A Type-2 Fuzzy Based Interval-Stochastic Risk Management Programming Model for Identifying Sustainable Water Resources Allocation Policies

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Abstract. In this study, a type-2 fuzzy based interval-stochastic risk management programming (TISRM) method is proposed for optimal irrigation water resources allocation associated with multiple uncertainties expressed as interval numbers, probability distributions, and type-2 fuzzy sets. TISRM can also reflect authorities’ attitudes towards system risk using a financial risk management measure by controlling the variability of the recourse cost. The developed method is applied to irrigation water resources allocation for the Zhangweinan River Basin in China. Solutions of irrigation water allocation under different probability distributions and confidence levels are generated. Results reveal that system benefit and satisfaction degree would decrease with the raised λ levels; the CVaR values would change with the increment of λ and β levels as well as the varied cases; the irrigation targets of all crops in all subareas are reach their lower bounds; the irrigation deficits would be different with risk levels and cases. The results can help the local authority to adjust the current food security policy.

1. Introduction
The optimal allocation of irrigation water resources is of great importance to guarantee food security taking into consideration the burgeoning global population which is expected to reach 9.7 billion in 2050 [1]. A number of mathematical techniques have been proposed to analyze economic, social and environmental impacts of alternative allocation actions, and thus aid the authorities in determining sustainable water resources allocation policies. Besides, the irrigation water resources allocation systems are often complicated due to the random available water and cultivated land conditions, varied water requirements, and changed market situations and their interrelationships [2]. Effective irrigation water resources allocation integrating uncertainties into a general optimization framework is essential.

Previously, a range of optimization methods were developed for irrigation water resources allocation in terms of interval-parameter programming (IPP), fuzzy mathematical programming (FMP), and stochastic mathematical programming (SP) [3-6]. For instance, Srivastava and Singh [7] proposed a fuzzy multiobjective-based goal programming (GP) model for optimizing crop cultivation patterns, where fuzzy solutions provide the necessary aspiration and tolerance levels for goal programming. Chen et al., [8] developed an interval multistage water allocation model to obtain the maximum food
production in reservoir irrigation systems, where rainfall was divided into five levels with probability distributions in each growth stage and other parameters were presented as intervals. Robert et al. [9] employed a stochastic dynamic programming model to figure out decisions on crop selection, irrigation investment and water allocation rates with different probabilities of borewell failure over a long-term planning horizon. Generally, the above models have advantages in their effectiveness for coping with single and/or dual uncertainties in water resources allocation system. Nevertheless, in many irrigation water resources allocation problems, several types of uncertainties often exist in a complex system. The conventional models have difficulty in dealing with multiple uncertainties. Specifically, SMP only take into account the expected loss/penalty due to the violated policies and ignores the risk caused by randomness [10]. Financial risk management (FRM) is an effective tool to cope with the above shortcoming. Yamout et al. [11] coupled FRM and two-stage stochastic programming for water resources allocation. Soltani et al. [12] employed a FRM named conditional value at risk (CVaR) for simultaneous agricultural water and return flow (waste load) allocation in rivers. Hu et al. [13] developed a multi-objective model to help water managers mitigate problems due to water scarcity, where CVaR was integrated into the model constraints to control the economic efficiency loss risk corresponding to variations in water availability.

Therefore, this study aims to develop a type-2 fuzzy based interval-stochastic risk management programming (TISRM) method for supporting irrigation water resources allocation. Through integrating IPP, TSP, FRM and T2FS into a general framework, TISRM cannot only deal with uncertainties expressed as interval numbers, probability distributions, and type-2 fuzzy sets, but also effectively quantify risks due to randomness. Then, the TISRM method will be applied to a real-world case for irrigation water resources allocation (surface water and groundwater) in the Zhangweinan River Basin, North China. A number of cases associated with different attitudes of authorities towards the objective function value and constraints as well as varied available water levels will be analyzed to obtain optimal water allocation patterns. The relationship among cropland planning and irrigation water utilization will be disclosed to obtain a maximized system benefit and a minimized system-failure risk.

2. Case study

2.1 Overview of the study area

The Zhangweinan River Basin (with longitude of 112~118°E and latitude of 35~39°N) is a tributary of the Haihe River (in North China), which covers parts of Shanxi, Henan, Hebei, and Shandong Provinces as well as Tianjing Municipality; total area of the basin is approximately 37,700 km². The basin is one of the most productive and intensively cultivated agricultural regions in North China; main cultivated crops include wheat, maize, and cotton. In the study area, more than 75% of the cropland needs to be irrigated (consuming 70-80% of the total water resources allocation) because the insufficient annual precipitation cannot fulfill the crop water requirement. Conjunctive use of surface water and groundwater is practiced in the study area to irrigate more croplands, increase agricultural production, and maintain agricultural system balance. Yuecheng Reservoir is the main reservoir for flow regulation for surface water supply in this basin [2]. The estimated amount of renewable groundwater resources in the study area is 3.635 billion m³/year.

2.2 Problem statement

Decreasing precipitation and increasing reservoirs and diversion channels in the upper reaches of the river lead to much less inflow of Yuecheng Reservoir now than that in decades ago.

In addition, the local authority initiates strategic changes to transfer most agricultural water to other sectors (e.g., municipal and industrial sectors). As a result, crop production relies heavily on groundwater irrigation. Consequent excessive groundwater pumping has led to continuous drawdown (averagely 1.5 m per year) in the water table during the last few decades. The implications of over-pumping include higher pumping cost, wasteful energy use, salt water intrusion, increased soil
salinity and waterlogging, soil compaction, and land subsidence. These issues have made the regional agricultural water system degrade (which cannot guarantee food security and can bring economic loss) and brought about severe damage to the local ecological and environmental sustainability. Therefore, advancing optimization models for finding the optimal strategy for the crops cultivation as well as the amount of surface water allocation and groundwater extraction with the consideration of environmental sustainability and economic development is essential.

3. Methodology

A type-2 fuzzy based interval-stochastic risk management programming (TISRM) model can be formulated by incorporating TSP, IPP, T2FS, and FRM into a general framework [14-17]:

$$\text{Max } \xi^s$$

Subject to:

$$(1 - \lambda) \sum_{j=1}^{n} c_j^s x_j^s - \sum_{j=1}^{n} \sum_{p=1}^{m} p_j^s x_j^s y_j^p + \lambda \cdot (\eta^s - \frac{1}{1-\beta} \sum_{r=1}^{s} \sum_{s=1}^{S} p_r^s V_r^s) \geq f^s + \Delta f^s \xi^s$$

(1.1)

$$\sum_{j=1}^{n} a_j^s x_j^s \leq \bar{b}_s^s - \Delta \bar{b}_s^s \xi^s$$

(1.2)

$$\sum_{j=1}^{n} a_j^s x_j^s + \sum_{j=1}^{n} a_j^s y_j^p \leq a_{t}^s - \Delta a_{t}^s \xi^s, \quad t = 1, 2, \ldots, m_s; \quad s = 1, 2, \ldots, S$$

(1.3)

$$V_s^s \geq \eta^s - \left[ \sum_{j=1}^{n} c_j^s x_j^s - \sum_{j=1}^{n} a_j^s y_j^p \right] \beta, \forall s = 1, 2, \ldots, S$$

(1.4)

$$x_j^s \geq 0, \quad j = 1, 2, \ldots, n$$

(1.5)

$$y_j^s \geq 0, \quad j = 1, 2, \ldots, n_s; \quad s = 1, 2, \ldots, S$$

(1.6)

$$V_s^s \geq 0, \forall s = 1, 2, \ldots, S$$

(1.7)

$$0 \leq \xi^s \leq 1$$

(1.8)

Where $\xi^s$ is a control variable corresponding to the membership grade of the fuzzy decision.

A $\xi^s$ level close to 1 corresponding to a solution with a high degree of satisfaction for the fuzzy goal/constraints; conversely, a $\xi^s$ level approaching 0 relates to a solution that has a low degree of satisfaction for the fuzzy goal/constraints. $x_j^s$ is the first-stage anticipated decisions made before the random variables are observed; $a_{t}^s$ is the random variable which takes interval discrete value with a probability level $p_s$; Denote $p_s$ as the probability of realization of scenario $s$, with $p_s > 0$ and $\sum_{s=1}^{S} p_s = 1$; $y_j^p$ is the second-stage decision variables (i.e. recourse variables) that depend on the realization of the first-stage random vector. $\beta$ is the confidence level; typically $\beta$ often range from 0.9 to 0.99. In order to maximize the system benefit and $V_s^s$ is the auxiliary decision variables, which is used to compute the conditional value-at-risk under level $s$.

4. Modeling formulation

Optimization of cropland planning and water resources allocation which considers the balance of socio-economic development, food security, resources conservation and environment protection can effectively support local sustainable development. In this study, the authorities are responsible for allocating surface water and groundwater to three main crops (i.e., wheat, maize, and cotton). The study area is divided into fifteen irrigation districts. A one-year planning horizon is subdivided into four periods on the basis of the water shortage response, including winter of last year, spring, summer and autumn of current year. The growth stages of wheat and maize cover periods one to three, while the growth stage of cotton spans across periods three and four. Therefore, the TISRM model for the
agricultural system management can be formulated as follows:

Max $\xi^z$

(1) Constraint for objective function:

$$1 - \lambda \geq \sum_{i=t}^{T} \sum_{j=1}^{J} \sum_{t=1}^{T} TS_{i,j}^{z} \times SB_{i}^{z} - \sum_{i=t}^{T} \sum_{j=1}^{J} \sum_{t=1}^{T} p_{i,j,t} \times CS_{i,j}^{z} \times SA_{i,j}^{z}$$

$$+ (1 - \lambda) \times \sum_{i=t}^{T} \sum_{j=1}^{J} \sum_{t=1}^{T} TG_{i,j}^{z} \times SG_{i}^{z} - \sum_{i=t}^{T} \sum_{j=1}^{J} \sum_{t=1}^{T} p_{i,j,t} \times CG_{i,j}^{z} \times GA_{i,j}^{z}$$

$$+ \lambda \times (\eta - \frac{1}{1 - \beta} \sum_{i=1}^{t} p_{i,j,t} V_{i,j,t}^{z}) \geq f^{z} + \Delta \xi^z$$

(2) Surface water supply constraints:

$$\sum_{i=t}^{T} \sum_{j=1}^{J} \sum_{t=1}^{T} WA_{i,j}^{z} \times (TS_{i,j}^{z} - SA_{i,j}^{z}) - \epsilon_{i,j,t}^z \leq \bar{R}_{i,j,t}^{z} - \Delta \bar{R}_{i,j,t}^{z} \times \xi^z, \quad \forall t, s$$

$$\epsilon_{i,j,t}^z + \sum_{i=t}^{T} \sum_{j=1}^{J} \sum_{t=1}^{T} WA_{i,j}^{z} \times (TS_{i,j}^{z} - SA_{i,j}^{z}) - \epsilon_{i,j,t}^z + \bar{R}_{i,j,t}^{z} - \Delta \bar{R}_{i,j,t}^{z} \times \xi^z, \quad \forall t, s$$

(3) Groundwater supply constraint:

$$\sum_{i=t}^{T} \sum_{j=1}^{J} (TG_{i,j}^{z} - GA_{i,j}^{z}) \times WA_{i,j}^{z} \leq \bar{Q}_{i,j,t}^{z} - \Delta \bar{Q}_{i,j,t}^{z} \times \xi^z, \quad \forall t, s$$

(4) Irrigation requirement constraint:

$$\sum_{i=t}^{T} \sum_{j=1}^{J} WA_{i,j}^{z} \times [(TS_{i,j}^{z} - SA_{i,j}^{z}) + (TG_{i,j}^{z} - GA_{i,j}^{z})] \leq TWD_{i,j,t}^{z}, \quad \forall i, t$$

$$\sum_{i=t}^{T} \sum_{j=1}^{J} \delta_{i,j,t}^{z} \times WA_{i,j}^{z} \times \left[\alpha_{i,j,t}^{z} \times (TS_{i,j}^{z} - SA_{i,j}^{z}) + (TG_{i,j}^{z} - GA_{i,j}^{z})\right] \geq TBW_{i,j,t}^{z}, \quad \forall i, t$$

$$WA_{i,j,t}^{z} = ET_{i,j,t}^{z} - R_{i,j,t}^{z} + \theta_{i,j,t}^{z} \times D_{i,j,t}^{z} - \theta_{i,j,t}^{z} \times D_{i,j,t}^{z} - \theta_{i,j,t}^{z} \times (D_{i,j,t}^{z} - D_{i,j,t}^{z}) + DP_{i,j,t}^{z}, \quad \forall i, j, t$$

$$\theta_{i,j,t}^{z} \leq \theta_{i,j,t}^{z} \leq \theta_{i,j,t}^{z}, \quad \forall i, j, t$$

$$D_{i,j,t}^{z} \leq D_{i,j,t}^{z}, \quad \forall i, j, t$$

(5) Aquifer hydrologic balance Constraints:

$$\sum_{i=t}^{T} \sum_{j=1}^{J} r_{i,j,t}^{z} \times WA_{i,j}^{z} \times [(TS_{i,j}^{z} - SA_{i,j}^{z}) + (TG_{i,j}^{z} - GA_{i,j}^{z})]$$

$$\sum_{i=t}^{T} \sum_{j=1}^{J} r_{i,j,t}^{z} \times (TS_{i,j}^{z} + TG_{i,j}^{z}) / 100 + \sum_{i=t}^{T} \sum_{j=1}^{J} r_{i,j,t}^{z} \times (TS_{i,j}^{z} - SA_{i,j}^{z}) \times WA_{i,j}^{z}$$

$$- \sum_{i=t}^{T} \sum_{j=1}^{J} (TG_{i,j}^{z} - GA_{i,j}^{z}) \times WA_{i,j}^{z} \geq PMA_{i,j,t}^{z}, \quad \forall j$$

$$PMA_{i,j,t}^{z} = \sum_{i=t}^{T} \sum_{j=1}^{J} \Delta h^{z} \times (TS_{i,j}^{z} + TG_{i,j}^{z}) \times SY_{i,j,t}^{z}, \quad \forall j$$

(6) Land area constraints:

$$0 \leq SA_{i,j,t}^{z} \leq TS_{i,j,t}^{z} \leq TS_{i,j,t}^{z}, \quad \forall i, j, t, s$$

$$0 \leq GA_{i,j,t}^{z} \leq TG_{i,j,t}^{z} \leq TG_{i,j,t}^{z}, \quad \forall i, j, t, s$$

$$TS_{i,j,t}^{z} = TS_{i,j,t}^{z} \quad \forall i, j, t$$

$$TG_{i,j,t}^{z} = TG_{i,j,t}^{z} \quad \forall i, j, t$$

(7) Risk management constraint:

$$V_{i,j,t}^{z} \geq \eta_{i,j,t}^{z} - \sum_{i=t}^{T} \sum_{j=1}^{J} \sum_{t=1}^{T} (TS_{i,j,t}^{z} \times SB_{i,j,t}^{z} + TG_{i,j,t}^{z} \times SG_{i,j,t}^{z})$$

$$+ \sum_{i=t}^{T} \sum_{j=1}^{J} \sum_{t=1}^{T} (CS_{i,j,t}^{z} \times SA_{i,j,t}^{z} + CG_{i,j,t}^{z} \times GA_{i,j,t}^{z}), \forall s = 1, 2, ..., S$$
(8) Non-negativity constraints:
\[ SA_{ijt}^e, WA_{ijt}^e, GA_{ijt}^e \geq 0, \quad \forall i, j, t, s \] 

The detailed nomenclatures for the variables and parameters are presented in the “Appendix”. The planning horizon is divided into periods according to growth stages of the three crops. Interval numbers are adopted to handle other uncertain parameters such as unit benefit of crop, irrigation target, and economic penalty.

5. Results and discussion

5.1 Satisfaction degree and system benefit
In this study, six risk weight levels (\( \lambda = 0, 0.2, 0.4, 0.6, 0.8, \) and 1) and three confidence levels (\( \beta = 0.9, 0.95, \) and 0.99) as well as six cases (which represent different attitudes of authorities towards the objective value and constraints) are taken into account to identify optimal agricultural water allocation policies within multiple subareas for irrigating multiple crops over a multi-period planning horizon. Figures 1 and 2 show the satisfaction degrees (\( \xi_{opt}^{\pm} \)) and system benefits (\( f_{opt}^{\pm} \)) under different risk levels (i.e. \( \lambda \) and \( \beta \)) and cases, respectively. It is indicated that no feasible solutions can be obtained under cases 3, 5, and 6. Case 3 represents that authorities are conservative to achieve high system benefit but, at the same time, they take optimistic attitudes towards constraints (e.g., available water resources), revealing a conflicting relationship between system benefit and constraints. Under cases 5 and 6, authorities are neutral in terms of system benefit, while they respectively hold optimistic and pessimistic attitudes towards constraints. It is revealed that the neutral attitudes to objective value are not appropriate to the allocation problem in this study. The solutions under cases 1, 2 and 4 are mostly presented as intervals, reflecting potential system condition variations caused by uncertain modeling inputs. It is indicated that \( \xi_{opt}^{\pm} \) and \( f_{opt}^{\pm} \) would varied with the changed cases. For instance, when \( \lambda = 0.2 \) and \( \beta = 0.9 \), the value of \( \xi_{opt}^{\pm} \) would be [0.578, 0.661] (with \( f_{opt}^{\pm} = [430.2, 1309.2] \times 10^6 \) RMBY), [0.536, 0.791] (with \( f_{opt}^{\pm} = [532.1, 1284.5] \times 10^6 \) RMBY), and [0.541, 712] (with \( f_{opt}^{\pm} = [488.1, 850.7] \times 10^6 \) RMBY) under cases 1, 2, and 4, respectively. Generally, \( f_{opt}^{-} \) would be ranked as: (\( f_{opt}^{-} \)) case 1 < (\( f_{opt}^{-} \)) case 4 < (\( f_{opt}^{-} \)) case 2 : \( f_{opt}^{-} \) would be ranked as: (\( f_{opt}^{+} \)) case 1 > (\( f_{opt}^{+} \)) case 2 > (\( f_{opt}^{+} \)) case 4. It is disclosed that the values of \( f_{opt}^{\pm} \) would be highly dependent on the authorities subjective attitudes. Under case 1, authorities would be aggressive to obtain high system benefit and take positive attitudes towards related constraint, leading to wider interval value of \( f_{opt}^{\pm} \). It is also displayed that system benefit and satisfaction degree would decrease with the raised \( \lambda \) levels. For example, under case 1 and \( \beta = 0.99 \), the values of \( \xi_{opt}^{\pm} \) and \( f_{opt}^{\pm} \) would be [0.662, 0.921] (with \( f_{opt}^{\pm} = [560.5, 1426.8] \times 10^6 \) RMBY), [0.449, 0.478] (with \( f_{opt}^{\pm} = [324.5, 1169.2] \times 10^6 \) RMBY), [0.148, 0.352] (with \( f_{opt}^{\pm} = [244.5, 992.24] \times 10^6 \) RMBY), and [0.012, 0.289] (with \( f_{opt}^{\pm} = [173.9, 516.38] \times 10^6 \) RMBY) under \( \lambda = 0, 0.4, 0.8, \) and 1, respectively. This is because that higher \( \lambda \) levels correspond to higher values of risk weight to minimize the financial risk, reflecting the risk aversion attitudes of authorities. When \( \lambda = 0 \), possess a risk-neutral attitude and would not consider the variability of the uncertain recourse costs. Besides, system benefits and satisfaction degrees would also reduce with the raised \( \beta \) levels. This is due to the fact that lower \( \beta \) levels reflect higher system reliability, leading to lower satisfaction degree and system benefits.
5.2 Optimal irrigation target

Figure 3 depicts the optimal targeted crop area irrigated by surface water and groundwater under different risk levels and cases. It is observed that optimal irrigation target would decrease with the raised $\lambda$ and $\beta$ levels. When $\lambda = 0$ and $\beta = 0.9$, the irrigation targets of all crops in all subareas are set as their upper bounds, revealing authorities’ positive attitudes towards water available to crops. The optimal targeted crop area irrigated by surface water and groundwater would be 186109.4 ha and 924647.6 ha. When $\lambda = 1$ and $\beta = 0.99$, the irrigation targets of all crops in all subareas are reach their lower bounds, presenting authorities’ negative attitudes towards water available to crops. The optimal targeted crop area irrigated by surface water and groundwater would be 172919.5 ha and 569222.5 ha. As the $\lambda$ and $\beta$ levels rise, the optimal target of wheat would firstly shrink due to its low benefit and penalty, revealing its less competiveness than maize and cotton. Moreover, the optimal irrigation area would be ranked as: case 1 > case 4 > case 2, which is mainly attributed to the different attitudes of authorities towards constraints (e.g., available water resources, canal capacity and total water shortage). Generally, optimal irrigation targets could be identified under varying system conditions. Variation in the values of crop area targets reflects different policies for managing water resources and planning agricultural activities under uncertainty.
Figure 3. Optimal target of crops irrigated by surface water and groundwater

6. Conclusions
In this study, a type-2 fuzzy based interval-stochastic risk management programming (TISRM) method is proposed for optimal irrigation water resources allocation associated with multiple uncertainties expressed as interval numbers, probability distributions, and type-2 fuzzy sets. TISRM can also reflect authorities’ attitudes towards system risk using a financial risk management measure by controlling the variability of the recourse cost. The developed method is applied to irrigation water resources allocation for the Zhangweinan River Basin in China. Solutions of irrigation water allocation under different probability distributions and confidence levels are generated. Results reveal that system benefit and satisfaction degree would decrease with the raised λ levels; the CVaR values would change with the increment of λ and β levels as well as the varied cases; the irrigation targets of all crops in all subareas are reach their lower bounds; the irrigation deficits would be different with risk levels and cases. The results can help the local authority to adjust the current food security policy.

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Appendix: Nomenclatures

\[
\begin{align*}
i & \quad \text{crop, } i = 1, 2, \ldots, I (I = 3 \text{ in this study}) \\
j & \quad \text{subarea, } j = 1, 2, \ldots, J (J = 15 \text{ in this study}) \\
t & \quad \text{planning time period, } t = 1, 2, \ldots, T (T = 4 \text{ in this study}); \\
s & \quad \text{level of water availability, } s = 1, 2, \ldots, 5 \text{ with } s = 1 \text{ representing low level (L), } s = 2 \text{ representing low-medium level (LM), } s = 3 \text{ representing medium level (M), } s = 4 \text{ representing medium-high level (MH), } s = 5 \text{ representing high level (H).} \\
g' & \quad \text{expected system benefit, which presented as fuzzy goal with type-2 membership function (RMB¥);} \\
SR_{it}^s & \quad \text{unit benefit of crop } i \text{ in subarea } j \text{ per unit of planting area irrigated by surface water (RMB¥/ha);} \\
TS_{it} & \quad \text{allocation target for surface water that is promised to crop } i \text{ in subarea } j \text{ during period } t \text{ (ha);} \\
CS_{it}^s & \quad \text{economic penalty to crop } i \text{ in subarea } j \text{ per unit of area not irrigated by surface water (RMB¥/ha);} \\
SA_{it}^s & \quad \text{cropland that not irrigated by surface water when available water level is } s \text{ (ha);} \\
SG_{it}^s & \quad \text{unit benefit of crop } i \text{ in subarea } j \text{ per unit of planting area irrigated by groundwater (RMB¥/ha);} \\
CG_{it}^s & \quad \text{economic penalty to crop } i \text{ in subarea } j \text{ per unit of area not irrigated by groundwater (RMB¥/ha);} \\
GA_{it}^s & \quad \text{cropland that not irrigated by groundwater when available water level is } s \text{ (ha);} 
\end{align*}
\]
targeted benefit (RMB¥)

\( \beta \)  
confidence level

\( p_i \)  
probability of occurrence

\( V_i \)  
auxiliary decision variables

\( \xi_i \)  
control variable corresponding to the membership grade of the fuzzy decision

\( WA_{ijt} \)  
irrigation quota for crop \( i \) in subarea \( j \) in period \( t \) (m³/ha);

\( \varepsilon_{s_{ijt}} \)  
surplus flow when water is delivered in period \( t-1 \) under scenario \( s \) (m³), and assuming no spilling for reservoir;

\( \varepsilon_{s_{ijt}} \)  
surplus flow when water is delivered in period \( t-2 \) under scenario \( s \) (m³), and assuming no spilling for reservoir;

\( \tilde{R}_{ijt} \)  
available water for irrigation in Yuecheng Reservoir under inflow level \( s \) during period \( t \) (m³)

\( \tilde{Q}_{ijt} \)  
available groundwater for irrigation under inflow level \( s \) during period \( t \) (m³)

\( TWD_{ijt} \)  
maximum water demand of crop \( i \) during period \( t \) (m³);

\( \delta_i \)  
conveyance efficiency of canal system (fraction);

\( \alpha_i \)  
field water application efficiency (fraction);

\( TWB_{ijt} \)  
minimum water demand of crop \( i \) during period \( t \) (m³);

\( ET_{ijt} \)  
actual amount of evaporation of crop \( i \) in subarea \( j \) in period \( t \) (m);

\( RI_{ijt} \)  
amount of effective precipitation of crop \( i \) in subarea \( j \) in period \( t \) (m);

\( \theta_{ijt} \)  
soil moisture content of crop \( i \) in subarea \( j \) in period \( t \) (m/m);

\( \theta_{ijt-1} \)  
soil moisture content of crop \( i \) in subarea \( j \) in period \( t-1 \) (m/m);

\( \theta_{ijt_{\text{max}}} \)  
maximum soil moisture content of crop \( i \) in subarea \( j \) (m/m);

\( \theta_{ijt_{\text{min}}} \)  
minimum soil moisture content of crop \( i \) in subarea \( j \) (m/m);

\( D_i \)  
average root depth of crops in period \( t \) (m);

\( D_{ijt} \)  
average root depth of crops in period \( t-1 \) (m);

\( DP_{ijt} \)  
deep percolation for crop \( i \) in subarea \( j \) during the period \( t \) (m);

\( rcl_{ijt} \)  
recharge factor for irrigation application losses in subarea \( j \) (fraction);

\( ral_{ijt} \)  
recharge factor for conveyance losses of canal water in subarea \( j \) (fraction);

\( rrf_{ijt} \)  
recharge factor for rainfall in subarea \( j \) (fraction);

\( PMA_{ijt} \)  
permissible annual groundwater mining allowance of the aquifer (m³);

\( \Delta h_i \)  
annual average groundwater table fluctuations (m);

\( SY_{ijt} \)  
specific yield of aquifer (fraction);

\( CQ_{ijt} \)  
capacity of the canal for delivering surface water to crop \( i \) during period \( t \) (m³)

\( QS_{ijt} \)  
capacity of the canal for delivering groundwater to crop \( i \) during period \( t \) (m³);

\( MS_{ijt} \)  
machine total water shortage for all crops during period \( t \) (m³);

\( MG_{ijt} \)  
machine water shortage for crop \( i \) over the planning horizon (m³);

\( \sigma_{ijt} \)  
Coefficient to guarantee water supply to food crops;

\( TS_{ijt_{\text{max}}} \)  
maximum allowable planting area of crop \( i \) in subarea \( j \) irrigated by surface water (ha);

\( TG_{ijt_{\text{max}}} \)  
maximum allowable planting area of crop \( i \) in subarea \( j \) irrigated by groundwater (ha);

\( \gamma \)  
Gini coefficient

\( RMD_{ijt} \)  
labor force requirement of crop \( i \) in subarea \( j \) during period \( t \) (unit/ha);

\( LA_{ijt} \)  
labor force availability in subarea \( j \) during period \( t \) (unit)