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Application of an Interval Two-Stage Robust (ITSR) Optimization Model for Optimization of Water Resource Distribution in the Yinma River Basin, Jilin Province, China

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Abstract: The present study is based on the application of an interval two-stage stochastic programming (ITSP) model in the Yinma River Basin. A robust method based on interval two-stage robust (ITSR) optimization is introduced to construct an optimization model of water resource distribution in order to solve the problems of water shortage in low-income and high-income areas caused by the unreasonable distribution of water resources. The model would help in reducing the system risk in the Yinma River Basin caused by an excessive pursuit of economic benefits. The model simulations show that the amount of water required for the water resource distribution is significantly reduced after balancing the risks and the water resource distribution of the water use departments is reduced by up to 20%. In addition, the situation of water scarcity of various water use departments shows a decreasing trend. There is no scarcity of water use in Panshi, Yongji, Shuangyang and Jiutai areas. The water shortage of water use departments in other areas is reduced by up to 97%. The allocation of reused water to ecological and environmental departments with higher water demand further solved the water shortage problem in low-income departments in the interval-two-stage planning model. In this study, after the introduction of the robust optimization method in the Yinma River Basin, the stability of the water resources distribution system is significantly improved. In addition, the risk of water use system in the interval-two-stage stochastic model can be avoided.

Keywords: interval-two-stage-robust optimization method; the Yinma River Basin; water management; optimize configuration; uncertainty

1. Introduction

China has a vast number of water resources; however, due to the vast territory, large population, small per capita water resources and uneven distribution of water resources in time and space, there is still a serious imbalance between supply and demand of the resource [1,2]. The main way to solve the problem of water shortage is the optimal distribution of areal water resources [3–5]. It can be achieved mainly through improving the distribution efficiency of water resources, scientifically allocating water among water use departments and reasonably solving the problem of competitive water usage among areas and departments [6,7]. The Yinma River Basin located in the middle of the Jilin Province is the main first-class tributary of the second Songhua River. It originates from Panshi City with a total length of the tributary of about 387 km and the basin area of about 18,247 km^2 [8]. The river basin is located in the core of the northeast black land and is one of the only two Golden Corn belts in the world. It is the main producing area for rice, corn and other crops in the province and the main national commodity grain base [9]. The proportion of urbanization in the river basin is 68%, with a relatively dense population. The increase in human population in recent years has caused shortage of water resources in the Yinma River Basin due to an unreasonable distribution of water resources [10,11].

Many studies about water resource distribution have been reported. For example, Chen [12] identified the possible impact of water resource distribution on river ecosystems; Dunia [13] developed an integer linear programming decision support model of water resource distribution to solve the problem of a serious water shortage caused by increased demand and reduced supply; Wan [14] constructed a rule-based areal water resource distribution model, which aims to alleviate the contradiction of water supply in the suburbs of central Guizhou. A few researchers have also reported studies on the water resource distribution of the Yinma River Basin. For example, Di [15] used particle swarm optimization and analytic hierarchy process to evaluate the temporal and spatial variation of water environment risk in the Yinma River Basin and adjusted the water environment index. Meng [16] also used the interval-two-stage optimization method from the view of the pollution-carrying capacity of the Yinma River Basin to allocate water resources. However, the model did not consider the system risk while pursuing the maximization of profits and over-allocated water resources to departments with high water income or low emission coefficient. It caused water resources loss in the high-income areas of the Yinma River Basin, scarcity of water resources in the low-income areas and the risk of areal water use systems.

The robust optimization method [17–21] is used to balance variable random quantity and the system risk while pursuing profit maximization. The optimization method is very effective in avoiding system risk and has achieved good results in different fields. For example, Guo [22] constructed an interval-two-stage-robust optimal carbon sequestration trading model. The model was applied to carbon sinks trading in Zhangjiakou and greatly optimized the distribution of carbon resources while increasing the stability of the carbon emission system. Tan [23] developed a distribution network dispatching method based on interval-two-stage-robust stochastic planning, which reduced the risk of distribution system network loss. In view of the uncertainty in the optimal design and operation of the water treatment system, Kammammettu [24] studied the two-stage adaptive nonlinear robust optimization problem and developed a robust operation strategy for the water treatment network by using the robust method in order to avoid the risk of excessive pollutant emissions in the water treatment process.

In the present study, a robust optimization method is presented and an optimization model of water resource distribution in the Yinma River Basin, based on the interval two-stage optimization method proposed by Meng, is constructed [16]. The developed model is known as the interval two-stage robust optimization method and it aims at the optimization of the basin economy to optimize the water resources of each planning area and water use departments and balance the relationship between economic benefits and water resource distribution in the system. It effectively avoids the risks caused by unreasonable water resource distribution and the waste of water resources caused by its excessive distribution to areas with low water use efficiency in the pursuit of economic benefits. This paper analyzes the optimization effect of the system after introducing a robust optimization method.

2. Model Formulation

2.1. The Interval Two-Stage Robust Optimization Method

In recent years, human activities are increasing day by day. The excessive development and utilization of water resources have led to great pressure on the water ecological environment in the Yinma River [9]. This paper constructs a water resource distribution model of the basin based on an interval-two-stage-robust stochastic (ITSR) optimization method. It aims at optimizing economic benefits and purposes to reset the water resource distribution in the basin. The method effectively avoids the risks that exist in the pursuit of economic benefits and increases the stability and reliability of the system, so as to solve the uneven water resource distribution caused by pursuing only economic benefits in the basin. In addition, it aims at formulating a reasonable and scientific plan for the water resource distribution. The formulas of ITSR are as follow [25]:

$$\min f = \sum_{j=1}^{n_1} c_j^{\pm} x_j^{\pm} + \sum_{j=1}^{n_1}\sum_{s=1}^{N} p_s d_j^{\pm} y_{js}^{\pm} + \rho \sum_{j=1}^{n_1}\sum_{s=1}^{N} p_s \left(d_j^{\pm} y_{js}^{\pm} - p_s \sum_{s=1}^{N} d_j^{\pm} y_{js}^{\pm} + 2\theta_s{}^{\pm} \right)$$

$$d_j^{\pm} y_{js}^{\pm} - p_s \sum_{s=1}^{N} d_j^{\pm} y_{js}^{\pm} + 2\theta_s{}^{\pm} \geq 0, j = 1,2,\ldots,n_1; s = 1,2,\ldots,N$$

$$\sum_{j=1}^{n_1} a_{rj}^{\pm} x_j^{\pm} \leq b_r^{\pm}, r = 1,2,\ldots,m_1$$

$$\sum_{j=1}^{n_1} a_{rj}^{\pm} x_j^{\pm} + \sum_{j=1}^{n_1} e_{ij}^{\pm} y_{js}^{\pm} \leq \hat{w}_{is}^{\pm}, i = 1,2,\ldots,m_2; s = 1,2,\ldots,N$$

$$x_j^{\pm} \geq 0, j = 1,2,\ldots,n_1$$

$$y_{js}^{\pm} \geq 0, j = 1,2,\ldots,n_1; s = 1,2,\ldots,N.$$

In this study, x represents water resource distribution; S represents available water resources scenarios; p_s represents probability on different water resources scenarios; d represents the quality of loss; y represents loss unit price; a represents pollution production coefficient/discharge coefficient; b represents water quota/control requirements; c represents unit water use income; ρ represents a robust coefficient, it reflects the attitude of decision makers in weighing the relationship between system economy and system risk. When $\rho = 0$, the model is an interval-two-stage stochastic programming model; the objective function is to maximize the economic benefit of the river basin but ignore the system risk. When $\rho > 0$, it indicates that the decision-makers begin to pay attention to the risk and the stability of the system cost and considers the variability of the cost, that is, the decision-makers begin to explore the economy of the system on the premise of ensuring the security of the system.

2.2. The Water Resources Distribution Model Based on Interval Two-Stage Robust Optimization Method Is Constructed in the Yinma River Basin

The ITSR optimization method was proposed to effectively increase the feasibility of solving the model and simultaneously avoiding the risk of ignoring the safety of water usage for pursuing maximized economic benefits. In this study, the robust coefficient ρ is introduced based on an interval-two-stage stochastic programming model and the optimization model of water resource distribution is constructed based on an interval two-stage robust optimization method. The main objective is to optimize economic benefits. In addition, the model addresses the shortage of water resources in the low-income areas and wastage of water resources in the high-income areas caused by an unscientific distribution of water resources in the interval-two-stage model that initiates areal water security problems as the unreasonable water resource distribution cause water shortage in the water use departments. The model can be expressed as follow:

Objective Function:

$$max f^{\pm} = f_1^{\pm} - f_2^{\pm} - f_3^{\pm} - f_4^{\pm} - f_5^{\pm} - f_6^{\pm} - f_7^{\pm}$$

(1) Water utilization benefits

$$f_1^{\pm} = \sum_{j=1}^{8}\sum_{k=1}^{4}\sum_{t=1}^{3} L_t \cdot UNB_{jkt}^{\pm} \cdot \left(IAW_{jkt}^{\pm} + RW_{jkt}^{\pm} \right) - \sum_{j=1}^{8}\sum_{k=1}^{4}\sum_{t=1}^{3}\sum_{h=1}^{3} L_t \cdot p_h \cdot PNB_{jkt}^{\pm} \cdot DW_{jkth}^{\pm}$$

among them, j is planning area, j = 1 to 8 are the 8 counties and cities through the Yinma River flows; k represents departments that using water, k = 1,2,3,4 represents industry, municipal life, ecological environment and agriculture, respectively; t denotes planning periods, t = 1 is the first planning period (2015–2020), t = 2 is the first planning period (2020–2025) and t = 3 is the third planning period (2025–2030); h is the available discharge level of the Yinma River Basin; L_t denotes length of period, each period is five years; $UNB^{\pm}_{jkt}$ is the unit water resources income of each water use department k in area j in period t (10^4 ¥/10^4 m^3); $PNB^{\pm}_{jkt}$ represents the water shortage loss of each water use department in area j in the period t (10^4 ¥/10^4 m^3); p_h represents the occurrence probability of scenario h; $IAW^{\pm}_{jkt}$ denotes the amount of water resources supplied in advance by the Yinma River Basin to the department k of the area j in the period t (10^4 m^3/year); $RW^{\pm}_{jkt}$ is the amount of reused water used by department k in area j in the period t; $DW^{\pm}_{jkth}$ is the lack of water in the Yinma River Basin at the level h in the period t because it does not meet the water resources distribution plan of the department k in area j (10^4 m^3/year).

(2) Water supply cost

$$f_2^{\pm} = \sum_{j=1}^{8}\sum_{k=1}^{4}\sum_{t=1}^{3} L_t \cdot \left(IAW^{\pm}_{jkt} - \sum_{h=1}^{3} p_h \cdot DW^{\pm}_{jkth}\right) \cdot CW^{\pm}_{jkt} + \sum_{j=1}^{8}\sum_{k=1}^{4}\sum_{t=1}^{3} L_t \cdot RW^{\pm}_{jkt} \cdot CRW^{\pm}_{jkt}$$

among them, $CW^{\pm}_{jkt}$ denotes the water resources use cost of each water use department k in area j in the period t (10^4 ¥/10^4 m^3); $CRW^{\pm}_{jkt}$ is the cost of water reusing for all water use departments in area j in the period t (10^4 ¥ /10^4 m^3).

(3) Wastewater treatment cost

$$f_3^{\pm} = \sum_{j=1}^{8}\sum_{k=1}^{4}\sum_{t=1}^{3} L_t \cdot \left(\begin{array}{l} IAW^{\pm}_{jkt} - \sum_{h=1}^{3} p_h \cdot DW^{\pm}_{jkth} \\ +RW^{\pm}_{jkt} \end{array} \right) \cdot \alpha^{\pm}_{jkt} \cdot CWW^{\pm}_{jkt} + \sum_{j=1}^{8}\sum_{k=1}^{4}\sum_{t=1}^{3} L_t \cdot RW^{\pm}_{jkt} \cdot CRWT^{\pm}_{jkt}$$

among them, $CWW^{\pm}_{jkt}$ represents the cost of sewage treatment for all water use departments in area j in the period t (10^4 ¥/10^4 m^3); $CRWT^{\pm}_{jkt}$ denotes the cost of water reuse for all water use departments in area j in the period t (10^4 ¥/10^4 m^3).

(4) Environmental capacity improvement cost

$$f_4^{\pm} = \sum_{i=1}^{11}\sum_{l=1}^{7}\sum_{t=1}^{3} ER^{\pm}_{ilt} \cdot Y^{\pm}_{ilt} \cdot CER^{\pm}_{ilt},$$

among them, i denotes the 11 water environment control units divided for the Yinma River Basin; r represents the controlled water pollutant, r = 1, r = 2 respectively stands for COD and ammonia nitrogen (COD is chemical oxygen demand); l is pollution carrying capacity improvement project, l = 1–7 represent separately wetlands, floating beds, corridors, pre-storehouses, conservation forests, silt removal and aeration; $ER^{\pm}_{ilt}$ denotes the maximum quantity restriction for project l in units i in the period t; $Y^{\pm}_{ilt}$ represents 0–1 planning parameter, 0 means project l is not implemented, 1 means project l is implemented; $CER^{\pm}_{ilt}$ is the engineering cost of pollution capacity improvement project of each control unit in period t.

(5) Restriction control penalty cost

$$f_5^{\pm} = \rho \sum_{j=1}^{8} \sum_{k=1}^{4} \sum_{t=1}^{3} \sum_{h=1}^{3} L_t \cdot p_h (PNB_{jkt}^{\pm} \cdot DW_{jkth}^{\pm} - p_h \sum_{h=1}^{3} PNB_{jkt}^{\pm} \cdot DW_{jkth}^{\pm} + 2\theta_h^{\pm})$$
$$f_6^{\pm} = \rho \sum_{j=1}^{8} \sum_{k=1}^{4} \sum_{t=1}^{3} \sum_{h=1}^{3} L_t \cdot p_h (CW_{jkt}^{\pm} \cdot DW_{jkth}^{\pm} - p_h \sum_{h=1}^{3} CW_{jkt}^{\pm} \cdot DW_{jkth}^{\pm} + 2\theta_h^{\pm})$$
$$f_7^{\pm} = \rho \sum_{j=1}^{8} \sum_{k=1}^{4} \sum_{t=1}^{3} \sum_{h=1}^{3} L_t \cdot p_h \begin{pmatrix} \alpha_{jkt}^{\pm} \cdot CWW_{jkt}^{\pm} \cdot DW_{jkth}^{\pm} \\ -p_h \sum_{h=1}^{3} \alpha_{jkt}^{\pm} \cdot CWW_{jkt}^{\pm} \cdot DW_{jkth}^{\pm} + 2\theta_h^{\pm} \end{pmatrix},$$

among them, $\alpha_{jkt}^{\pm}$ represents the wastewater emission coefficient for department k in the period t in area j; ρ is the robust coefficient, the value is 0, 0.8 and 1; θ_h is relaxation variable.

Restrictions:

(1) Water supply restrictions [16]

$$\sum_{k=1}^{4} \left(IAW_{jkt}^{\pm} - DW_{jkth}^{\pm} \right) \leq AWQ_{th}^{\pm};\ \forall t, h DW_{jkth}^{\pm} \leq IAW_{jkt}^{\pm};\ \forall j, k, t, h,$$

where $AWQ_{th}^{\pm}$ is the amount of available water resources under the level h of period t (10^4 m^3/year).

(2) Departments water demand restrictions [16]

$$IAW_{jkt}^{\pm} - DW_{jkth}^{\pm} + RW_{jkt}^{\pm} \geq WD_{\min jkt}^{\pm};\ \forall j, k, t, h$$
$$IAW_{jkt}^{\pm} - DW_{jkth}^{\pm} + RW_{jkt}^{\pm} \leq WD_{\max jkt}^{\pm};\ \forall j, k, t, h$$

among them, $WD_{\min jkt}^{\pm}$, $WD_{\max jkt}^{\pm}$ represent separately the lowest and highest water consumption quota of various water use departments in the area j in the period t (10^4 ¥/10^4 m^3).

(3) Areal wastewater treatment capacity restrictions [16]

$$\sum_{k=1}^{2} \left(IAW_{jkt}^{\pm} - DW_{jkth}^{\pm} + RW_{jkt}^{\pm} \right) \cdot \alpha_{jkt}^{\pm} \leq ATW_{jkt}^{\pm}, \forall j, k, t, h$$

among them, $ATW_{jkt}^{\pm}$ denotes the capacity of sewage treatment of department k in the period t in area j (10^4 tons/year).

(4) Areal wastewater reuse capacity restrictions [16]

$$\sum_{k=1}^{2} \left(IAW_{jkt}^{\pm} - DW_{jkth}^{\pm} + RW_{jkt}^{\pm} \right) \cdot \alpha_{jkt}^{\pm} \cdot \xi_{jkt} \geq \sum_{k=1}^{4} RW_{jkt}^{\pm}, \forall j, t$$

among them, ξ_{jkt} the reuse rate of water department.

(5) Restrictions on total amount control of pollutants [16]

$$\sum_{k=1}^{4} \left(IAW_{jkt}^{\pm} - DW_{jkth}^{\pm} + RW_{jkt}^{\pm} \right) \cdot \alpha_{jkt}^{\pm} \cdot \beta_{jkt}^{\pm} \cdot EC_{krt}^{\pm} \leq TED_{jrt}^{\pm}, \forall j, r, t, h$$

among them, $\beta_{jkt}^{\pm}$ denotes the sewage discharge coefficient of water use department k in area j in the period t; $EC_{krt}^{\pm}$ is the pollutant discharge concentration of the wastewater produced by each water use department k after centralized treatment in the period t (tons/10^4 m^3); $TED_{jrt}^{\pm}$ represents the maximum total amount of pollutants in area j in the period t (tons/year).

(6) Restriction of pollution-carrying capacity of river basin [16]

$$\sum_{j=1}^{8}\sum_{k=1}^{4}\begin{pmatrix} IAW^{\pm}_{jkt} - DW^{\pm}_{jkth} \\ +RW^{\pm}_{jkt} \end{pmatrix} \cdot \alpha^{\pm}_{jkt} \cdot \beta^{\pm}_{jkt} \cdot EC^{\pm}_{krt} \cdot IDR_{krt} \cdot X_{ij}$$
$$-\sum_{l=1}^{7} EER^{\pm}_{ilrt} \cdot ER^{\pm}_{ilt} \cdot Y^{\pm}_{ilt} \leq ALD^{\pm}_{irth}, \forall i, r, t, h$$

among them, IDR_{krt} denotes the inflow coefficient of pollutants discharged by each water use department in the period t; X_{ij} represents the discharge coefficient of area j to water environment control unit i; $ALD^{\pm}_{irth}$ denotes the pollution carrying capacity of at level h in period t (tons/year); $EER^{\pm}_{ilrt}$ denotes the capacity to enhance the pollutant discharge of the control unit i through the pollution carrying capacity improvement project in the period t (tons/year).

(7) Non-negative restriction [16]

$$DW^{\pm}_{jkth}, RW^{\pm}_{jkt}, ER^{\pm}_{ilt} \geq 0.$$

(8) Robust restriction

$$PNB^{\pm}_{jkt} \cdot DW^{\pm}_{jkth} - p_h \sum_{h=1}^{3} PNB^{\pm}_{jkt} \cdot DW^{\pm}_{jkth} + 2\theta^{\pm}_{h} \geq 0;\ \forall j, k, t, h$$
$$CW^{\pm}_{jkt} \cdot DW^{\pm}_{jkth} - p_h \sum_{h=1}^{3} CW^{\pm}_{jkt} \cdot DW^{\pm}_{jkth} + 2\theta^{\pm}_{h} \geq 0;\ \forall j, k, t, h$$
$$\alpha^{\pm}_{jkt} \cdot CWW^{\pm}_{jkt} \cdot DW^{\pm}_{jkth} - p_h \sum_{h=1}^{3} \alpha^{\pm}_{jkt} \cdot CWW^{\pm}_{jkt} \cdot DW^{\pm}_{jkth} + 2\theta^{\pm}_{h} \geq 0;\ \forall j, k, t, h$$

2.3. The Value Range of Economic Constraints and Environmental Constraints

In this paper, the economy as the center and the environment as the center are reflected in the constraints. Among them, areal wastewater treatment capacity restrictions, areal wastewater reuse capacity restrictions and restriction of pollution-carrying capacity of river basin on total amount control of pollutants are the constraint that take the environment as the center and robust restriction is the constraint that takes the economy as the center. The data are now sorted out into Tables 1–5.

Environmental class:

Table 1. The range of treatment capacity of sewage discharged by various water use departments in area j during the period t (10^4 tons/year).

Areas	Department	T = 1	T = 2	T = 3
J = 1	K = 1	[1070.00, 1070.00]	[1177.00, 1123.50]	[1412.40, 1179.68]
	K = 2	[10,950.00, 10,950.00]	[12,045.00, 11,497.50]	[14,454.00, 12,072.38]
	K = 3	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
	K = 4	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 2	K = 1	[2585.10, 2585.10]	[2843.61, 2714.36]	[3412.33, 2850.07]
	K = 2	[1275.00, 1275.00]	[1402.50, 1338.75]	[1683.00, 1405.69]
	K = 3	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
	K = 4	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 3	K = 1	[270.00, 270.00]	[297.00, 283.50]	[356.40, 297.68]
	K = 2	[1368.75, 1368.75]	[1505.63, 1437.19]	[1806.75, 1509.05]
	K = 3	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
	K = 4	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 4	K = 1	[750.00, 750.00]	[825.00, 787.50]	[990.00, 826.88]
	K = 2	[1350.00, 1350.00]	[1485.00, 1417.50]	[1782.00, 488.38]
	K = 3	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
	K = 4	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]

Table 1. *Cont.*

J = 5	K = 1	[3534.10, 3534.10]	[3887.51, 3710.81]	[4665.01, 3896.35]
	K = 2	[1095.00, 1095.00]	[1204.50, 1149.75]	[1445.40, 1207.24]
	K = 3	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
	K = 4	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 6	K = 1	[319.00, 319.00]	[350.90, 334.95]	[421.08, 351.70]
	K = 2	[547.50, 547.50]	[602.25, 574.88]	[722.70, 603.62]
	K = 3	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
	K = 4	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 7	K = 1	[8500.00, 8500.00]	[9350.00, 8925.00]	[11,220.00, 9371.25]
	K = 2	[29,565.00, 29,565.00]	[32,521.50, 31,043.25]	[39,025.80, 32,595.41]
	K = 3	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
	K = 4	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 8	K = 1	[875.00, 875.00]	[962.50, 918.75]	[1155.00, 964.69]
	K = 2	[1200.00, 1200.00]	[1320.00, 1260.00]	[1584.00, 1323.00]
	K = 3	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
	K = 4	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]

Table 2. The range of reuse water consumption of department *k* in area *j* during period *t* (10^4 m^3/ year).

Areas	Department	T = 1	T = 2	T = 3
J = 1	K = 1	[184.40, 0.00]	[320.20, 0.00]	[481.64, 481.64]
	K = 2	[0.00, 86.25]	[0.00, 86.70]	[0.00, 87.10]
	K = 3	[407.58, 505.71]	[474.42, 664.80]	[527.05, 353.56]
	K = 4	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 2	K = 1	[0.00, 0.00]	[0.00, 0.00]	[0.00, 139.80]
	K = 2	[0.00, 13.58]	[0.00, 66.40]	[0.00, 66.65]
	K = 3	[335.60, 267.85]	[393.04, 259.34]	[424.11, 154.04]
	K = 4	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 3	K = 1	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
	K = 2	[0.00, 40.10]	[0.00, 40.60]	[0.00, 41.15]
	K = 3	[208.17, 134.02]	[243.33, 160.29]	[274.24, 182.71]
	K = 4	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 4	K = 1	[67.91, 0.00]	[102.18, 0.00]	[148.20, 0.00]
	K = 2	[0.00, 70.10]	[0.00, 70.65]	[0.00, 71.15]
	K = 3	[361.67, 302.19]	[418.25, 381.11]	[466.88, 464.11]
	K = 4	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 5	K = 1	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
	K = 2	[0.00, 64.15]	[0.00, 64.50]	[0.00, 64.80]
	K = 3	[327.70, 214.40]	[386.24, 254.65]	[414.72, 287.71]
	K = 4	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 6	K = 1	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
	K = 2	[0.00, 0.00]	[0.00, 27.55]	[0.00, 27.65]
	K = 3	[124.09, 124.09]	[146.15, 94.90]	[166.04, 110.73]
	K = 4	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 7	K = 1	[784.86, 0.00]	[1216.12, 0.00]	[2118.36, 0.00]
	K = 2	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
	K = 3	[4735.23, 4789.06]	[5672.73, 5640.26]	[6321.98, 6515.96]
	K = 4	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 8	K = 1	[13.81, 0.00]	[243.10, 0.00]	[352.30, 0.00]
	K = 2	[0.00, 69.35]	[0.00, 70.55]	[0.00, 71.80]
	K = 3	[354.27, 242.83]	[230.12, 296.91]	[194.17, 338.50]
	K = 4	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]

Table 3. The range of the maximum total amount of pollutants in area *j* during the period *t* (tons/year).

Areas	Pollution	T = 1	T = 2	T = 3
J = 1	R = 1	[11,331.82, 11,152.21]	[10,198.64, 10,036.99]	[9178.78, 9033.29]
	R = 2	[812.42, 799.54]	[731.18, 719.59]	[658.06, 647.63]
J = 2	R = 1	[5630.28, 5541.04]	[5067.25, 4986.94]	[4560.53, 4488.24]
	R = 2	[495.89, 488.03]	[446.30, 439.23]	[401.67, 395.31]
J = 3	R = 1	[9805.01, 9649.60]	[8824.51, 8684.64]	[7942.06, 7816.18]
	R = 2	[537.59, 529.07]	[483.83, 476.17]	[435.45, 428.55]
J = 4	R = 1	[26,910.25, 23,835.35]	[24,219.22, 21,451.81]	[21,797.30, 19,306.63]
	R = 2	[1304.28, 1155.25]	[1173.85, 1039.72]	[1056.47, 935.75]
J = 5	R = 1	[34,731.30, 34,180.81]	[31,258.17, 30,762.73]	[28,132.35, 27,686.45]
	R = 2	[2128.55, 2094.81]	[1915.69, 1885.33]	[1724.12, 1696.80]
J = 6	R = 1	[6601.18, 6496.55]	[5941.06, 5846.90]	[5346.96, 5262.21]
	R = 2	[387.63, 381.48]	[348.86, 343.33]	[313.98, 309.00]
J = 7	R = 1	[35,123.98, 34,567.27]	[31,611.58, 31,110.54]	[28,450.43, 27,999.49]
	R = 2	[5581.30, 5492.83]	[5023.17, 4943.55]	[4520.85, 4449.19]
J = 8	R = 1	[32,417.50, 28,713.32]	[29,175.75, 25,841.98]	[26,258.18, 23,257.79]
	R = 2	[1666.91, 1476.44]	[1500.22, 1328.80]	[1350.20, 1195.92]

Table 4. The range of pollution-carrying capacity at the level *h* of the period *t* (tons/year).

Areas	Pollution	Department	H = 1	H = 2	H = 3
I = 1	R = 1	T = 1	[390.00, 351.00]	[464.10, 414.18]	[543.00, 480.45]
		T = 2	[360.00, 324.00]	[428.40, 382.32]	[501.23, 443.49]
		T = 3	[315.00, 283.50]	[374.85, 334.53]	[438.57, 388.05]
	R = 2	T = 1	[19.50, 17.55]	[23.21, 20.71]	[27.15, 24.02]
		T = 2	[18.00, 16.20]	[21.42, 19.12]	[25.06, 22.17]
		T = 3	[16.50, 14.85]	[19.64, 17.52]	[22.97, 20.33]
I = 2	R = 1	T = 1	[87.00, 78.30]	[103.53, 92.39]	[121.13, 107.18]
		T = 2	[75.00, 67.50]	[89.25, 79.65]	[104.42, 92.39]
		T = 3	[66.00, 59.40]	[78.54, 70.09]	[91.89, 81.31]
	R = 2	T = 1	[7.80, 7.02]	[9.28, 8.28]	[10.86, 9.61]
		T = 2	[7.20, 6.48]	[8.57, 7.65]	[10.02, 8.87]
		T = 3	[6.90, 6.21]	[8.21, 7.33]	[9.61, 8.50]
I = 3	R = 1	T = 1	[645.00, 580.50]	[767.55, 684.99]	[898.03, 794.59]
		T = 2	[630.00, 567.00]	[749.70, 669.06]	[877.15, 776.11]
		T = 3	[600.00, 540.00]	[714.00, 637.20]	[835.38, 739.15]
	R = 2	T = 1	[37.50, 33.75]	[44.63, 39.83]	[52.21, 46.20]
		T = 2	[36.00, 32.40]	[42.84, 38.23]	[50.12, 44.35]
		T = 3	[33.00, 29.70]	[39.27, 35.05]	[45.95, 40.65]
I = 4	R = 1	T = 1	[1305.00, 1174.50]	[1552.95, 1385.91]	[1816.95, 1607.66]
		T = 2	[1260.00, 1134.00]	[1499.40, 1338.12]	[1754.30, 1552.22]
		T = 3	[1215.00, 1093.50]	[1445.85, 1290.33]	[1691.64, 1496.78]
	R = 2	T = 1	[73.50, 66.15]	[87.47, 78.06]	[102.33, 90.55]
		T = 2	[70.50, 63.45]	[83.90, 74.87]	[98.16, 86.85]
		T = 3	[66.00, 59.40]	[78.54, 70.09]	[91.89, 81.31]
I = 5	R = 1	T = 1	[295.50, 265.95]	[351.65, 313.82]	[411.42, 364.03]
		T = 2	[285.00, 256.50]	[339.15, 302.67]	[396.81, 351.10]
		T = 3	[270.00, 243.00]	[321.30, 286.74]	[375.92, 332.62]
	R = 2	T = 1	[19.50, 17.55]	[23.21, 20.71]	[27.15, 24.02]
		T = 2	[18.90, 17.01]	[22.49, 20.07]	[26.31, 23.28]
		T = 3	[18.00, 16.20]	[21.42, 19.12]	[25.06, 22.17]

Table 4. *Cont.*

I = 6	R = 1	T = 1	[1830.00, 1647.00]	[2177.70, 1943.46]	[2547.91, 2254.41]
		T = 2	[1770.00, 1593.00]	[2106.30, 1879.74]	[2464.37, 2180.50]
		T = 3	[1680.00 1512.00]	[1999.20, 1784.16]	[2339.06, 2069.63]
	R = 2	T = 1	[99.00, 89.10]	[117.81, 105.14]	[137.84, 121.96]
		T = 2	[93.00, 83.70]	[110.67, 98.77]	[129.48, 114.57]
		T = 3	[85.50, 76.95]	[101.75, 90.80]	[119.04, 105.33]
I = 7	R = 1	T = 1	[690.00, 621.00]	[821.10, 732.78]	[960.69, 850.02]
		T = 2	[660.00, 594.00]	[785.40, 700.92]	[918.92, 813.07]
		T = 3	[615.00, 553.50]	[731.85, 653.13]	[856.26, 757.63]
	R = 2	T = 1	[43.50, 39.15]	[51.77, 46.20]	[60.57, 53.59]
		T = 2	[42.00, 37.80]	[49.98, 44.60]	[58.48, 51.74]
		T = 3	[39.00, 35.10]	[46.41, 41.42]	[54.30, 48.04]
I = 8	R = 1	T = 1	[1110.00, 999.00]	[1320.90, 1178.82]	[1545.45, 1367.43]
		T = 2	[1005.00, 904.50]	[1195.95, 1067.31]	[1399.26, 1238.08]
		T = 3	[900.00, 810.00]	[1071.00, 955.80]	[1253.07, 1108.73]
	R = 2	T = 1	[57.00, 51.30]	[67.83, 60.53]	[79.36, 70.22]
		T = 2	[51.00, 45.90]	[60.69, 54.16]	[71.01, 62.83]
		T = 3	[46.50, 41.85]	[55.34, 49.38]	[64.74, 57.28]
I = 9	R = 1	T = 1	[2610.00, 2349.00]	[3105.90, 2771.82]	[3633.90, 3215.31]
		T = 2	[2370.00, 2133.00]	[2820.30, 2516.94]	[3299.75, 2919.65]
		T = 3	[2130.00, 1917.00]	[2534.70, 2262.06]	[2965.60, 2623.99]
	R = 2	T = 1	[135.00, 121.50]	[160.65, 143.37]	[187.96, 166.31]
		T = 2	[124.50, 112.05]	[148.16, 132.22]	[173.34, 153.37]
		T = 3	[111.00, 99.90]	[132.09, 117.88]	[154.55, 136.74]
I = 10	R = 1	T = 1	[14,100.00, 12,690.00]	[16,779.00, 14,974.20]	[19,631.43, 17,370.07]
		T = 2	[12,750.00, 11,475.00]	[15,172.50, 13,540.50]	[17,751.83, 15,706.98]
		T = 3	[11,550.00, 10,395.00]	[13,744.50, 12,266.10]	[16,081.07, 14,228.68]
	R = 2	T = 1	[705.00, 634.50]	[838.95, 748.71]	[981.57, 868.50]
		T = 2	[630.00, 567.00]	[749.70, 669.06]	[877.15, 776.11]
		T = 3	[570.00, 513.00]	[678.30, 605.34]	[793.61, 702.19]
I = 11	R = 1	T = 1	[945.00, 850.50]	[1124.55, 1003.59]	[1315.72, 1164.16]
		T = 2	[855.00, 769.50]	[1017.45, 908.01]	[1190.42, 1053.29]
		T = 3	[780.00, 702.00]	[928.20, 828.36]	[1085.99, 960.90]
	R = 2	T = 1	[46.50, 41.85]	[55.34, 49.38]	[64.74, 57.28]
		T = 2	[42.00, 37.80]	[49.98, 44.60]	[58.48, 51.74]
		T = 3	[37.50, 33.75]	[44.63, 39.83]	[52.21, 46.20]

Economic class:

Table 5. The range of robust restriction (tons/year).

Species	Upper Limit	Lower Limit
Stabilize the cost of water shortage	0.00	12,673,946.38
Stabilize the use cost of water resources	0.00	20,265.92
Stabilize the cost of sewage treatment	0.00	4414.19

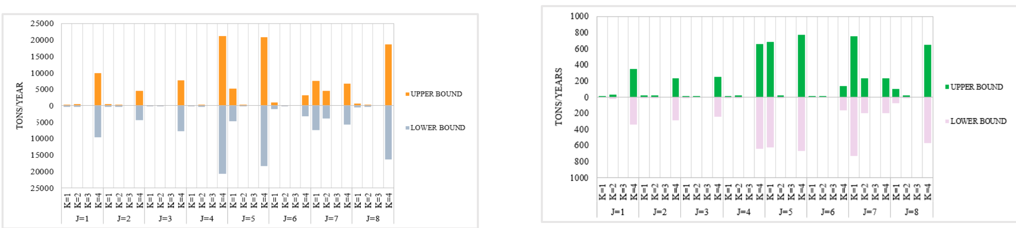
3. Results Analysis and Discussion

This study uses Lingo11 software to solve the ITSR optimization model for water resource distribution. The scenario analysis is set up in the Yinma River Basin from the point of view of total pollutant control, economic benefit and water resource distribution. This paper takes the simulation results of the water resource distribution model based on the ITSP method constructed by Meng [16] as the original scheme and for comparison.

3.1. Total Pollutant Control in the Yinma River Basin Based on ITSR Optimization Method

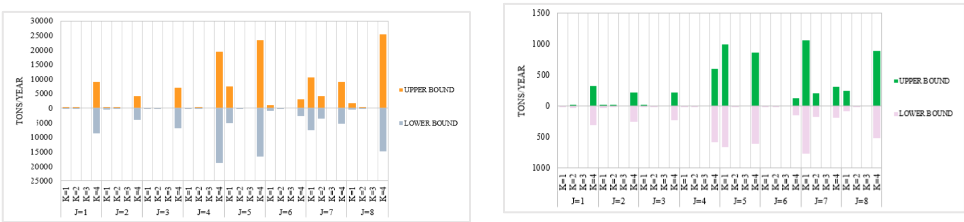
3.1.1. Analysis of the Changes in Sewage Discharge in the Yinma River Basin Based on the ITSR Optimization Method

According to Figures 1–3, the emissions of COD and ammonia nitrogen in the different departments of the different planning areas of the Yinma River Basin change with the advancing period. The emissions of the two pollutants in the industrial department increased with the advance of the period. For example, in the industrial department of Yongji area, in the first planning period, the emissions of COD and ammonia nitrogen are 408.48 tons/year and 19.09 tons/year, respectively; in the second planning period, the emissions of COD and ammonia nitrogen are 513.15 tons/year and 23.95 tons/year, respectively; in the third planning period, the emissions of COD and ammonia nitrogen are 640.50 tons/year and 29.89 tons/year, respectively. The main reason for this increase is because the industrial department is a department with high pollutant discharge and low water use efficiency. With the advance of the period, the water resource distribution increases, increasing the amount of the discharge of pollutants. However, the emissions of two kinds of pollutants from the municipal living department and the agricultural department show an opposite trend. For example, in the Panshi area, in the first planning period, the emissions of COD and ammonia nitrogen from the municipal living department are [378.04, 447.59] tons/year and [25.14, 29.77] tons/year, respectively and the emissions of COD and ammonia nitrogen from the agricultural department are [9534.42, 9875.25] tons/year and [342.00, 351.12] tons/year, respectively. In the second planning period, the emissions of COD from the municipal living department are [345.67, 411.36] tons/year and the emissions of ammonia nitrogen are [22.73, 27.05] tons/year. In the agricultural department, emissions of COD is [8589.67, 9011.25] tons/year and the emissions of ammonia nitrogen are [308.11, 320.40] tons/year. In the third planning period, the emissions of COD and ammonia nitrogen from the municipal living department are [305.85, 365.82] tons/year and [19.85, 23.75] tons/year, respectively and the emissions of COD and ammonia nitrogen from the agricultural department are [7672.19, 8266.48] tons/year and [268.87, 287.16] tons/year, respectively. Even after the optimal distribution of water resources in the Yinma River Basin, the discharge of pollutants from the agricultural department is still dominant. This may be due to the fact that the fertilizers used in agricultural production are rich in ammonia nitrogen and with farming and irrigation, the pollutants in chemical fertilizers seep into the water body through the soil. Compared with the simulation results of the original model, the emissions of pollutants from the agricultural department with the largest amount of emissions reduced in all areas and the maximum reduction is about 15%.



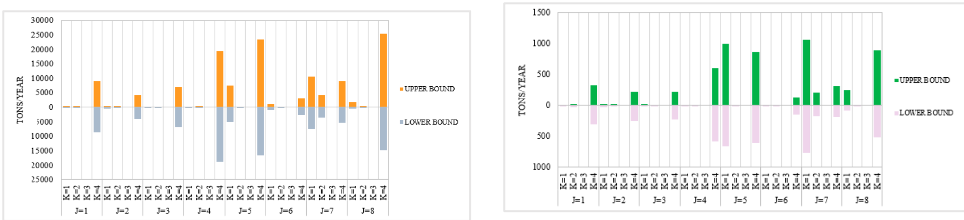
(**a**) (**b**)

Figure 1. The emissions of COD and ammonia nitrogen from different water use departments in different areas of the Yinma River Basin in the first planning period. (**a**) The emissions of COD in the first planning period; (**b**) The emissions of ammonia nitrogen in the first planning period.



(**a**) (**b**)

Figure 2. The emissions of COD and ammonia nitrogen from different water use departments in different areas of the Yinma River Basin in the second planning period. (**a**) The emissions of COD in the second planning period; (**b**) The emissions of ammonia nitrogen in the second planning period.

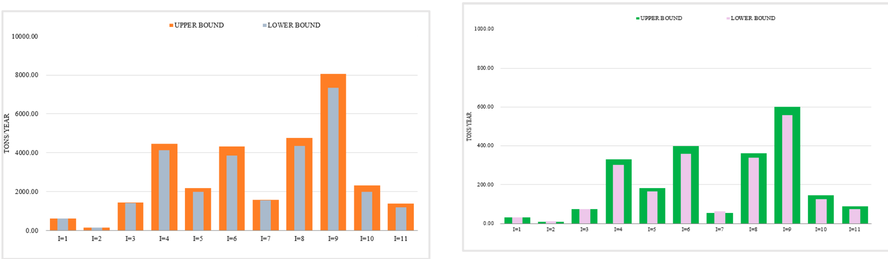


(**a**) (**b**)

Figure 3. The emissions of COD and ammonia nitrogen from different water use departments in different areas of the Yinma River Basin in the first planning period. (**a**) The emissions of COD in the third planning period; (**b**) The emissions of ammonia nitrogen in the third planning period.

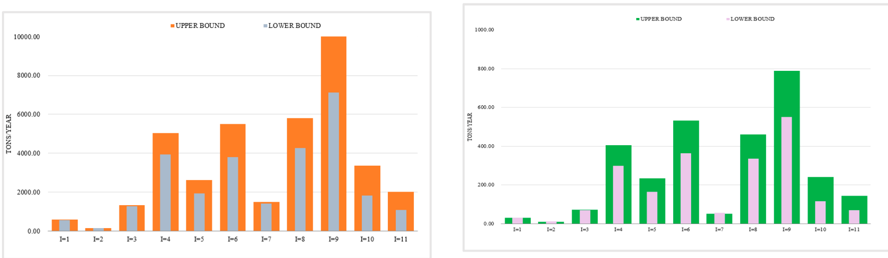
3.1.2. Analysis of the Change of Pollutants Inflow Variation in the Yinma River Basin Based on the ITSR Optimization Method

The amount of COD and ammonia nitrogen entering the river by different control units in each planning period of the Yinma River basin is shown in Figures 4–6. The amounts of these pollutants changes with the advance of the period. In the upper reaches of the Yinma River, the Chalu River, the Shuangyang River, the middle reaches of the Yinma River, the Wukai River, the lower reaches of the Yinma River and the upper reaches of the Yitong River, the amount of pollutants entering the river decreased with the advance of the planning period. For example, in the first planning period, the emissions of COD and ammonia nitrogen in the upper reaches of the Yinma River are [602.82, 624.99] tons/year and [31.81, 32.95] tons/year, respectively; in the second planning period, the emissions of COD and ammonia nitrogen are [554.09, 577.73] tons/year and [29.74, 30.96] tons/year, respectively; in the third planning period, the emissions of COD and ammonia nitrogen are [510.93, 540.12] tons/year and [27.56, 29.02] tons/year, respectively. The amount of pollutants entering the Yitong River, the urban section of Changchun, the Xinkai River, the middle reaches of the Yitong River and the lower reaches of the Yitong River, however, increases with the advance of the planning period. For example, in the first planning period, the emissions of COD and ammonia nitrogen in the urban section of the Yitong River in Changchun are [4357.10, 4756.10] tons/year and [338.49, 362.25] tons/year, respectively; in the second planning period, the emissions of COD is [4261.59, 5806.25] tons/year and the emissions of ammonia nitrogen is [336.18, 461.47] tons/year; in the third planning period, the emissions of COD is [4157.29, 6412.96] tons/year and the emissions of ammonia nitrogen is [331.27, 526.38] tons/year. This may be caused by economic development. The scale of the water department in Changchun City and Nongan Country also expanded, which increased pollutant emissions. The urban section of the Yitong River in Changchun and the Xinkai River are the main receiving water bodies in these two areas. According to the discharge and acceptance relationship of the Yinma River Basin, the pollutants enter the river in the urban section of the Yitong River in Changchun and the Xinkai River and are carried out by the middle reaches of the Yitong River and the lower reaches of the Yitong River. Therefore, the amount of pollutants entering the river in the above four planning areas has increased.



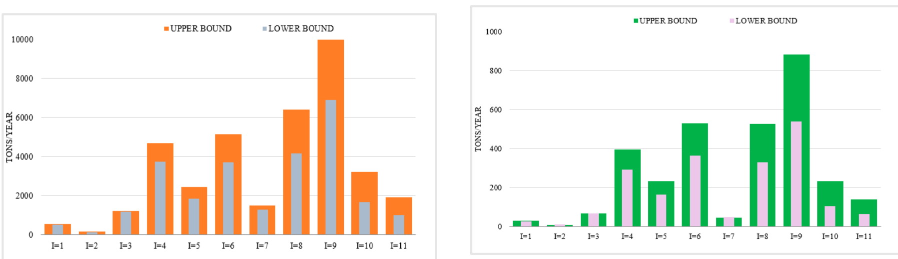
(**a**) (**b**)

Figure 4. The amounts of COD and ammonia nitrogen flow into the river on different control units in the Yinma River Basin in the first planning period. (**a**) The amount of COD flow into the river in the first planning period; (**b**) The amount of ammonia nitrogen flow into the river in the first planning period.



(**a**) (**b**)

Figure 5. The amounts of COD and ammonia nitrogen flow into the river on different control units in the Yinma River Basin in the second planning period. (**a**) The amount of COD flow into the river in the second planning period; (**b**) The amount of ammonia nitrogen flow into the river in the second planning period.



(**a**) (**b**)

Figure 6. The amounts of COD and ammonia nitrogen flow into the river on different control units in the Yinma River Basin in the third planning period. (**a**) The amount of COD flow into the river in the third planning period; (**b**) The amount of ammonia nitrogen flow into the river in the third planning period.

3.2. Figures, Tables and Schemes

The economic benefit of the Yinma River Basin system is illustrated in Figure 7. The economic benefit of the system is sensitive to the change of the robust coefficient and shows a downward trend. When ρ = 0, the water resource distribution model of the Yinma River Basin is based on the ITSR method and the model is more economical for the planning of the Yinma River Basin; when ρ = 0.8, the decision-makers choose to sacrifice economic benefits to mitigate risks. That is, the decision-makers pay more attention to the stability and controllability of the system. With an increasing ρ, the robustness of the system increases [25]; when ρ = 1, the decision-makers are an anti-risk people and pay more attention to the stability and feasibility of the system to reduce the system risk [20].

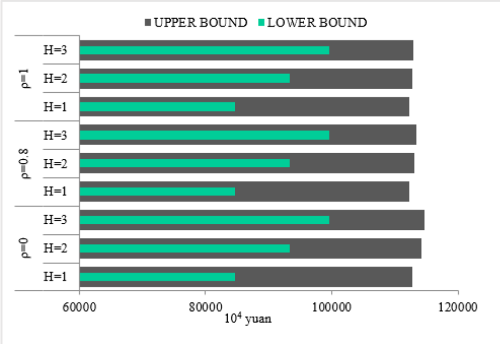


Figure 7. System economic benefits of the Yinma River Basin with different robust coefficients and different scenarios.

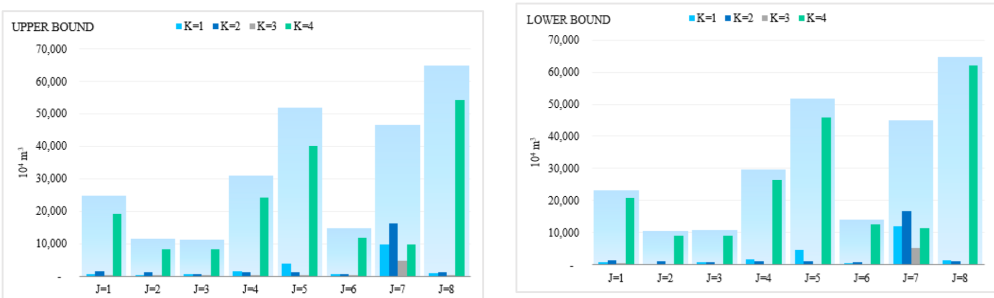
For example, under the level of low available water resources, when ρ = 0, the economic benefit of the Yinma River Basin is [112,768.86, 84,648.95] × 10^4 ¥; when ρ = 0.8, the economic benefit of the basin system is [112,359.35, 84,696.38] × 10^4 ¥; when ρ = 1, the economic benefit of the basin system is [112,240.52, 84,696.38] × 10^4 ¥. It can be seen that with the increase of the robust coefficient, the economic benefit of the system decreases gradually. However, the system risk also decreases balancing the relationship between economy and stability. Although a part of the economic benefits is sacrificed while setting a high robust value to generate low economic benefits, it can improve the stability of the system [26]. It is shown that a higher level of robustness can be used to reflect the low-risk system failures. This means that high robust value and low economy can maintain s higher system reliability and the system with a higher level of robustness has a lower risk of system failure and can maintain higher system stability.

After applying the ITSR model, the decline of the economic benefit of the system is mainly due to the industrial adjustment of the industrial and agricultural sectors, which is in line with the requirements of national environmental protection. In order to promote economic and social development, as well as the improvement of people's material and cultural life, the National Development and Reform Commission issued the Guidance Catalog for Industrial Structure Adjustment. The purpose of this policy is to make rational use of resources, coordinate with various industrial departments, provide products and services needed by society, provide full employment opportunities for workers, promote the application of advanced industrial technology and obtain the best economic benefits. The policy includes three major categories: encouragement, restriction and elimination, encouraging the planting of drought-tolerant crops, encouraging the construction of environmental protection enterprises, limiting the number of enterprises that have an impact on the environment and eliminating industrial enterprises that cannot make rational use of water resources. and reduce the planting of rice and other crops that have a high demand for water resources. In addition to the Guidance Catalog for Industrial Structure Adjustment, policies such as Water Pollution Prevention and Control Plans also explicitly ban industries that have a high demand for water resources and cause serious environmental pollution. Although the implementation of these policies will affect some economic interests, the implementation of these policies is necessary in view of sustainable development. China has made great efforts to develop the economy in the early days of the founding of the people's Republic of China and it is necessary to take the development path of high scientific and technological content, good economic benefits, low resource consumption, less environmental pollution, security and giving full play to the advantages of human resources. We will strive to promote the fundamental transformation of the mode of economic growth.

3.3. Analysis the Change of Water Resources Distribution Scheme Based on ITSR Optimization Method

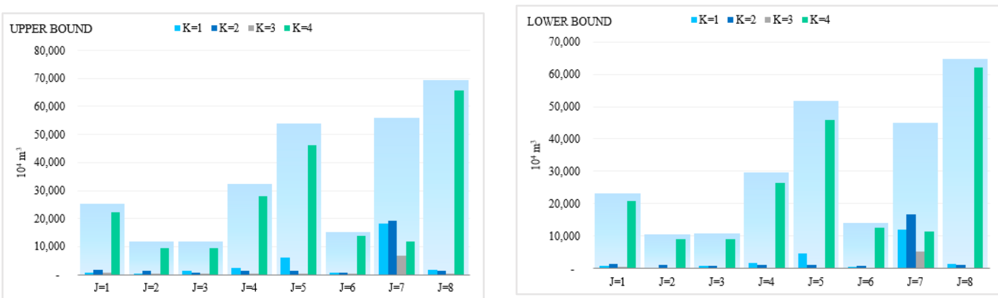
3.3.1. Water Resources Distribution Scheme Based on ITSR Optimization Method

Under the limitation of areal sewage treatment capacity, if water resources are over-allocated to areas or departments with high water income or low discharge coefficient, it may cause the wastage of water resources. Therefore, in order to maximize the benefit of water resources as well as the utilization of water resources, the scheme of water resources distribution in the planning areas of the Yinma River should be adjusted [27]. With different robust coefficients, the initial scheme of water resource distribution for each water-use department of 4 planning areas in different planning periods is shown in Figures 8–10. Table 6 is water resources allocation of interval two-stage stochastic programming (ITSP) model and interval two-stage robust (ITSR) model in the first planning period.



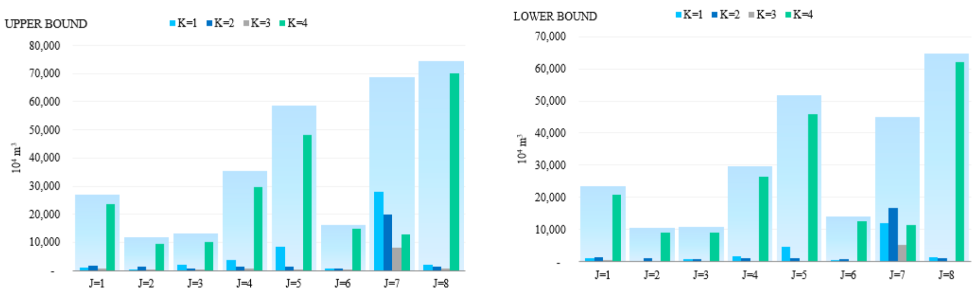
(**a**) (**b**)

Figure 8. Optimal scheme of water resources distribution in the Yinma River Basin in the first planning period. (**a**) Upper bound of water resources; (**b**) Lower bound of water resources.



(**a**) (**b**)

Figure 9. Optimal scheme of water resources distribution in the Yinma River Basin in the second planning period. (**a**) Upper bound of water resources; (**b**) Lower bound of water resources.



(**a**) (**b**)

Figure 10. Optimal scheme of water resources distribution in the Yinma River Basin in the third planning period. (**a**) Upper bound of water resources; (**b**) Lower bound of water resources.

Table 6. Water resources allocation of interval two-stage stochastic programming (ITSP) model and interval two-stage robust (ITSR) model in the first planning period (10^4 m^3/ year).

Areas	Interval-Two-Stage				Interval-Two-Stage-Robust			
	Industrial	Municipal	Ecological	Agriculture	Industrial	Municipal	Ecological	Agriculture
J = 1	[574, 910]	[1380, 2083]	[396, 498]	[20.727, 26.334]	[573, 758]	[1380, 1736]	[396, 498]	[20,727, 21,945]
J = 2	[168, 266]	[1058, 1609]	[304, 383]	[8939, 11.358]	[222, 222]	[1111, 1341]	[304, 383]	[8939, 9465]
J = 3	[731, 926]	[642, 978]	[182, 229]	[9116, 11.384]	[772, 772]	[642, 815]	[182, 229]	[9116, 9487]
J = 4	[1366, 2167]	[1122, 1699]	[326, 410]	[26.298, 33.028]	[1738, 1806]	[1122, 1416]	[326, 410]	[26.298, 27.523]
J = 5	[4475, 5678]	[1026, 1565]	[300, 377]	[45.819, 57 545]	[4475, 4732]	[1026, 1283]	[300, 377]	[45.819, 45.819]
J = 6	[538, 684]	[438, 664]	[126, 157]	[12.696, 16 243]	[538, 538]	[641, 553]	[126, 157]	[12.696, 13,536]
J = 7	[9114, 14,440]	[16,685, 22,583]	[4410, 5524]	[11.272, 14.158]	[10.378, 12.033]	[16.685, 18.539]	[5081, 5524]	[11.272, 11.272.00]
J = 8	[1036, 1549]	[1110, 1691]	[319, 401]	[61.958, 77.813]	[1173, 1291]	[1110, 1387]	[319, 401]	[61.958, 61.958]

After the adjustment, the water resource distribution schemes of the four planning areas change differently in different water use departments and planning periods. For example, in Panshi area, the upper and lower limitations of water resource distribution of industrial departments and municipal living departments in the first planning period are, respectively, [573.60, 758.00] × 10^4 m^3/year and [1380.00, 1736.00] × 10^4 m^3/year, which are [20%, 16.7%] lower than those without adjustment; in the second planning period, the upper and lower limitations of water resource distribution are [768.80, 1089.00] × 10^4 m^3/year and [1387.20, 1754.00] × 10^4 m^3/year, respectively and the limitations are 16.7% and 16.9% lower than the ones without adjustment; in the third planning period, the upper and lower limits of water resource distribution are [1047.37, 1049.37] × 10^4 m^3/year and [1393.60, 1771.00] × 10^4 m^3/year, respectively and the limitations are [20%, 17%] and [20%, 16.9%] lower than those without adjustments.

The upper and lower limits of the water resource distribution scheme of the ecological and environmental departments have not changed in different planning periods. The lower limits of water resource distribution of the agricultural department have also not changed in the different planning periods; however, the upper limit is 17% lower than the ones without adjustment. To sum up, the total water resource distribution in the planning area is reduced, indicating a reduction in the water demand of the area after adjustment, which means the normal water demand of the area can be met through less water resource distribution. The change of water resource distribution in other planning areas is also similar to the change in the Panshi area and has shown a downward trend. After adjustment, less water resource distribution can fulfill the water request of the different water use departments in different planning areas for each period avoiding wastage of water resources. Also, the proportion of water resource distribution in each area has not changed significantly after adjustment except for Changchun. The agricultural department is still the main water production department and accounts for more than 80% of the water resource distribution. In the Yinma River Basin, the water resource distribution increases with the advance of the planning period because of the increasing water demand of various water use departments.

The water requirement in the Yinma River Basin optimized by the robust method is significantly lower than the water resource distribution model of the basin based on the ITSP method. This is because of the reallocation of the unreasonable water usage in the original model by the robust method, promoting the water resource distribution more scientifically [28] and reducing the wastage of water resources in high-income areas in the basin.

3.3.2. Analysis of the Change of Water Shortage for the Water Uses Departments in Each Planning Area Based on the ITSR Optimization Method

Water shortage is one of the main factors required to be considered in the water resource distribution. The more water shortage means the more gap between actual water supply and water demand and the worse stability of water supply. In the Yinma River Basin, applying the robust optimization method for water resource distribution significantly decreased the water shortage. The water shortage in different water use departments with different robust coefficients is shown in

Figures 11–13. Tables 7–9 are water shortage of ITSP model and ITSR model in different water use departments under different levels of available water resources in the different planning periods.

Figure 11. Water shortage in different water use departments in different situations in the first planning period.

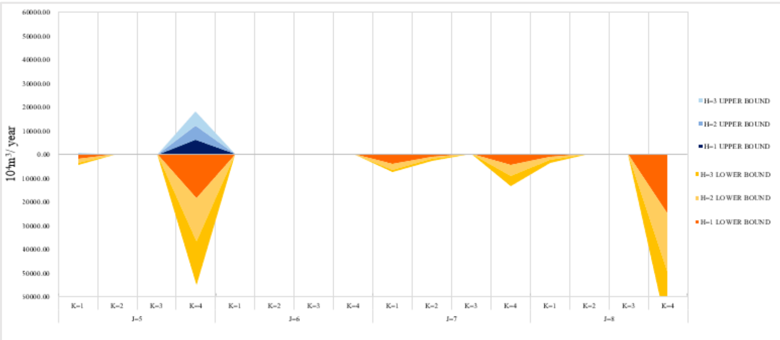


Figure 12. Water shortage in different water use departments in different situations in the second planning period.

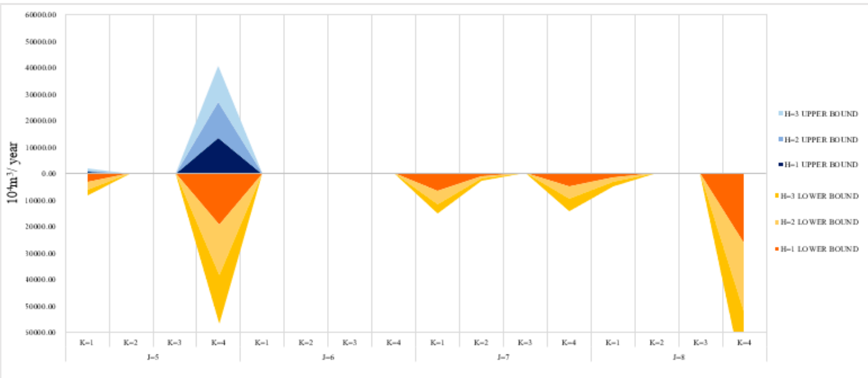


Figure 13. Water shortage in different water use departments in different situations in the third planning period.

Table 7. Water shortage of ITSP model and ITSR model in different water use departments under low levels of available water resources in the first planning period (10^4 m^3/ year).

Areas	Interval-Two-Stage				Interval-Two-Stage-Robust			
	Industrial	Municipal	Ecological	Agriculture	Industrial	Municipal	Ecological	Agriculture
J = 1	[0.00, 0.00]	[345.00, 746.66]	[426.00, 195.94]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 2	[0.00, 0.00]	[470.01, 583.49]	[343.68, 345.67]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 3	[0.00, 0.00]	[160.40, 221.72]	[0.00, 213.62]	[5914.80, 6826.40]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 4	[0.00, 0.00]	[280.40, 430.68]	[0.00, 357.59]	[17,248.80, 19,878.60]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 5	[440.00, 2037.71]	[256.60, 459.05]	[0.00, 262.04]	[30,053.40, 34,635.30]	[1052.85, 1614.34]	[0.00, 0.00]	[0.00, 0.00]	[13,745.70, 18,237.60]
J = 6	[16.76, 16.76]	[225.20, 259.63]	[129.58, 134.45]	[0.00, 0.00]	[94.94, 94.94]	[0.00, 0.00]	[0.00, 0.00]	[12,696, 13,536]
J = 7	[0.00, 0.00]	[3707.80, 5014.09]	[0.00, 349.83]	[7394.40, 8521.60]	[261.64, 1420.25]	[0.00, 926.95]	[0.00, 0.00]	[3381.60, 4508.80]
J = 8	[0.00, 0.00]	[277.40, 405.21]	[365.21, 364.47]	[13,038.89, 46,833.80]	[460.40, 830.60]	[0.00, 0.00]	[0.00, 0.00]	[18,587.40, 24,783.20]

Table 8. Water shortage of ITSP model and ITSR model in different water use departments under medium levels of available water resources in the first planning period (10^4 m^3/ year).

Areas	Interval-Two-Stage				Interval-Two-Stage-Robust			
	Industrial	Municipal	Ecological	Agriculture	Industrial	Municipal	Ecological	Agriculture
J = 1	[0.00, 0.00]	[0.00, 746.66]	[0.00, 195.94]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 2	[0.00, 0.00]	[00.00, 583.49]	[0.00, 345.67]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 3	[0.00, 0.00]	[0.00, 221.72]	[0.00, 00.00]	[0.00, 6826.40]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 4	[0.00, 0.00]	[0.00, 430.68]	[0.00, 0.00]	[0.00, 9049.65]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 5	[0.00, 1049.51]	[0.00, 459.05]	[0.00, 0.00]	[0.00, 0.00]	[480.60, 1126.42]	[0.00, 0.00]	[0.00, 0.00]	[13,745.70, 18,237.60]
J = 6	[16.76, 16.76]	[0.00, 259.63]	[0.00, 134.45]	[0.00, 0.00]	[94.94, 94.94]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 7	[0.00, 0.00]	[0.00, 5014.09]	[0.00, 0.00]	[0.00, 8521.60]	[0.00, 153.75]	[0.00, 926.95]	[0.00, 0.00]	[3381.60, 4508.80]
J = 8	[0.00, 0.00]	[0.00, 405.21]	[0.00, 0.00]	[0.00, 46,833.80]	[0.00, 830.60]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 24,783.20]

Table 9. Water shortage of ITSP model and ITSR model in different water use departments under high levels of available water resources in the first planning period (10^4 m^3/year).

Areas	Interval-Two-Stage				Interval-Two-Stage-Robust			
	Industrial	Municipal	Ecological	Agriculture	Industrial	Municipal	Ecological	Agriculture
J = 1	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 2	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 3	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 4	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 5	[0.00, 13.00]	[0.00, 459.05]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 614.65]	[0.00, 0.00]	[0.00, 0.00]	[12,542.66, 18,237.60]
J = 6	[16.76, 16.76]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[94.94, 94.94]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
J = 7	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 926.95]	[0.00, 0.00]	[0.00, 4508.80]
J = 8	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 11,608.56]

As shown in Table 7, in the first planning period, the water shortage of the agricultural department in Shuangyang area under the level of low available water resources is [0.00, 20.39] × 10^4 m^3/year; the water shortage of the industrial department in Dehui area under the levels of low, medium and high available water resources are [1052.85, 1614.34] × 10^4 m^3/year, [480.60, 1126.42] × 10^4 m ^{3}/year and [0.00, 614.65] × 10^4 m^3/year, respectively. In the same region, the water shortage in the agricultural department under the levels of low and medium are both [13,745.70, 18,237.60] × 10^4 m^3/year and under high level is [12,542.66, 18,237.60] × 10^4 m^3/year. The water shortage of the industrial department in Yitong area under the levels of low, medium and high available water resources are all 94.94 × 10^4 m^3/year; the water shortage of the low and medium levels of available water resources in the industrial department in Changchun City are [1132.19, 1420.25] × 10^4 m^3/year and [0.00, 153.75] × 10^4 m ^{3}/year, respectively. The water shortage of the agricultural department in Changchun City under the levels of low, medium and high available water resource levels are [3381.60, 4508.80] × 10^4 m^3/year, [3381.60, 4508.80] ×10^4 m^3/year and [1315.13, 4508.80] × 10^4 m^3/year, respectively. The water shortage of the industrial department in Nongan area under the levels of low and medium available water resources are [611.04, 830.60] × 10^4 m^3/year and [0.00, 830.60] × 10^4 m^3/year, respectively and the water shortage of the agricultural department under the levels of low, medium and high available water resources levels are [18,587.40, 24,783.20] × 10^4 m^3/year, [18,587.40, 24,783.20] ×10^4 m^3/year and [0.00,11,608.56] × 10^4 m^3/year, respectively. The upper and lower limits of water shortage in other planning areas are all 0. It indicates that except for the water use departments in the above-mentioned areas, the water resource distribution of the water use departments in other areas can fulfill the water request of that area. The water shortage of the industrial department in the Dehui area is 76% lower than that of the original model and the water shortage of the agricultural department is 70% lower than that of the original model. The water shortage of the agricultural department of Changchun City is 90% lower than that of the original model and the water shortage of the same department in the Nongan area is 70% lower than that of the original model.

As shown in Table 8, in the second planning period, the levels of water shortage of the industrial department in Dehui area under three available water resources levels are [163.22, 2147.42] × 10^4 m^3/year, [163.22, 1581.86] × 10^4 m^3/year and [163.22, 988.65] × 10^4 m^3/year, respectively. The levels of water shortage of the agricultural department under three available water resources levels for the same area are all [6062.65, 18,420.40] × 10^4 m^3/year. The levels of water shortages of the industrial department in Yitong area under three available water resources levels are all [108.71, 131.50] × 10^4 m^3/year. The levels of water shortage of the industrial department in Changchun city under three available water resources levels are all [0.00, 938.60] × 10^4 m^3/year and the water shortage of the agricultural department under three available water resources levels are all [0.00, 4531.60] × 10^4 m^3/year. The levels of water shortage of the industrial department in the Nongan area under three available water resources levels are all [0.00, 1177.00] × 10^4 m^3/year and the water shortage of the agricultural department under three available water resources levels are all [0.00, 24,908.40] × 10^4 m^3/year. Except for some of the water use departments in the above-mentioned areas, the upper and lower limits of water shortage in all the water use departments in other planning areas are 0. The water shortage of the agricultural department in Dehui area, Changchun City and Nongan area are 97%, 90% and 86% lower than that of the original model, respectively.

According to Table 9, in the third planning period, except for the industrial departments in Dehui and Nongan areas, the water shortage decreased in all the water use departments for all the areas. In the three planning periods, compared with the original model data, the upper and lower limits of water shortage in the industrial departments in Dehui, Yitong, Changchun and Nongan areas increased under low and medium available water resource levels. This is due to the income of water use in the industrial department is high and in the water resource distribution model of the Yinma River Basin based on the ITSP method, the stability and reliability of the system are seldom considered. In order to achieve higher economic benefits, excessive water resources are distributed to the water use departments with higher water use benefits. This causes the water resource distribution of the departments with low water efficiency and a high discharge coefficient to be lower than the water quota and restricts the development of the department. Thus, it leads to the problem of areal water use security [29].

The water resource distribution model based on the ITSR optimization method reset the water resource distribution scheme to reasonably reduce the amount of water distributed to the departments with high water use income. The reduced part is appropriately allocated to the departments with low water use income and high sewage discharge so that these departments can also meet the water quota of this department, thus increasing the stability of the system. On the whole, the amount of water shortage in the Yinma River basin is reduced. That is, in the Yinma River Basin, the degree to which the water supply of various water use departments can fulfill the water request has increased, reducing the risk of water usage in the basin that caused water shortage and the stability of the water supply is ensured.

3.3.3. Redistribution of the Used Water in the Different Water Use Departments in Each Planning Area Based on the ITSP Optimization Method

It is shown in Figures 14–16 that after optimal distribution, the used water in the Yinma River Basin is mainly reallocated to the ecological environment department accounting for more than 60% of the total used water redistribution in the Panshi area, 70% of the total used water redistribution in Jiutai area and 80% of the total used water redistribution in Shuangyang area, Dehui area and Changchun City and 90% of the total used water redistribution in Yongji and Yitong. The ecological and environmental department has a higher demand for water resources. In order to reduce the system risk caused by unscientific water distribution in the pursuit of economic benefits in the original model, most of the used water is reallocated to the ecological and environmental departments with high water demand increasing the stability of the system.

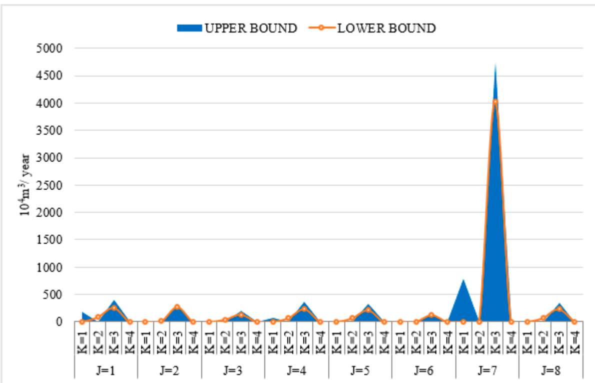


Figure 14. Water reuse in water use departments under the low level of available water resources.

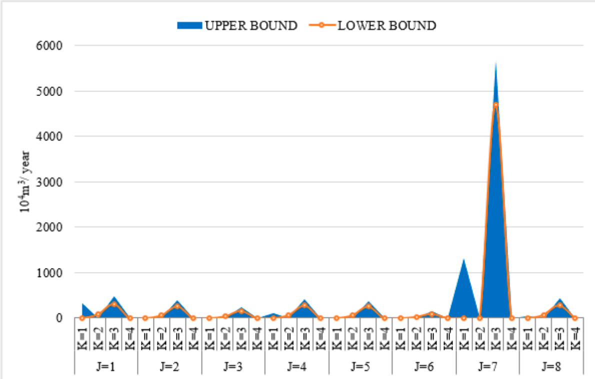


Figure 15. Water reuse in water use departments under the medium level of available water resources.

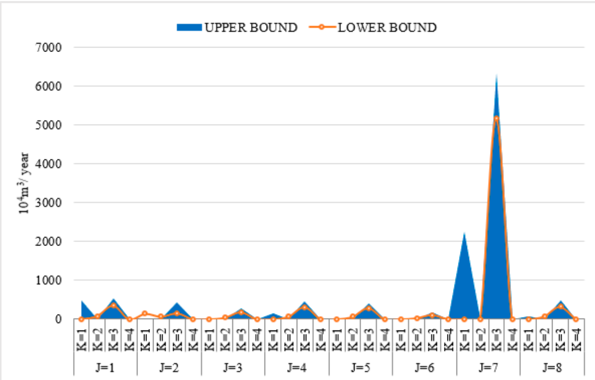


Figure 16. Water reuse in water use departments under the high level of available water resources.

3.4. Scenario Analysis Based on the ITSP Optimization Method

3.4.1. Scenario Analysis Under Low Water Resources Utilization Level in the First Planning Period

Under the scenario of low water resource utilization level in the first planning period, when the water shortage is the lowest, the water shortage of the different water use departments in each planning area is shown in Table 10. At this time, there is no lack of water usage in Panshi, Yongji, Shuangyang and Jiutai, the municipal and the ecological environment departments in Dehui, the ecological environment and the agricultural departments in Yitong, the ecological environments departments in Changchun and the municipal and the ecological environment departments in the Nongan area. The water shortage of the industrial departments in Dehui, Yitong, Changchun and Nongan areas has increased and that of the ecological and environmental departments has decreased after the robust optimization. This is because the original model pays attention to the economic benefits of the system, allocates too much water to the industrial department with high water use income and less water to the ecological environment department with low water use income. This leads to the wastage of excess water resources in the industrial department and limited development of the ecological and environmental department as the water resources distribution cannot meet the demand for the development of the department. The robust optimization method, in order to ensure a balanced development of various departments, appropriately reduce the water resource distribution in departments with high water use benefits, allocate more water resources to the departments with higher development needs and effectively alleviate the overall water shortage in the Yinma River Basin reducing the water risk that may be caused by water shortage and improves the safety of water use in the system. The economic benefit of the system in the Yinma River Basin is 975.5506×10^4 ¥, although it is lower in the case of the robust optimization, the water shortage in the Yinma River Basin has been improved to the greatest extent and the stability of the system has significantly improved. Generally, after adding the robust optimization method, the risk of lack of water use in the Yinma River Basin has been well avoided, the security and stability of the system have been significantly improved and the scheme of water resource distribution has become more scientific. In addition, it meets the national requirement for scientific allocation of the water resources between areas and the water use departments.

Table 10. The distribution scheme of reused water in the Yinma River Basin under different levels of available water resources and different robust coefficients (10^4 m^3/year).

Areas	Interval-Two-Stage				Interval-Two-Stage-Robust			
	Industrial	**Municipal**	**Ecological**	**Agriculture**	**Industrial**	**Municipal**	**Ecological**	**Agriculture**
Panshi	0.00	545.83	310.97	0.00	0.00	0.00	0.00	0.00
Yongji	0.00	526.75	344.68	0.00	0.00	0.00	0.00	0.00
Shuangyang	0.00	191.06	106.81	6370.60	0.00	0.00	0.00	0.00
Jiutai	0.00	355.54	178.80	18,563.70	0.00	0.00	0.00	0.00
Dehui	1238.86	357.83	131.02	32,344.35	1333.60	0.00	0.00	16,036.65
Yitong	16.76	242.42	132.02	0.00	94.94	44.22	0.00	0.00
Changchun	0.00	4360.95	174.92	7958.00	840.94	463.48	0.00	3945.20
Nongan	0.00	341.31	364.84	29,936.35	645.50	0.00	0.00	21,685.30

3.4.2. Analysis of the Influence of Different Robust Coefficients on the Economic Benefit of the System

In the Yinma River Basin, the effect of selecting different robust coefficients for the water resource distribution model, based on the ITSP optimization method, is mainly reflected in the economic benefits of the system. The range of the robust coefficient is between 0 and 1 and the larger the robust coefficient, the decision-makers pay more attention to the stability and security of the system and choose to sacrifice the appropriate economic benefits to avoid the system risk. In this paper, the robust coefficients selections are 0, 0.8 and 1. Taking the low level of available water resources as an example, when the robust coefficient is 0, the economic benefit of the system is 987.09×10^4 ¥ and the model is the water resources distribution model of the Yinma River Basin based on the ITSP method. At this time, the decision-makers pursue the maximization of economic benefit and ignore the risk of system water use in the model simulation. When the robust coefficient is 0.8, the economic benefit of the system is 985.28×10^4 ¥, indicating that the decision-makers began to pay attention to the safety and stability of the system, balancing the relationship between the water risk and the economic benefit of the system and optimizing the economic benefit of the system while reducing the risk of water use of the system. When the robust coefficient is 1, the economic benefit of the system is 984.68×10^4 ¥ and the decision-makers put the risk of water use of the system first and choose to sacrifice more economic benefits to maximize the safety and stability of the system. The different selection of robust coefficient, therefore, has an influence on the economic benefit of the system and on the overall system risk. The decision-makers can choose the appropriate robust coefficient according to the specific situation in practical application and provide a scientific and feasible scheme. It provides theoretical support for Yinma River water resources allocation scheme and provides a more scientific and feasible scheme for decision makers to choose.

4. Conclusions

This paper constructs a water resource distribution model of the Yinma River Basin based on an interval-two-stage-robust optimization method and optimally adjusts the water resource distribution, ensuring optimized economic benefits of the system. At the same time, the discharge of pollutants in the Yinma River Basin is significantly reduced, the maximum reduction of the emissions of pollutants is 15%. After the introduction of the robust optimization method, the water resource distribution is more scientific and reasonable, the regional water demand can be met with less water resources allocation and the water demand can be reduced by 20% at most. In addition, it solves the problem of wastage of water resources in the areas with high economic benefits in the basin, avoids the risk of water usage caused by water shortage in low economic income areas under the interval-two-stage stochastic method, ensures the development of low economic income areas and increases the rationality, stability and feasibility of the system.

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