrm{MAXWT}_{\mathrm{t}}^{\pm}, \quad \forall t \tag{8}$$

(c) Water supply for tourism

$$\sum_{j=1}^{3} AR_{jt}^{\pm} \le \mathrm{MAXWR}_{\mathrm{t}}^{\pm}, \quad \forall t \tag{9}$$

(d) Water supply for household

$$\sum_{j=1}^{3} AR_{kjt}^{\pm} \le \mathrm{MAXWR}_{\mathrm{t}}^{\pm}, \quad \forall t \tag{10}$$

4) Songhua River Watershed wastewater treatment capacity constraints

$$\sum_{k=1}^{2}\sum_{j=1}^{3} \mathrm{RI}_{\mathrm{kjt}}^{\pm} \cdot AI_{kjt}^{\pm} + \sum_{j=1}^{3} \mathrm{RT}_{\mathrm{jt}}^{\pm} \cdot AT_{jt}^{\pm} + \sum_{j=1}^{3} \mathrm{RR}_{\mathrm{jt}}^{\pm} \cdot AR_{jt}^{\pm} \leq \mathrm{MAXUT}_{\mathrm{t}}^{\pm}, \quad \forall t \tag{11}$$

5) Songhua River Watershed eco-environment constraints

(a) Soil erosion control

$$\sum_{i=1}^{3}\sum_{j=1}^{3} \mathrm{CSL}_{\mathrm{ijt}}^{\pm} \cdot P_{ijt}^{\pm} \leq \mathrm{MAXCS}_{\mathrm{t}}^{\pm}, \quad \forall t \tag{12}$$

(b) Nitrogen discharge control

$$\sum_{i=1}^{3}\sum_{j=1}^{3} \mathrm{QN}_{\mathrm{ijt}}^{\pm} \cdot P_{ijt}^{\pm} + \left(\sum_{k=1}^{2}\sum_{j=1}^{3} \mathrm{QNI}_{\mathrm{kjt}}^{\pm} \cdot AI_{kjt}^{\pm} + \sum_{j=1}^{3} \mathrm{QNT}_{\mathrm{jt}}^{\pm} \cdot AT_{jt}^{\pm} + \sum_{j=1}^{3} \mathrm{QNR}_{\mathrm{jt}}^{\pm} \cdot AR_{jt}^{\pm} \right) \left(1 - \mathrm{NRE}_{\mathrm{t}}^{\pm}\right) \leq \mathrm{MAXTN}_{\mathrm{t}}^{\pm}, \quad \forall t \tag{13}$$

(c) Phosphor discharge control

$$\sum_{i=1}^{3}\sum_{j=1}^{3} \mathrm{QS}_{\mathrm{ijt}}^{\pm} \cdot P_{ijt}^{\pm} + \left(\sum_{k=1}^{2}\sum_{j=1}^{3} \mathrm{QPI}_{\mathrm{kjt}}^{\pm} \cdot AI_{kjt}^{\pm} + \sum_{j=1}^{3} \mathrm{QPT}_{\mathrm{jt}}^{\pm} \cdot AT_{jt}^{\pm} + \sum_{j=1}^{3} \mathrm{QPR}_{\mathrm{jt}}^{\pm} \cdot AR_{jt}^{\pm} \right) \left(1 - \mathrm{PRE}_{\mathrm{t}}^{\pm}\right) \leq \mathrm{MAXTP}_{\mathrm{t}}^{\pm}, \quad \forall t \tag{14}$$

where f = the expected net system benefit ($); t = time period, $t = 1, 2, 3$ (where t = 1 for 2014–2018, 2 for 2019 to 2023, 3 for 2024 to 2028); i = the type of crop, $i = 1, 2, 3, 4$ (where i = 1 for corn, 2 for soybean, 3 for potato, 4 for rice); j = sub-region, j = 1, 2, 3 (where j = 1 for Inner Mongolia, 2 for Jilin, 3 for Heilongjiang); k = the type of industry, k = 1, 2 (where k = 1 for metallurgical industry, 2 for food industry);$\mathrm{EP}_{\mathrm{ijt}}^{\pm}$ = market price of crop i in sub-region j in period t ($/kg); $\mathrm{YP}_{\mathrm{ijt}}^{\pm}$ = yield of crop i in sub-region j in period t (kg/km^2); $\mathrm{EI}_{\mathrm{kjt}}^{\pm}$ = unit benefit of water allocated to industry k in sub-region j in period t ($/m^3); $\mathrm{ET}_{\mathrm{jt}}^{\pm}$ = unit benefit of water allocated to tourism in sub-region j in period t ($/m3); $\mathrm{ER}_{\mathrm{jt}}^{\pm}$ = unit benefit of water allocated to household in sub-region j in period t ($/m^3); $\mathrm{KR}_{\mathrm{jt}}^{\pm}$ = cost for pumping and delivering the surface water in sub-region j in period t ($/m^3); $KG^{\pm}_{jt}$ = cost for pumping and delivering the ground water in sub-region j in period t ($/m^3); $KWI^{\pm}_{kt}$ = treatment cost of wastewater from industry k in period t ($/tonne); $KWT^{\pm}_{kt}$ = treatment cost of wastewater from tourism industry in period t ($/tonne); $KWR^{\pm}_{t}$ = treatment cost of wastewater from household in period t ($/tonne); $RI^{\pm}_{kjt}$ = unit wastewater discharge by industry k in sub-region j in period t (tonne/m^3); $RT^{\pm}_{jt}$ = unit wastewater discharge by tourism industry in sub-region j in period t (ton/m^3); $RR^{\pm}_{jt}$ = unit wastewater discharge by household in sub-region j in period t (tonne/m^3);$MAXA_{jt}$ = the maximum area allocated to crop i in sub-region j in period t (km^2); $MINA_{jt}$ = the minimum area allocated to crop i in sub-region j in period t (km^2);$MAXR^{\pm}_{t}$ = the maximum allocated surface water amount in sub-region j in period t (m^3); $MAXG^{\pm}_{t}$ = the maximum allocated groundwater amount in sub-region j in period t (m^3); $RDP^{\pm}_{ijt}$ = the unit irrigation demand for crop i in sub-region j in period t (m^3/km^2);$MAXWP^{\pm}_{t}$ = the maximum water amount allocated to agriculture in period t (m^3); $MAXWI^{\pm}_{maxt}$ = the maximum water amount allocated to industry in period t (m^3); $MAXWT^{\pm}_{maxt}$ = the maximum water amount allocated to tourism in period t (m^3); $MAXWR^{\pm}_{maxt}$ = the maximum water amount allocated to household in period t (m^3);$MAXUT^{\pm}_{t}$ = total wastewater treatment capacity in period t (tonne);$CSL^{\pm}_{ijt}$ = amount of soil loss from the land planted with crop i in sub-region j in period t (kg/km^2); $MAXCS^{\pm}_{t}$ = the allowed amount of soil loss in period t (kg);$QN^{\pm}_{ijt}$ = nitrogen percent content of the soil in sub-region j in period t (%); $QNI^{\pm}_{kjt}$ = unit nitrogen discharge by industry k in sub-region j in period t (tonne/m^3); $QNT^{\pm}_{jt}$= unit nitrogen discharge by tourism industry in sub-region j in period t (tonne/m^3); $QNR^{\pm}_{jt}$= unit nitrogen discharge by household in sub-region j in period t (tonne/m^3); $NRE^{\pm}_{t}$ = nitrogen removal efficiency in period t (%); $MAXTN^{\pm}_{t}$ = the allowed amount of nitrogen discharge in period t (kg);$QS^{\pm}_{ijt}$ = phosphorus percent content of the soil in sub-region j in period t (%); $QPI^{\pm}_{kjt}$= unit phosphor discharge by industry k in sub-region j in period t (tonne/m^3); $QPT^{\pm}_{jt}$ = unit phosphor discharge by tourism industry in sub-region j in period t(tonne/m^3); $QPR^{\pm}_{jt}$ = unit phosphor discharge by household in sub-region j in period t (tonne/m^3); $PRE^{\pm}_{t}$ = phosphor removal efficiency in period t (%); $MAXTP^{\pm}_{t}$ = the allowed amount of phosphor discharge in period t (kg).

Table 3 Benefits of water supply for end-users, and costs for pumping and delivering water resources ($/m^3)

		Period		
		t = 1	*t* = 2	*t* = 3
End-user	Metallurgical industry	[27.57, 29.56]	[25.53, 27.31]	[23.77, 24.67]
	Food industry	[14.86, 15.09]	[14.29, 14.45]	[13.64, 13.77]
	Tourism	[9.11, 9.25]	[8.76, 8.86]	[8.36, 8.44]
	Household	[14.26, 25.3]	[31.95, 43.42]	[44.77, 45.48]
Water resource type	Surface drainage water Groundwater	[0.0033, 0.0034]	[0.0032, 0.0033]	[0.0031, 0.0032]
	Groundwater	[0.0056, 0.0062]	[0.0054, 0.0059]	[0.0052, 0.0057]
	River water	[0.0062, 0.0063]	[0.0060, 0.0061]	[0.0058, 0.0059]

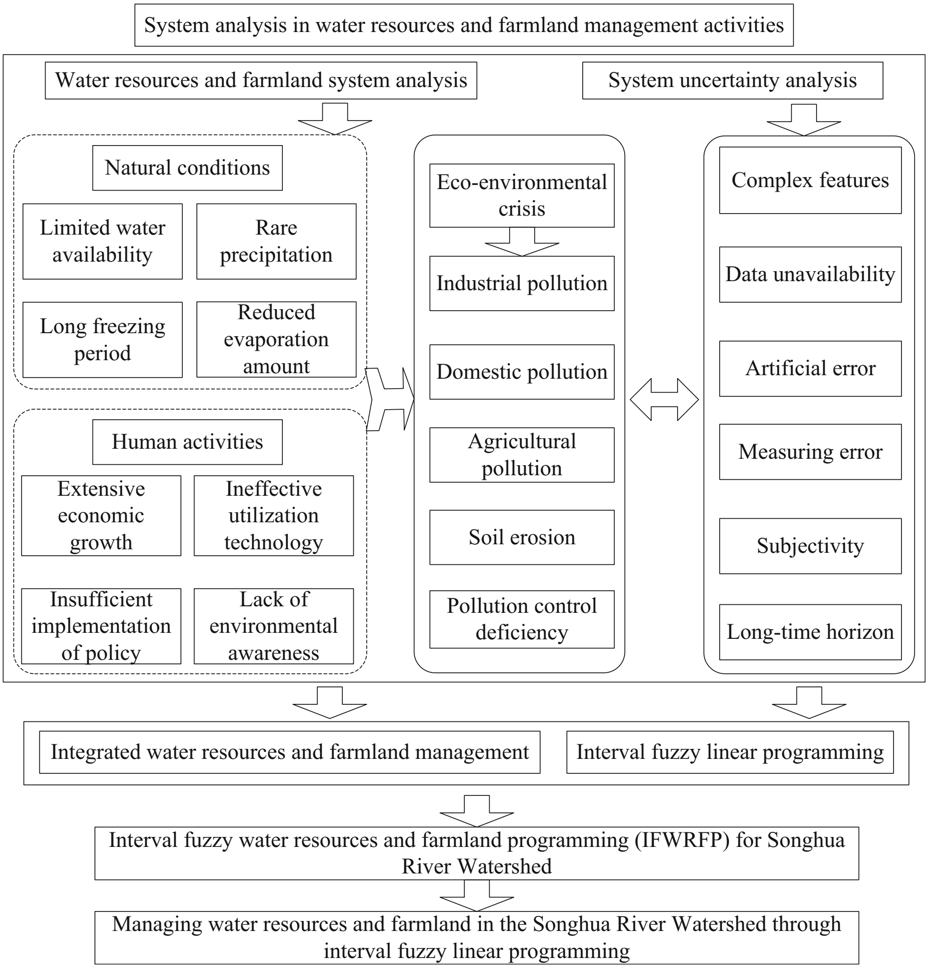

Fig. 3 Interactive relationships in watershed system

Solution Algorithm

The constructed IFWRFP model can be generalized as an interval fuzzy linear programming (IFLP) problem that is formulated as follows:

$$\max f^{\pm} \cong C^{\pm} X^{\pm} \tag{15}$$

subject to:

$$A^{\pm} X^{\pm} \leq B^{\pm} \tag{16}$$

$$X^{\pm} \geq 0 \tag{17}$$

where $A^{\pm} \in \{R^{\pm}\}^{m \times n}$, $B^{\pm} \in \{R^{\pm}\}^{m \times 1}$, $C^{\pm} \in \{R^{\pm}\}^{1 \times n}$, $X^{\pm} \in \{R^{\pm}\}^{n \times 1}$, and $\{R^{\pm}\}$ denotes sets of interval numbers. The IFLP model is equivalent to an interval linear programming model if the fuzziness in the objective function (15) and the constraints (16) is removed. For the latter model, a two-step solution algorithm (Huang et al. 1993, 1996; Cai et al. 2007, 2012) can be employed to solve it, generating interval-form solutions as follows:

$$x_{jopt} = \left[x_{jopt}^{-}, x_{jopt}^{+}\right] \quad \text{for any } j \in \{1, 2, \ldots, n\} \tag{18}$$

$$f_{opt} = \left[f_{opt}^{-}, f_{opt}^{+}\right] \tag{19}$$

Based on the fuzzy flexible programming (Huang et al. 1993), both of the flexibility in constraints as well as the fuzziness in system objective can be assigned membership functions and represented by fuzzy sets. 'Fuzzy constraints' and a 'fuzzy goal' can then be expressed as a membership grade (λ) corresponding to the overall satisfaction degree of constraints and the objective. By incorporating an interval membership grade ($\lambda^{\pm}$) into the existing interval linear model (Huang et al. 1996; Chakraborty and Chandra 2005; Lin and Huang 2008; Cheng et al. 2015a), the IFLP model can be equivalently reformulated as follows:

$$\max \lambda^{\pm} \tag{20}$$

subject to:

$$C^{\pm} X^{\pm} \leq f^{+} - \left(1 - \lambda^{\pm}\right) \cdot \left(f^{+} - f^{-}\right) \tag{21}$$

$$A^{\pm} X^{\pm} \leq b_i^{+} - \left(1 - \lambda^{\pm}\right) \cdot \left(b_i^{+} - b_i^{-}\right) \tag{22}$$

$$X^{\pm} \geq 0 \tag{23}$$

$$0 \leq \lambda^{\pm} \leq 1 \tag{24}$$

where f^{-} and f^{+} are the lower and upper bounds of the objective's aspiration level, respectively; $\lambda^{\pm}$ is a control variable corresponding to the satisfaction degree for the fuzzy decision (Huang et al. 1993; Huang et al. 1996).

Through employing the two-step solution algorithm (Huang et al. 1993, 1996; Cai et al. 2012) again, this model would be transformed into two sub-models. The first sub-model corresponding to the upper bound of $\lambda^{\pm}$ can be formulated as:

$$\max \lambda^{+} \tag{25}$$

subject to:

$$\sum_{j=1}^{k} c_j^- x_j^- + \sum_{j=k+1} c_j^- x_j^+ \leq f^+ - (1-\lambda^+)\cdot(f^+ - f^-) \tag{26}$$

$$\sum_{j=1}^{k_1} |a_{ij}|^+ Sign\left(a_{ij}^+\right) x_j^- + \sum_{j=k_1+1}^{n} |a_{ij}|^- Sign\left(a_{ij}^-\right) x_j^+ \leq b_i^+ - (1-\lambda^+)\cdot\left(b_i^+ - b_i^-\right), \forall i, j \tag{27}$$

$$x_j^- \geq 0, j = 1, 2, \ldots, k_1 \tag{28}$$

$$x_j^+ \geq 0, j = k_1 + 1, k_1 + 2, \ldots, n \tag{29}$$

$$0 \leq \lambda^+ \leq 1 \tag{30}$$

$$x_j \in X^{\pm} \tag{31}$$

Based on the optimal solutions from formulas (25) to (31), the second sub-model corresponding to the lower bound of $\lambda^{\pm}$ can be presented as follows:

$$\max \lambda^- \tag{32}$$

subject to:

$$\sum_{j=1}^{k} c_j^+ x_j^+ + \sum_{j=k+1} c_j^+ x_j^- \leq f^+ - (1-\lambda^+)\cdot(f^+ - f^-) \tag{33}$$

$$\sum_{j=1}^{k_1} |a_{ij}|^- Sign\left(a_{ij}^-\right) x_j^+ + \sum_{j=k_1+1}^{n} |a_{ij}|^+ Sign\left(a_{ij}^+\right) x_j^- \leq b_i^+ - (1-\lambda^+)\cdot\left(b_i^+ - b_i^-\right), \forall i \tag{34}$$

$$x_j^+ \geq x_{jopt}^- \geq 0, j = 1, 2, \ldots, k_1 \tag{35}$$

$$x_{jopt}^+ \geq x_j^- \geq 0, j = k_1 + 1, k_1 + 2, \ldots, n \tag{36}$$

$$0 \leq \lambda^- \leq \lambda_{opt}^+ \tag{37}$$

$$x_j \in X^{\pm} \tag{38}$$

According to this solution algorithm, the IFWRFP model for water resources and farmland management in the Songhua River Watershed can be solved, and the corresponding lower and upper bounds of solutions can be obtained. The generated interval solutions can provide decision makers with multiple decision alternatives according to practical situations and their preferences.

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