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DEVELOPMENT OF AN AGRICULTURAL WATER RESOURCE PROGRAMMING MODEL FOR THE SHUYANG TOWN WATERSHED UNDER UNCERTAINTY

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Abstract

The agricultural water resource distribution is usually associated with many uncertainties related to incomplete historical records, seasonal and demand fluctuations, and complex relationships between water resources and environmental and economic factors. These uncertainties aggravate the complexity of agricultural water resource allocation and of achieving economic objectives. Therefore, an uncertain fuzzy set programming (UFSP) model for agricultural water-system planning in Shuyang town was developed. The uncertain factors affecting the allocation of agricultural water resources, including agricultural income and developmental and sewage treatment costs, are represented by fuzzy sets. The results show that the total local agricultural economic income of Shuyang town can be increased from (23.77, 25.57) to (33.12, 39.67) billion yuan in three stages corresponding to the increase in land for planting, animal husbandry, and forestry and the development of agricultural ecotourism. Furthermore, the study compared the results from the three methods, as well as from the UFSP, UFSP-β, and UFSP-U models. The comparison shows that the UFSP model has more advantages in predicting the total agricultural economic income than the other models, which reflects the uncertainty of the local agricultural water resource system and, consequently, leads to greater economic benefits.

Key words: programming model, Shuyang town, uncertainty, water resources

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1. Introduction

The water environment refers to the space in which the formation, distribution, and transformation of water in nature occurs. Water is necessary for life and directly or indirectly affects human life and development. Water pollution and degradation of water resources are serious environmental problems worldwide (Akhtar et al., 2020). Agricultural point and nonpoint sources cause water pollution (Lu and Xie, 2018). In the last century, the Clean Water Act of the United States of America defined nonpoint source pollution as pollution caused by pollutants entering surface and underground water bodies in a wide area (Chakraborti, 2020). In agricultural production activities, sediment, nutrients, pesticides, and other organic or inorganic pollutants from farmland, which are not absorbed by crops or fixed in soil, enter water bodies through farmland surface runoff, soil flow, farmland drainage, and underground leakage through precipitation or irrigation, thus causing agricultural nonpoint source pollution (Geng and Sharplry, 2019). China faces serious soil erosion.

The amount of topsoil loss in China is approximately 5 billion tons every year (Zhang et al., 2018). As a result, many pesticides and chemical fertilizers flow into rivers and lakes along with topsoil (Schomburg et al., 2018). The loss of nitrogen, phosphorus, potassium, and other nutrients causes pollution in two-thirds of the lakes in China (Strokal et al., 2016). Shuyang town is located in southwestern Zhangzhou city, which is located in the mountainous

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area of southern Fujian Province. The forest cover of Shuyang town is as high as 76.2%, and the area contains a large amount of agricultural products. To improve the yield of agricultural products, fertilizers containing nitrogen and phosphorus as well as a large quantity of livestock manure are used, and these materials eventually flow into rivers and lakes through surface runoff and subsurface flow and pollute water bodies (Molina-Navarro et al., 2018). The water environment consists of uncertain factors and complex changes (Garrote, 2017; Jin et al., 2018a; 2018b; 2019; Kennen et al., 2018; Wang et al., 2020). First, the change in water flow that transports pollutants is a random process with uncertainty, which is affected by climate, soil, and human and organismic activities (Puttock et al., 2017; Romero et al., 2019; Xie et al., 2020). Second, the composition and quantity of pollutants entering a water body are also uncertain in terms of time and space (De Girolamo et al., 2019; Naveen et al., 2019). Finally, physical, chemical, biological, and other pollutants affect water bodies (Naveen et al., 2017; Pereira et al., 2018). Variations in terms of dilution, diffusion, decomposition, coagulation, and precipitation follow certain rules in chemical reactions, but they also cause uncertain variations (Ardell, 2020; Verma and Samanta, 2017).

Therefore, uncertainty analysis of a water environment model is very meaningful (Abbaspour et al., 2018). Through the establishment of a mathematical model, the quantitative relationships among these factors can be determined, providing technical support for the planning, control, and management of water resources. As demand increases and competition among users intensifies, effective redistribution of the existing water supplies becomes increasingly important in extremely arid areas. Yang Yu et al. (2017) proposed a hydrological simulation method to help decision makers and stakeholders resolve potential water resource sharing conflicts (Yu et al., 2017). By combining a land-use map with a water-allocation method, the water-allocation problem in a large watershed was solved (Ronco et al., 2017). One study developed an assessment framework for an agricultural water-supply system in a study of water resource management under climate change. The framework evaluated and sorted different alternatives of an agricultural water supply system according to sustainable development standards to ensure the rationality of agricultural water supply planning. Tang et al. (2020) proposed a multiobjective remote-sensing method for agricultural water resource management to formulate sustainable agricultural land and water resource management strategies at the grid scale (Tang et al., 2020; Wang and Xie, 2018).

Commonly used methods for water environmental planning include linear programming, nonlinear programming, uncertain interval planning, dynamic programming, multiobjective programming, genetic algorithms, and fuzzy algorithms, which provide solutions for the problem of irrigation water allocation under uncertain conditions. An inexact nonlinear mλ-measure fuzzy chance constrained programming (INMFCCP) model was established to provide a reliable scientific basis for irrigation water management in arid areas (Zhang et al., 2018). Owing to the complexity caused by the uncertainty and risk in agricultural water management systems, a risk-based interval stochastic optimization model was proposed. This method can balance the expected benefits, penalties, and risks of agricultural water allocation simultaneously while also handling the uncertainty of agricultural water supply and demand using a probability distribution with a random boundary interval. Cai et al. (2018) proposed an export coefficient-based inexact fuzzy bilevel multiobjective programming (EC-IFBLMOP) model for agricultural nonpoint source pollution management in China (Cai et al., 2018). The model can effectively deal with multiple uncertainties represented by discrete intervals and fuzzy membership functions. In this paper, the uncertainty interval method is used to establish a mathematical model for the water environment, carry out optimal planning of agricultural land, and ensure the socioeconomic and environmental development of Shuyang town. More research in this field is shown in Table 1.

Based on previous research, this study proposes a planning model based on an interval fuzzy water environment model, which is applied for the optimal planning of land resources in Shuyang town. In this study, through the investigation of the status and development of agricultural non-point source pollution and the summary of the status of agricultural water resources in Shuyang Town, an interval fuzzy linear programming model was established using an environmental mathematical modeling method based on uncertainty analysis. In this study, parameters such as ammonia nitrogen and phosphorus are used as constraints, and the economic and ecological benefits are maximized by formulating a reasonable land planning plan. Also, in the research, two solutions and software have been used to horizontally solve and compare the results of the main interval fuzzy water environment model, and establish another two models in order to obtain the comparison results. Finally, in the direction of providing the best plan for the land use planning of Shuyang Town, the results of the model are used in combination with the actual situation to consider the shortcomings and propose improvements.

2. Materials and methods

2.1. Overview of the study area

Fujian Province is mountainous county. The geography of the province is locally described as "eight mountains, one water body, and one agricultural field". Shuyang town of Nanjing County is located in southwestern Zhangzhou city and mountainous area of Minnan territory with a forest cover of 76.2% (Fig. 1). Shuyang town has a total area of 184 km^2, of which 19.3 million ha are mountainous and 2.5 million ha are arable land. There are 18 administrative villages within the jurisdiction with a total population of more than 26.000 people. The town has an average elevation of approximately 400 meters, and the highest altitude is 1399 meters. The climate is typically subtropical and mild, with abundant rainfall suitable for the plant growth like as wheat, maize and other crops. As there are many mountains and vast fields, Shuyang town produces a wealth of agricultural and allied products and is an important production area for bamboo, fruit, tea, flue-cured tobacco, and vegetables in Zhangzhou. The town's tea production area is over 60.000 ha, accounting for 60% of the county's production.

At the same time, pollution of the water environment is inevitable. In the planting industry, villagers usually use fertilizers containing nitrogen and phosphorus. These fertilizers are easily lost through runoff during rainfall or irrigation, and flow into groundwater through the soil layer. The aquaculture, captive poultry, and livestock industries produce a large amount of excrement that is rich in nutrients and bacteria. In this country, the overgrazing in grasslands results in the retention of large amounts of livestock manure; in addition, livestock fences are overused in farmland. Domestic waste flow into rivers and lakes along with surface runoff and subsurface flows, polluting water bodies.

Table 1. Pervious research in this field

Article	***Research content***	***Remaining problem***
Zhang et al. (2018)	An inexact and nonlinear mλ measurement fuzzy chance constrained programming model is established, which provides a reliable scientific basis for irrigation water management in arid areas (Zhang et al., 2018).	None
Cai et al. (2018)	Aiming at the complexity caused by the uncertainty and risk in the agricultural water management system, a risk-based interval stochastic optimization model is proposed. This method can balance the expected benefits, penalties and risks of agricultural water allocation at the same time, and at the same time use the probability distribution of the random boundary interval to deal with the uncertainty of agricultural water supply and demand (Cai et al., 2018).	It cannot fully reflect the actual system structure in reality and this method has limitations in solving the uncertainty problem expressed by the probability density function.
Niu (2016)	An interactive two-stage interval fuzzy programming model (ITFSP) is proposed, which can effectively deal with the double uncertainty problem of fuzzy parameters with interval boundaries in practical problems. At the same time, it can also obtain the degree of satisfaction of economic goals and the feasibility of constraints. Degree of complex trade-off (Niu, 2016).	The water quantity and water quality factors are not considered in the management plan, and the constraint targets are limited to parameters related to economic considerations.
Zhang et al. (2021)	An interval fuzzy two-stage stochastic quadratic programming method based on conditional risk value is proposed to deal with and quantify the nonlinear problems in the scheme caused by the scale economy effect of facilities (Zhang et al., 2021).	None
Shan et al. (2021)	Aiming at the uncertainty expression of various factors in practical problems, a sustainable management method of agricultural water resources in arid areas based on vine copula and cloud model is proposed. The autocorrelation of reference evapotranspiration and runoff is considered in the optimization model, and the cloud model is used to express the uncertainty of human subjective judgment (Shan et al., 2021).	No in-depth discussion of the dependence structure between reference evapotranspiration and runoff and hidden physical processes

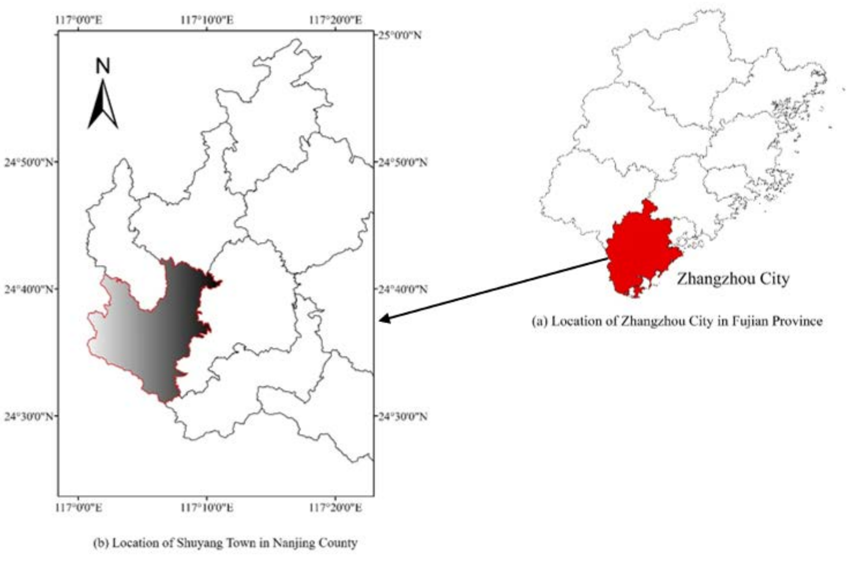


Fig. 1. Location of the study area in the Fujian Province, China

Therefore, agricultural resources such as plant nutrients are valuable substances that promote the growth of crops. However, if excessive nutrients enter natural water bodies, then water quality is deteriorated, thereby affecting the development of fisheries and, more importantly, harming human health. When the concentration of nitrogen and phosphorus in the water exceeds 0.2 mg/L and 0.02 mg/L, respectively, they promote the proliferation of algae and other green plants, resulting in changes in water transparency and dissolved oxygen content and the growth of large patches of algal blooms in rivers and lakes and red tides in the ocean. The death and deterioration of algae cause a significant reduction in the dissolved oxygen content in water, which leads to poor water quality and causes the death of fish and other aquatic organisms. This phenomenon leads to local environmental degradation, and therefore, it is necessary to manage local agricultural systems.

The expansion of the aquaculture industry has led to a decrease in local water resources. In aquaculture, poultry and livestock in captivity produce large amounts of excrement rich in nutrients and bacteria. In addition, livestock fences are overused in farmland. These excreta flow into rivers and lakes along with surface runoff and groundwater flow, thereby polluting water bodies. Excessive nutrients entering natural water bodies will cause deterioration of water quality and further affect the development of fisheries and harm human health. Therefore, it is necessary to manage the local agricultural system.

In terms of its forestry background, the forest area of Nanjing County where Shuyang Town is located is very developed. The main forest products are orchids, bamboo and other forest products. Nanjing County is the county with the largest area of orchids in the province. In addition, the production and sales of Dendrobium (*Dendrobium officinale*), Anoectochilus, and Pleurotus eryngii are the highest among the provinces. The impact of pollution on forestry is relatively small.

2.2. Modeling formulation

Interval linear planning (ILP) is a representation of uncertainties in a linear planning model with a number of intervals. The intervals have known upper and lower bounds but are not known to be variables in the form of specific distributions. The interval linear planning model (Huang, 1992) can be represented as follows (Eqs. 1-3):

$$\max f^{\pm} = C^{\pm} X^{\pm} \tag{1}$$

which is subject to:

$$A_i^{\pm} X^{\pm} \le B_i^{\pm} \tag{2}$$

$$X^{\pm} \ge 0 \tag{3}$$

2.2.1. Agricultural water model development

The water environmental model considered in this study is a function of the total agricultural income of Shuyang town, and the constraints are total water consumption, restriction of the loss of pollutant runoff, land resources, and non-negative constraints. Specifically, the actual production practices, agricultural market prices, costs, pollutant emissions, and rainy-season and dry-season runoffs have uncertainties; therefore, they are expressed in terms of interval numbers and fuzzy numbers during computations. The model is set for three five-year plan terms: 2016–2020, 2021–2025, and 2026–2030.

To account for forestry, the forestry correction coefficient of β is used, as only a small part of the forest industry obtains economic benefits, and most efforts are focused on maintaining the ecological benefits of soil and water conservation. Therefore, when calculating total economic benefits, it is unreasonable to include the entire economic value of forestry. The water safety factor θ is used to constrain total water consumption. This factor is used because several farmers have funded the construction of water diversion systems to draw water from the hills to irrigate farmland or for domestic use. Water leakage during transit causes wasted water resources. Therefore, the water safety factor is introduced here to guarantee that the water supply capacity is utilized accurately to avoid an insufficient water supply.

2.2.2. Objective function

Eq. (4) is a brief concept to describe the value of local agricultural water resources that can be benefits from agriculture, forestry, and animal husbandry.

$$MAXf^{\pm} = (a) - (b) - (c) \tag{4}$$

Eq. (5) is a brief idea to describe the value of local agricultural water resources can be the benefits from agriculture, forestry, and animal husbandry.

$$\sum_{i=1}^{3}\sum_{j=1}^{6}\sum_{k=1}^{3}\left(X^{\pm}_{1jk} \cdot P^{\pm}_{1jk} + X^{\pm}_{2jk} \cdot P^{\pm}_{2jk} + X^{\pm}_{3jk} \cdot P^{\pm}_{3jk} \cdot \beta_k \right) \tag{5}$$

Eq. (6) indicates planting costs of agriculture and forestry and the cost of breeding livestock.

$$\sum_{i=1}^{3}\sum_{j=1}^{6}\sum_{k=1}^{3}\left(X^{\pm}_{ijk} \cdot C^{\pm}_{ijk} \right) \tag{6}$$

Eq. (7) represents costs of treating contaminated wastewater from agriculture, animal husbandry, and forestry to meet discharge standards.

$$CW \cdot \sum_{i=1}^{3}\sum_{j=1}^{6}\sum_{k=1}^{3}\left(X^{\pm}_{ijk} \cdot WW^{\pm}_{ijk} \right) \tag{7}$$

The constraints corresponding to the agricultural water function are listed below:

① Water constraint:

The water constraint provides the highest water consumption for various types of land during various periods. The maximum water limit (Eq. 8) is considered in the ILP system for Shuyang town. This constraint is established to ensure that the amount of water consumption in the planning horizon is less than that of the highest water consumption.

$$\sum_{i=1}^{2}\sum_{j=1}^{6}\sum_{k=1}^{3}\left(1+\theta_k\right)X^{\pm}{}_{ijk}\cdot W^{\pm}{}_{ijk}\le Wt^{\pm}{}_{k} \tag{8}$$

② Maximum runoff loss allowed for dissolved nitrogen:

The runoff loss for the dissolved nitrogen constraint provides the maximum amount of dissolved nitrogen that is allowed to be lost by various types of land during different periods. The maximum runoff loss allowed for dissolved nitrogen (Eq. 9) is considered in the ILP system for Shuyang town. This constraint is established to ensure that the amount of dissolved nitrogen in the planning horizon is less than the maximum runoff loss of allowed dissolved nitrogen.

$$\sum_{i=1}^{3}\sum_{j=1}^{6}\sum_{k=1}^{3}X^{\pm}{}_{ijk}\cdot JL^{\pm}_{ijk}\cdot N^{\pm}_{ijk}\le U^{\pm}{}_{1k}\cdot\sum_{j=1}^{6}\sum_{k=3}^{3}X^{\pm}{}_{1jk} \tag{9}$$

③ Maximum runoff loss allowed for dissolved phosphorus:

The runoff loss for the dissolved phosphorus constraint provides the maximum amount of dissolved phosphorus allowed to be lost by various types of land during different periods. The maximum runoff loss of allowed dissolved phosphorus (Eq. 10) is considered in the ILP system for Shuyang town. This constraint is established to ensure that the amount of dissolved phosphorus in the planning horizon is less than the maximum allowed runoff loss of dissolved phosphorus.

$$\sum_{i=1}^{3}\sum_{j=1}^{6}\sum_{k=1}^{3}X^{\pm}{}_{ijk}\cdot JL^{\pm}_{ijk}\cdot P^{\pm}_{ijk}\le U^{\pm}{}_{2k}\cdot\sum_{j=1}^{6}\sum_{k=3}^{3}X^{\pm}{}_{1jk} \tag{10}$$

④ Total land use constraint:

The total land use constraint provides the limitation of the maximum land use of various types of land during different periods. The total land use constraint (Eq. 11) is considered in the ILP system for Shuyang town. This constraint is established to ensure that the amount of land use in the planning horizon is less than the total land use constraint.

$$\sum_{i=1}^{3}\sum_{j=1}^{6}\sum_{k=1}^{3}\left[X^{\pm}{}_{ijk}\right]\le S_t \tag{11}$$

⑤ Agricultural planting scale constraints:

The agricultural planting constraints (Eq. 12) describe the maximum and minimum available land for various agricultural land types during different periods in Shuyang town.

$$MINNY_k\le\sum_{i=1}^{1}\sum_{j=1}^{6}\sum_{k=1}^{3}X^{\pm}{}_{ijk}\le MAXNY_k \tag{12}$$

⑥ Animal husbandry scale constraints:

The animal husbandry scale constraints (Eq. 13) describe the maximum and minimum available land for various animal husbandry land types during different periods in Shuyang town.

$$MINXM_k\le\sum_{i=2}^{2}\sum_{j=1}^{6}\sum_{k=1}^{3}X^{\pm}{}_{ijk}\le MAXXM_k \tag{13}$$

⑦ Forestry scale constraints:

The forestry scale constraints (Eq. 14) describe the maximum and minimum available land for different forestry land types during different periods in Shuyang town.

$$MINLY_k\le\sum_{i=3}^{3}\sum_{j=1}^{6}\sum_{k=1}^{3}X^{\pm}{}_{ijk}\le MAXLY_k \tag{14}$$

⑧ Non-negative constraints Eq. (15):

$$X^{\pm}{}_{ijk}\ge 0 \tag{15}$$

where i indicates the three main categories of land use, i = 1, 2, 3, where i = 1 for agricultural land use, 2 for grazing land use, and 3 for forestry land use; j implies six small categories under each category, j = 1, 2, 3, 4, 5, and 6, where j = 1 for tea in agricultural land, 2 for vegetables, 3 for fruit trees, 4 for field crops, 5 for tubers, and 6 for flowers; j = 1 for pigs in grazing land, 2 for cows, 3 for sheep, 4 for chicken, 5 for ducks, and 6 for goose; and j = 1 for bamboo, 2 for Masson's pine, 3 for eucalyptus, 4 for *Castanopsis hystrix*, and 5 for camphor. k represents the planning cycles named for the 13th, 14th, and 15th five-year plans that run throughout China, where each stage consists of five years and where k = 1 for years 2016–2020, 2 for years 2021–2025, and 3 for years 2026–2030. X (square meters) represents the area of land occupied by each crop; St (square meters) represents the total land area that can be controlled; P (RMB/m^2) represents the revenue yield per unit area of land for each crop; C (RMB/m^2) represents the cost of land per crop; β represents the forestry correction factor; θ represents the water use safety factor; *WW* (tons/mu) represents the amount of wastewater that needs to be treated per crop area; *CW* (RMB) represents the cost of treating each ton of wastewater; *W* (cubic meters/mu) represents the amount of water required for each type of land; *Wt* (cubic meters) represents the maximum water limit; *JL* (cubic meters/mu) represents land runoff per crop area; *N* (mg/L) represents the dissolved nitrogen concentration on land for each crop; *P* (mg/L) represents the dissolved phosphorus concentration on land for each crop; *U* (kg/mu) represents the maximum allowable runoff loss of dissolved nitrogen and phosphorus; *MINNY* (mu) represents the minimum amount of land for agriculture; *MAXNY* (mu) represents the maximum amount of land for agriculture; *MINXM* (mu) represents the minimum amount of land for animal husbandry; *MAXXM* (mu) represents the maximum amount of land for animal husbandry; *MINLY* (mu) represents the minimum amount of land for forestry; and *MAXLY* (mu) represents the maximum amount of land for forestry.

The interval linear planning (ILP) model is established in three stages. In each stage, the total income from agriculture, animal husbandry, and forestry is used to subtract the total costs of the same three categories in terms of planting or growing and sewage treatment from the discharge standards to obtain the total agricultural income of Shuyang town in one cycle. The detailed process of the ILP model can be described as follows:

Step 1: Formulate the ILP model under three planning cases, which correspond to (k = 1, 2, and 3) cycles of the total agricultural income of Shuyang town.

Step 2: Calculate the benefits of planting and breeding and the planting and sewage treatment costs based on distributed computing.

Step 3: Formulate the objective function and relevant constraints of the model and obtain the lower bound of the objective function.

Step 4: Formulate the objective function and relevant constraints of the model and obtain the upper bound of the objective function.

Step 5: Calculate the total agricultural income of Shuyang town in each stage according to the function interval of each component of the objective function in each stage. Based on the final calculation, compute the total agricultural income in each cycle and provide the optimal plan for land use in Shuyang town.

2.3.3. Data Process

The data used in this paper come from actual surveys and government websites, all of which are reliable and contain valid data.

According to the 2015 pollution-source survey of the Environmental Protection Bureau of Zhang Zhou City, farmland livestock and poultry manure have an average farmland load carrying capacity of 1 ton/ha. Table 2 shows the water demand of stock farming. However, in some areas, it has reached 1.96 tons/ha due to the unreasonable distribution of livestock and poultry. Livestock and poultry excrement loads on farmland in local areas far exceed their actual requirements, resulting in serious pollution. However, pollution control in the livestock industry is not difficult. In accordance with national standards, if a sufficient number of biogas digesters, biochemical ponds, and sequestering forests are created through ecological engineering, then pollution control can be implemented to achieve emission standards or even zero emissions.

According to the survey, Shuyang town has a sewage treatment plant that can handle agricultural and domestic wastewater. The operating costs of sewage treatment plants are classified into personnel costs, power costs, maintenance fees, pharmaceutical expenses, and other expenses. Personnel costs include staff salaries and surcharges, management fees, and vehicle fees. The power fee includes the whole plant's electricity fee.

Maintenance costs include daily equipment maintenance fees, instrument calibration fees, equipment overhaul fees, and pipeline maintenance fees. The drug charge includes various chemical reagents, flocculants, and disinfection chemicals. These costs are formulated as $C = A + W + P + M + R + Q$; assuming that the total investment is 25 million yuan, the loan interest rate is 6% per annum, and the depreciation period is 25 years. Thus, the monthly treatment cost is $C = A + W + P + M + R + Q =$ 547,347 yuan, and the treatment cost per ton is C ÷ (30 × 30000) = 0.61 yuan.

In 2011, China carried out the first national water conservancy census and determined the status of rivers, lakes and water conservancy projects; the socioeconomics of water use; and the capacity structure of the water conservancy industry. The results show that the irrigated area of China is 66.8 million ha and the water consumption for irrigation is 405.78 billion cubic meters in each stage, accounting for 65.3% of the total water. In other words, the average water consumption of China's planting industry is 404 m^3/mu. Shuyang town is located in the mountainous area of southern Fujian. Compared with the northern Fujian, Shuyang town is rich in water resources, and the crop-water demand is higher than the national average level. According to the 2014 survey of the irrigation network, the average agricultural water consumption per mu in Fujian Province is 600–800 cubic meters. According to GB 3838-2002, Environmental quality standards for surface water: the standard limit value for class V for total nitrogen is 2 mg/L, and that for total phosphorus is 0.4 mg/L.

This model includes three five-year plan cycles from 2016 to 2030. According to the general trend of economic development in the future, rising prices will inevitably lead to upward trends of income and cost. As the tourism industry of Shuyang town becomes increasingly popular, the demand for special agricultural products, such as tea, banana, passion fruit, grapefruit, beef, chicken, duck meat, and bamboo, will also increase. Based on the limitation of the existing cultivated land, some suitable forestland will be developed for planting. Therefore, when forecasting the second and third cycles, the data were increased within a reasonable range.

3. Results and discussion

The data for the three stages (i.e., *k*-1, *k*-2, and *k*-3) are entered into a linear model based on fuzzy intervals, and the results are discussed below.

With k = 1, representing 2016–2020, the total economic income from agriculture in Shuyang town was RMB 2,377,331.12 million; in k = 2, representing 2021–2025, it was RMB 2,557,376.8 million, an increase over the previous cycle of 11.24%; and in k = 3, representing 2026–2030, it was RMB 27,233,367 million, an increase of 4.7% over the previous stage.

Based on the analysis of the above economic scenarios, agricultural income in Shuyang town will increase every year. Before 2025, there will be a substantial increase because tourism development gives rise to an increase in demand for all agricultural and forestry products. Furthermore, more migrants are expected to return home from the city, thereby driving agricultural development. With changes in land use, total agricultural revenues will increase (Figs. 2-4). The total area of Shuyang town is 278,000 mu. In 2016–2020 (K = 1), the planting area was (54561, 57638) mu, accounting for 19–21% of the total area. Animal husbandry accounts for (1664, 1895) mu or 1% of the total area. Forest use accounts for (159352, 165662) mu or 57– 59% of the total area.

Table 2. Water demand of stock farming

	Pig	***Cow***	***Sheep***	***Chicken***	***Duck***	***Goose***
Water demand (L/Day)	(7,13)	(15,30)	(10-15)	(0.5,1)	(1,1.5)	(1,1.5)

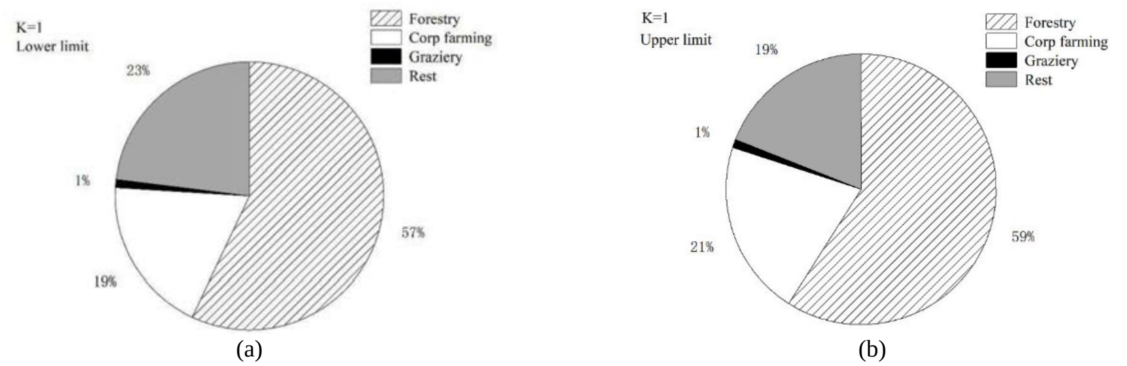


Fig. 2. Proportional of land use areas of forestry, crop farming, graziery and the rest in stage 1: (a) the ratio in the lower limit and (b) the ratio in the upper limit

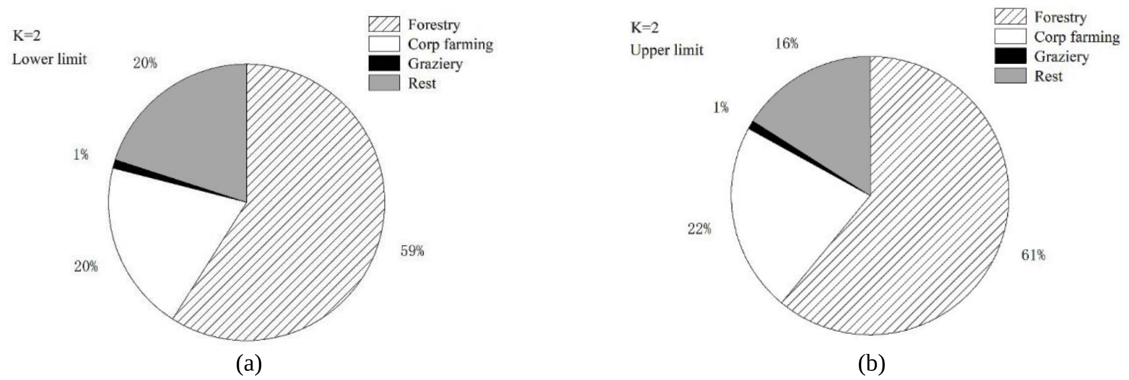


Fig. 3. Proportional land use areas of forestry, crop farming, graziery and the rest in stage 2: (a) the ratio in the lower limit and (b) the ratio in the upper limit

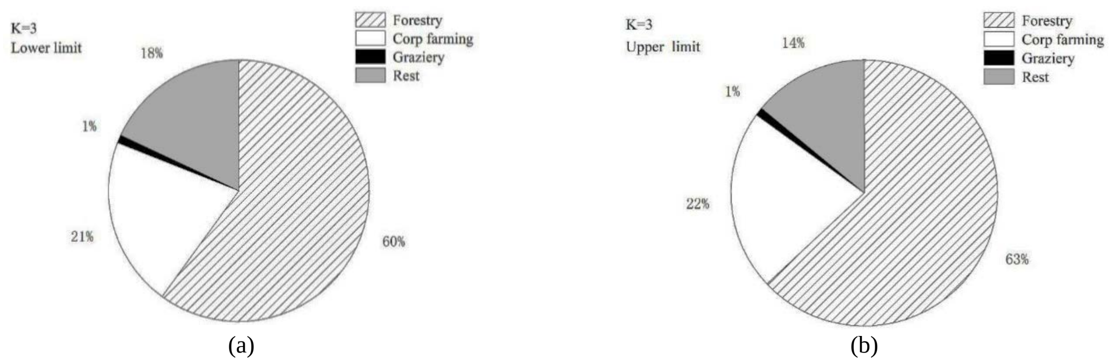


Fig. 4. Proportional land use area of forestry, crop farming, graziery and the rest in stage 3: (a) the ratio in the lower limit and (b) the ratio in the upper limit

Other types of land account for (3000, 63000) mu or 19–23%. These results matched the historical statistical data.

In 2021–2025 (k = 2), the planting area will be (57090, 59919) mu, accounting for 20–22% of the total area. Animal husbandry will account for (1767, 2003) mu or 1% of the total area. Forest use will account for (163518, 171071) mu or 59–61% of the total area. Other types of land will account for 45000–56000 mu or 16–20%.

In 2026–2030 (k = 3), the planting area will be (60064, 62096) mu, accounting for 21–22% of the total area. Animal husbandry will account for (1833, 2167) mu or 1% of the total area. Forest use will account for (167474, 174150) mu or 60–63% of the total area. Other types of land will account for (40000, 49000) mu or 14–18%.

Thus, with the increase in total income, all types of land utilization are likely to increase, with the largest increase in forested land, followed by cultivation. Owing to its small base, animal husbandry will increase marginally from the overall point of view.

The intervals of the area used in the three cycles for various types of crops, livestock, agriculture, animal husbandry, and forestry are shown in Figs. (5-7). In agriculture, tea is the most widely cultivated crop, occupying 50% of the agricultural area and 10% of the total land area. The area under cultivation increases significantly during the three stages for tea, followed by fruit trees. In animal husbandry, chicken, beef, and pork show the fastest growth rates. These growth rates can be attributed to the expected growth of tourism in Shuyang town.

The uncertain fuzzy set programming (UFSP) model has a wide range of intervals that lead to a large range of calculations and accurate results. Therefore, we compare the mean, interval, and fuzzy interval methods, as well as UFSP, UFSP-β, and UFSP-U, to analyze the advantages of the UFSP model in determining the total agricultural economic returns.

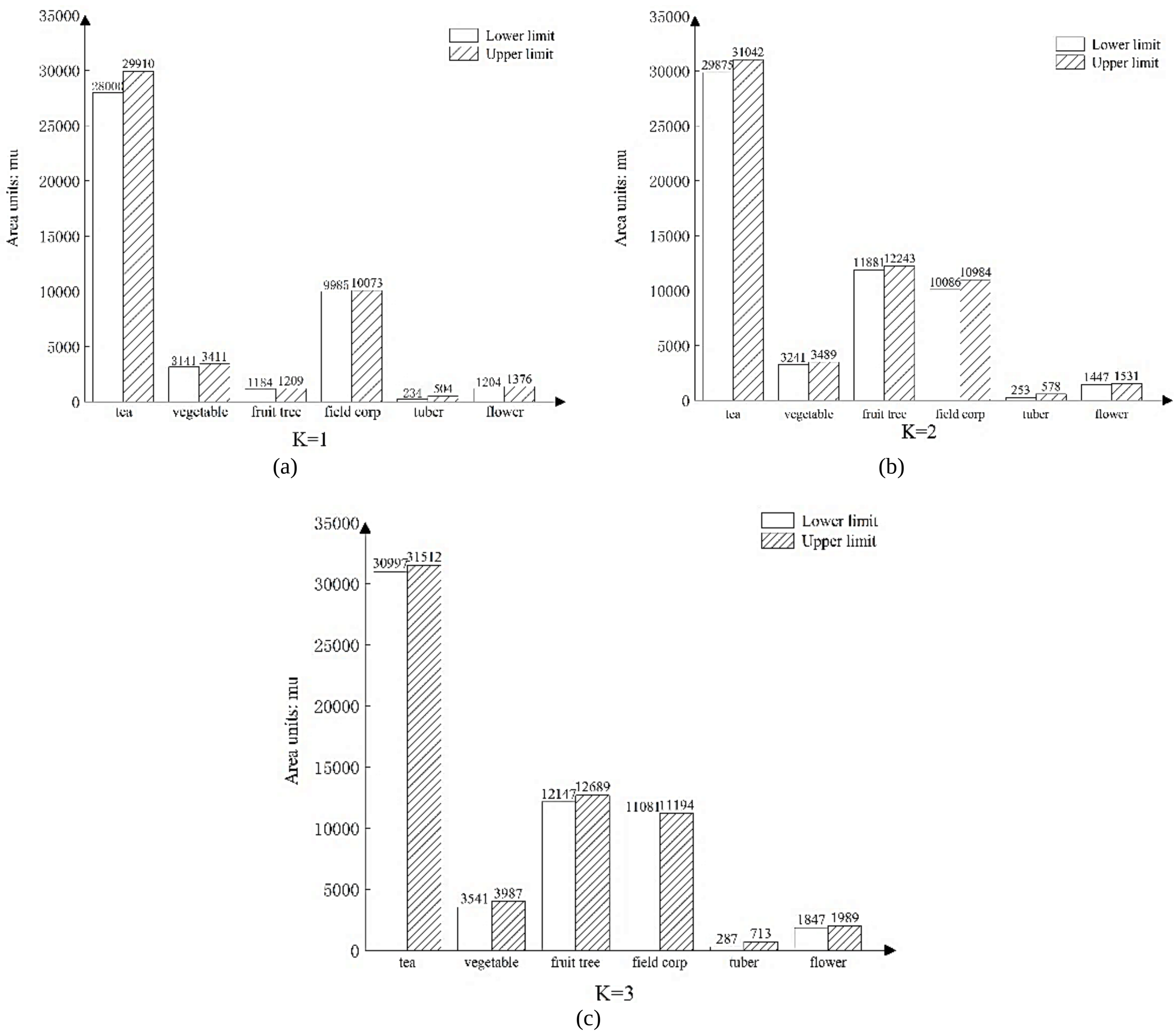
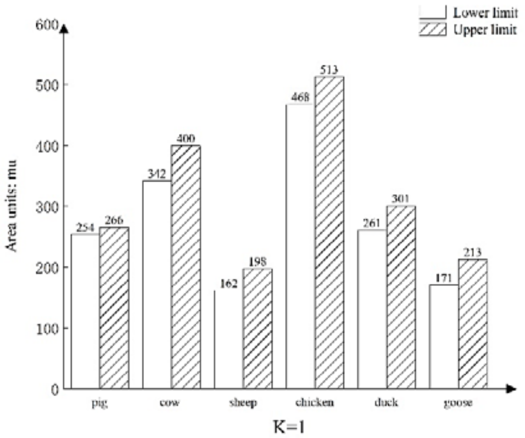
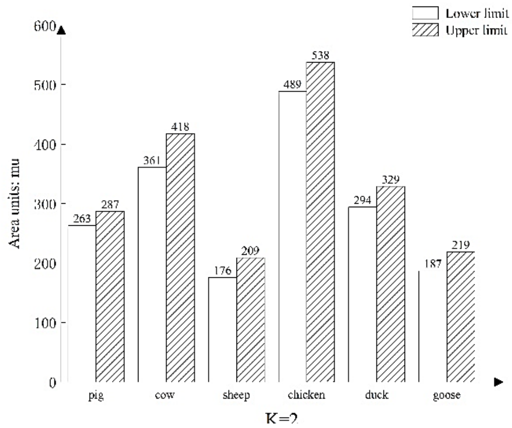


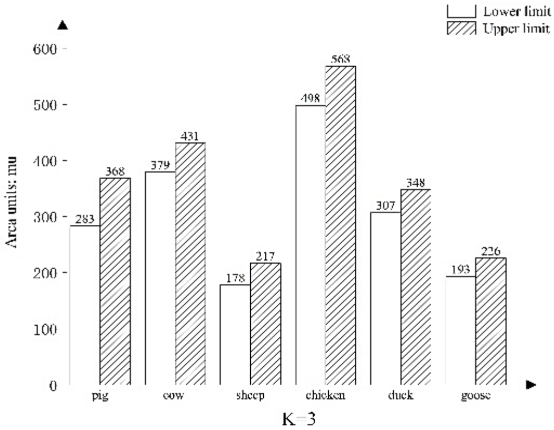
Fig. 5. Yield of crops in different regions and periods



(a)

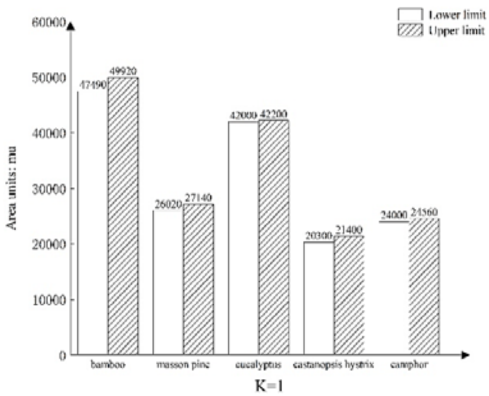


(b)

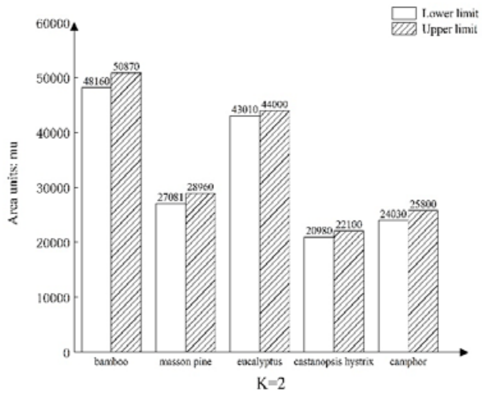


(c)

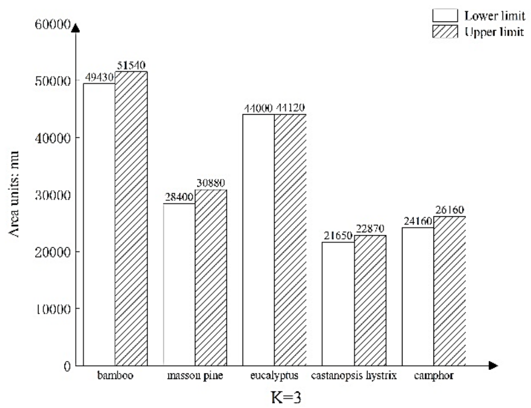
Fig. 6. The output of animal husbandry in different regions and periods



(a)



(b)



(c)

Fig. 7. Tree production in different regions at different times

3.1. Horizontal comparison

The results of the three methods are compared horizontally, and the advantages of the interval fuzzy method are analyzed:

- when $k = 1$, the results obtained by the mean, interval, and interval fuzzy methods are 27.97 billion yuan, (25.2, 32.09) billion yuan, and (23.77, 33.12) billion yuan, respectively (Fig. 8).
- when $k = 2$, the results obtained by the mean, interval, and interval fuzzy methods are 3.25 billion yuan, (27.47, 36.57) billion yuan, and (25.57, 37.68) billion yuan, respectively.
- when $k = 3$, the results obtained by the mean, interval, and interval fuzzy methods are 3.699 billion yuan, (28.81, 37.69) billion yuan, and (27.13, 37.69) billion yuan, respectively.

The results of the mean method (algorithm. 1) provide a definite number, which shows its uniqueness. However, the market price, cost, pollutant emissions, and rainy-season and dry-land runoff of agricultural products are uncertain in practice. A definite output cannot represent dynamic changes in the data. Therefore, the solution obtained by the mean method is less significant. The range of interval solutions obtained by the interval method (algorithm 2) is more conservative than that of the interval fuzzy method because adding floating values up and down due to interval blurring extends the solution to a wider range. Therefore, the benefits obtained by the interval fuzzy algorithm are more valuable and practical.

3.2. Vertical comparison

Comparative models (models two and three) (Eqs. 16-24) were established to discuss the advantages compared to model one with a vertical comparison as a reference.

3.2.1. Model 2

$$MAXf = \sum_{i=1}^{3}\sum_{j=1}^{6}\sum_{k=1}^{3}\left[X^{\pm}_{ijk}\cdot\left(P^{\pm}_{ijk}-C^{\pm}_{ijk}\right)\right]-CW\cdot\sum_{i=1}^{3}\sum_{j=1}^{6}\sum_{k=1}^{3}\left(X^{\pm}_{ijk}\cdot WW^{\pm}_{ijk}\right) \tag{16}$$

Subject to:

$$\sum_{i=1}^{2}\sum_{j=1}^{6}\sum_{k=1}^{3}\left(1+\theta_k\right)X^{\pm}_{ijk}\cdot W^{\pm}_{ijk}\le Wt^{\pm}_{k} \tag{17}$$

$$\sum_{i=1}^{3}\sum_{j=1}^{6}\sum_{k=1}^{3}X^{\pm}_{ijk}\cdot JL^{\pm}_{ijk}\cdot N^{\pm}_{ijk}\le U^{\pm}_{1k}\cdot\sum_{j=1}^{6}\sum_{k=3}^{3}X^{\pm}_{1jk} \tag{18}$$

$$\sum_{i=1}^{3}\sum_{j=1}^{6}\sum_{k=1}^{3}X^{\pm}_{ijk}\cdot JL^{\pm}_{ijk}\cdot P^{\pm}_{ijk}\le U^{\pm}_{2k}\cdot\sum_{j=1}^{6}\sum_{k=3}^{3}X^{\pm}_{1jk} \tag{19}$$

$$\sum_{i=1}^{3}\sum_{j=1}^{6}\sum_{k=1}^{3}\left[X^{\pm}_{ijk}\right]\le S_t \tag{20}$$

$$MINNY_k\le\sum_{i=1}^{1}\sum_{j=1}^{6}\sum_{k=1}^{3}X^{\pm}_{ijk}\le MAXNY_k \tag{21}$$

$$MINXM_k\le\sum_{i=2}^{2}\sum_{j=1}^{6}\sum_{k=1}^{3}X^{\pm}_{ijk}\le MAXXM_k \tag{22}$$

$$MINLY_k\le\sum_{i=3}^{3}\sum_{j=1}^{6}\sum_{k=1}^{3}X^{\pm}_{ijk}\le MAXLY_k \tag{23}$$

$$X^{\pm}_{ijk}\ge 0 \tag{24}$$

Based on model one, model two removes the forestry correction coefficient:

- when $k = 1$, the total agricultural benefits are (143.34, 205.93) billion yuan;
- when $k = 2$, they are (191.26, 252.94) billion yuan;
- when $k = 3$, they are (198.53, 274.24) billion yuan. (Fig. 9) shows that the results of model two with the forestry correction coefficient significantly deviated from the scope of the actual situation.

As 84–88% of forestry exists for ecological benefits, the rest is used for human production and life enhancement, such as papermaking, handicrafts, and urban greening. From the investigations conducted thus far, it can be reliably stated that the inhabitants and government realize the direct economic benefits of trees and hence protect them instead of cutting them down. Trees generate fresh air, conserve water, and provide clean water for the population.

3.2.2. Model 3

$$MAXf = \sum_{i=1}^{3}\sum_{j=1}^{6}\sum_{k=1}^{3}\left[X^{\pm}_{ijk}\cdot\left(P^{\pm}_{ijk}-C^{\pm}_{ijk}\right)\right]- -CW\cdot\sum_{i=1}^{3}\sum_{j=1}^{6}\sum_{k=1}^{3}\left(X^{\pm}_{ijk}\cdot WW^{\pm}_{ijk}\right) \tag{25}$$

Subject to:

$$\sum_{i=1}^{2}\sum_{j=1}^{6}\sum_{k=1}^{3}\left(1+\theta_k\right)X^{\pm}_{ijk}\cdot W^{\pm}_{ijk}\le Wt^{\pm}_{k} \tag{26}$$

$$\sum_{i=1}^{3}\sum_{j=1}^{6}\sum_{k=1}^{3}\left[X^{\pm}_{ijk}\right]\le S_t \tag{27}$$

$$MINNY_k\le\sum_{i=1}^{1}\sum_{j=1}^{6}\sum_{k=1}^{3}X^{\pm}_{ijk}\le MAXNY_k \tag{28}$$

$$MINXM_k\le\sum_{i=2}^{2}\sum_{j=1}^{6}\sum_{k=1}^{3}X^{\pm}_{ijk}\le MAXXM_k \tag{29}$$

$$MINLY_k\le\sum_{i=3}^{3}\sum_{j=1}^{6}\sum_{k=1}^{3}X^{\pm}_{ijk}\le MAXLY_k \tag{30}$$

$$X^{\pm}_{ijk}\ge 0 \tag{31}$$

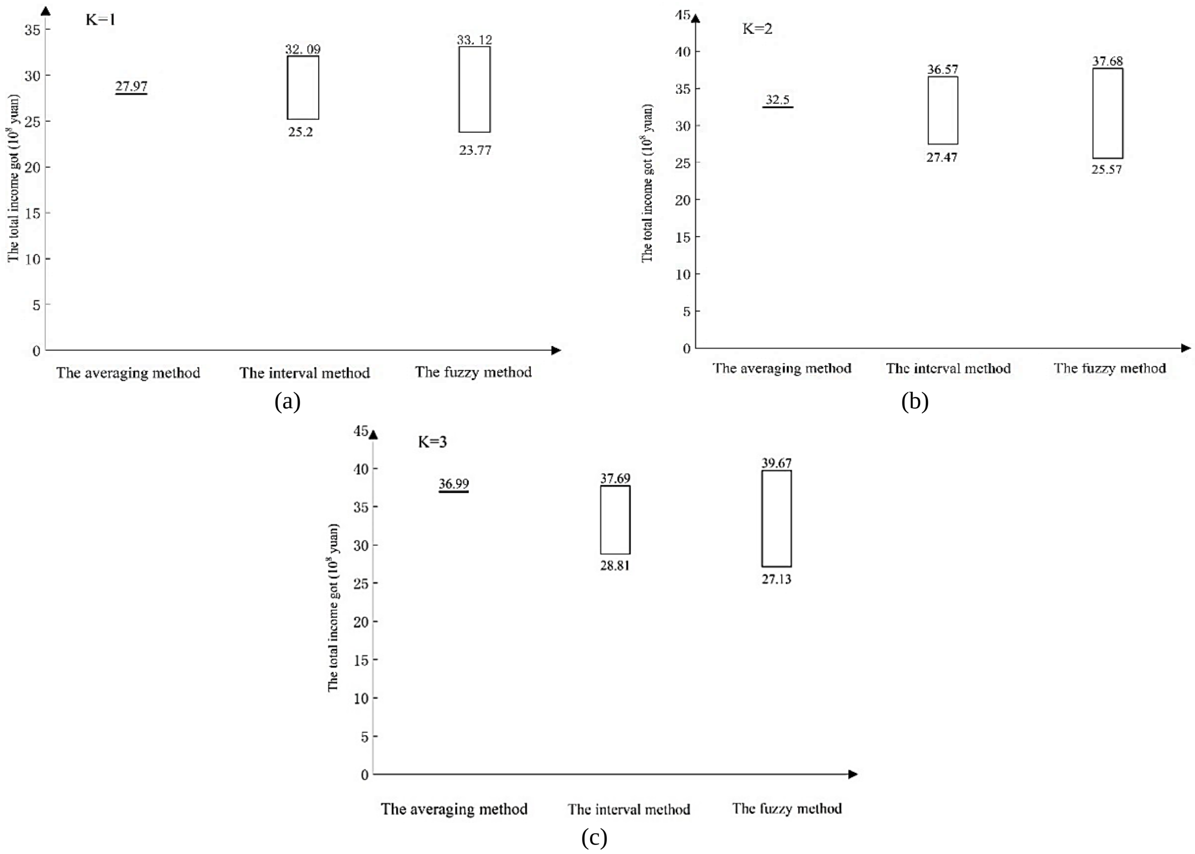


Fig. 8. Benefits of different models in different periods

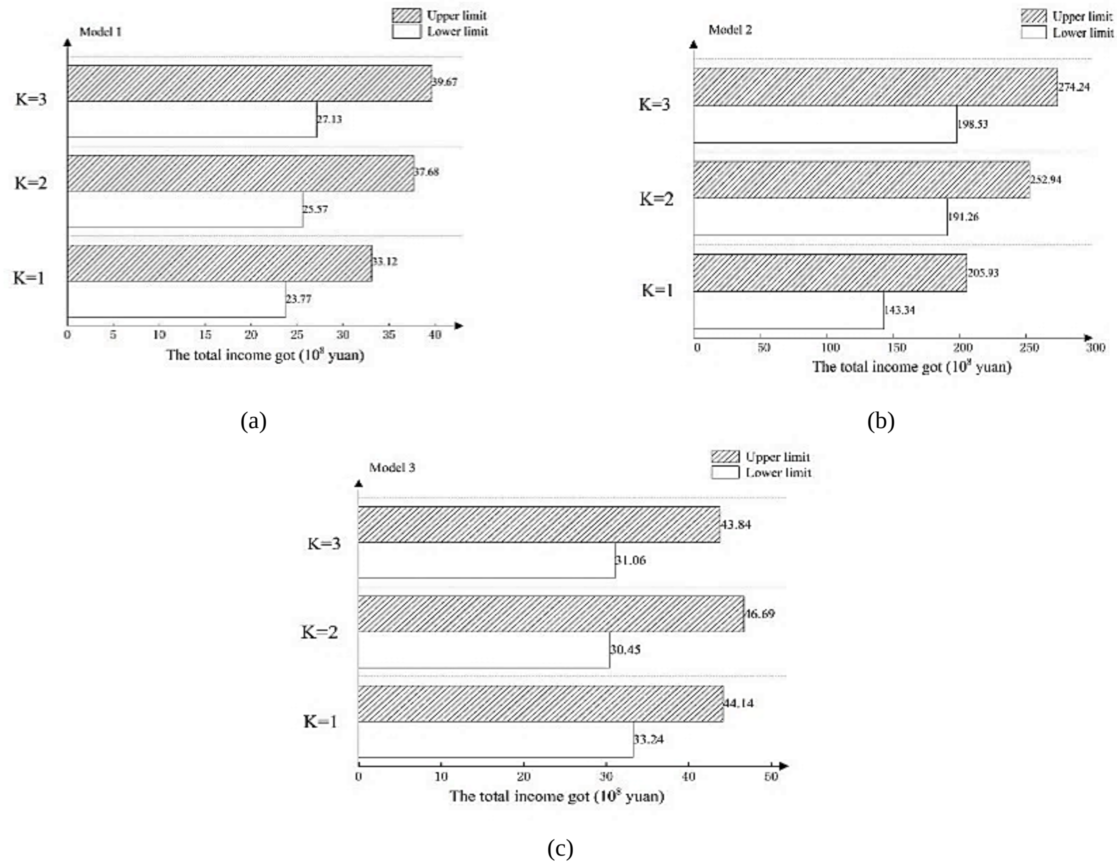


Fig. 9. Calculation of agricultural economic income: (a) the situation in model 1, (b) model 2, and (c) model 3

The third model (Eqs. 25-31) are build based on model one, which removes the constraints of nutrient loss and maximum allowable runoff loss in terms of dissolved nitrogen and dissolved phosphorus in soil:

- when k = 1, the total agricultural benefits are (33.24, 44.14) billion yuan;
- when k = 2, they are (30.45, 46.69) billion yuan;
- when k = 3, they are (31.06, 43.84) billion yuan. In these three cycles, model one scored increases of 38.5%, 24%, and 15%, respectively.

In summary, model one takes the water environmental factors into account and is useful for reasonable land-use planning.

4. Conclusions

This study proposes an uncertain fuzzy set programming model (UFSP) to support agricultural water-system planning in Shuyang town. The UFSP model combines fuzzy numbers and interval linear programming in a framework, which applies fuzzy numbers to interval values to solve the risk of interval representation uncertainty. The superiority of the UFSP model was analyzed by comparing three different models and solutions for water-system planning for Shuyang town.

In this process, the future economic development of Shuyang town was predicted and found to be in line with expectations. The algorithm used in the water environmental model based on the interval fuzzy method cannot represent dynamic changes in data, and the solution range of the interval method is smaller than that of the fuzzy interval algorithm. Therefore, the agricultural water-system planning provided by the interval fuzzy algorithm is more reasonable. In addition, the uncertain fuzzy set programming model without the forestry correction coefficient and the uncertain fuzzy set programming model without nutrient loss were set up. Through a comparative experiment, it was established that a forestry coefficient and restricting nutrient loss are required to achieve reliable results.

Although this study is the first attempt to apply the uncertain fuzzy set programming model for planning water resources for Shuyang town, the results show that the UFSP model is an effective tool for decision makers dealing with water resources to achieve long-term water planning and management in Shuyang town. The UFSP model can also be combined with other optimization techniques to address various uncertainties in the government land resource management system.

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