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A Bayesian network-based bi-level multi-objective programming model for uncertainty agricultural water management and allocation optimization

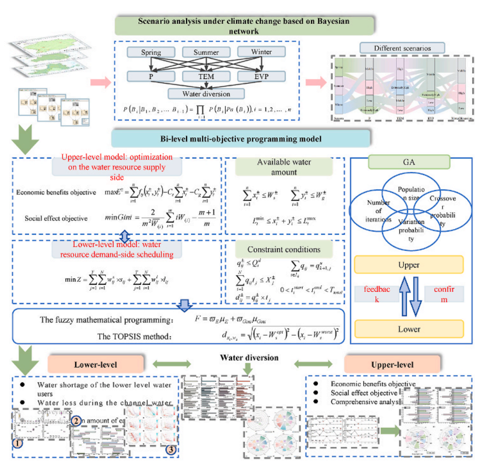
Lingzi Wang [a], Rengui Jiang [a,*], Yong Zhao [b], Jiancang Xie [a], Xiao Zhang [a,**], Ganggang Zuo [a], Simin Wang [a], Xixi Lu [c]

[a] State Key Laboratory of Eco-hydraulics in Northwest Arid Region of China, Xi'an University of Technology, Xi'an, 710048, China
[b] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing, 100038, China
[c] Department of Geography, National University of Singapore, Kent Ridge, 119260, Singapore

HIGHLIGHTS

- A Bayesian network-based bi-level multi-objective programming model was proposed.
- Multiple water diversion scenarios under climate uncertainties were systematically identified.
- Balance between economic efficiency and fairness in water allocation was achieved.
- The proposed model significantly enhanced the resilience of agricultural water management.

GRAPHICAL ABSTRACT



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ABSTRACT

Water resource management in irrigation districts is of pivotal importance for safeguarding agricultural production, promoting regional economic development, and maintaining social stability. The development of a scientific and reasonable water allocation model has emerged as a pivotal research area in the context of sustainable development of irrigation districts, particularly in the context of climate change. This study explores the use of a combination of methodologies for agricultural water management under uncertainty conditions, including Bayesian network, interval parameter programming, and a bi-level multi-objective programming model approach. The Bayesian network has been demonstrated to quantify the nonlinear effects of precipitation, temperature, evaporation, and other factors on water diversion. The bi-level multi-objective programming model is designed to balance economic efficiency and social equity between the macro and micro decision-making

* Corresponding author. Xi'an University of Technology, No. 5 South Jinhua Road, Xi'an City, Shaanxi Province, China.
** Corresponding author.
E-mail addresses: rgjiang@xaut.edu.cn (R. Jiang), zhangxiao1989@xaut.edu.cn (X. Zhang).

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levels. A case study conducted in Jiaokou Irrigation District, Shaanxi Province of China, demonstrated the adaptability of the model under different scenarios. The findings indicate that the aggregate benefits of the irrigation district under the normal scenario can amount to 3.30×10^9 yuan. The fluctuation in the mean value of water diversion is less than about 15 %. The Gini coefficient is maintained within the range of 0.02–0.29. This study rationally and dynamically allocates water resources through multi-model coupling, achieving scientific management of agricultural water resources. It offers novel concepts and specialized technical assistance for the harmonized implementation of the Sustainable Development Goals at the irrigation district level, with the objective of addressing the progressively intricate challenges posed by water scarcity and uncertainty.

Nomenclature

IPCC	Intergovernmental Panel on Climate Change	BLMOP	Bi-level multi-objective programming model
SDGs	Sustainable Development Goals	GI	Gini coefficient
CVaR	Conditional value at risk	BLMOIBSP	Bi-level multi-objective interval-bi-stochastic programming
IPP	Interval parameter programming	ITSP	Interval two-stage stochastic programming
TSP	Two-stage stochastic programming	CAO	Chaotic Aquila Optimizer
IP	Integer programming	DAG	Directed Acyclic Graphical
BN	Bayesian network	CPT	Conditional Probability Table

1. Introduction

The reconfiguration of the hydrological system triggered by global climate change is profoundly altering the pattern of water allocation in irrigated areas. Global climate change and its intensified impacts on water resources have led to a prominent contradiction between the supply and demand of water resources in irrigation districts, and agricultural water management is now facing unprecedented challenges. On the one hand, factors such as uneven precipitation distribution and increased evaporation caused by rising temperatures have made the available amount of water resources increasingly unstable (Chen et al., 2015). On the other hand, the expansion of the scale of agricultural production and the improvement in the requirements for the quality and yield of agricultural products have resulted in the continuous growth of water demand in irrigation districts. In recent decades, global terrestrial evapotranspiration has shown a significant upward trend, and the spatial and temporal distribution of precipitation has become more uneven (Zhang et al., 2024). According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), global water demand for irrigated agriculture will increase by 20–30 % by 2050 compared to current levels, driven by climate warming. The risk of water scarcity in arid and semi-arid areas will increase by more than 40 % compared to the end of the 20th century, directly threatening the food security of 1.9 billion people (IPCC, 2023; Deng et al., 2025). Due to the uncertainty of the hydrological environment and the imbalance in water resource allocation, the risk of regional agricultural irrigation water shortage is relatively high, which has seriously affected the sustainable development of the agricultural system (Niu et al., 2016).

In accordance with the Sustainable Development Goals (SDGs), SDG2 calls for the establishment of climate-resilient food production systems. SDG6 focuses on clean water and sanitation, explicitly calling for the achievement of sustainable management and efficient use of water resources. SDG13 emphasizes the enhancement of society's resilience to climate change and the level of adaptation (McElwee et al., 2020; Filho et al., 2023). As the primary entity responsible for ensuring food security and the predominant unit of water consumption, the efficiency of water allocation in irrigation districts directly impacts the realization of these objectives. Currently, the complexity of water management in irrigation districts is exacerbated by the dual pressures of climate change and increased irrigation demand (Sutcliffe et al., 2021). Anomalous precipitation patterns and increased evapotranspiration have led to significant spatial and temporal variability in water supply. The frequent occurrence of extreme weather events poses a significant challenge to the emergency response capacity of irrigation districts (Wang et al., 2025). This poses a direct threat to the food security target of SDG2 and the climate resilience requirement of SDG13. The demand for water resources is increasing due to the growth in the scale of agricultural production and the growing sophistication of crop water requirements (Cao et al., 2021). Conventional allocation methods are inadequate in meeting the stringent water efficiency standards outlined in SDG6. In this context, a novel approach to the management of water resources in irrigated districts has emerged: the construction of an intelligent configuration system capable of realizing the dynamic coupling of hydrological and meteorological elements. It is essential to enhance the ability of irrigation districts to cope with climate change, as well as to improve the efficiency of water use in irrigation districts. This can be achieved through precise control of water quantity, reduction of water loss, and optimization of irrigation cycles. The provision of theoretical innovation and technical support for the synergistic implementation of SDG2, SDG6, and SDG13 at the irrigation district level is essential.

2. Literature review

2.1. Research progress on uncertainty analysis

Most traditional water resource allocation methods formulate water use plans based on historical average climatic conditions (Asif et al., 2023). However, under the new circumstances triggered by climate change, the limitations of such methods have become increasingly prominent. The temperature rise has accelerated the evaporation rate of water, and the imbalance in the distribution of precipitation in terms of time and space has intensified, and extreme climate events such as droughts and floods have become more frequent, all of which have brought a huge impact on the traditional agricultural water management model (Zhang et al., 2015). In recent years, numerous scholars have carried out extensive and in-depth research on the optimization problems of agricultural water management under uncertain conditions (Sun et al., 2019; Li et al., 2016). A variety of methods and models have been explored to improve the utilization efficiency of water resources and the scientific nature of management decisions (Cosgrove and Loucks, 2015). Zhou et al. (2022) combined the Copula function, two-stage stochastic programming, conditional value at risk (CVaR), and chance-constrained programming to propose a stochastic model for the risk regulation of agricultural water resources. Under the conditions of changes in runoff and the water requirements of crops in the irrigation area, by adjusting parameters such as risk preference and violation probability, they regulated the water shortage risk in the irrigation district and determined the multidimensional impacts of different water allocation schemes on agricultural economic benefits, social benefits, and the ecological environment. Zhao et al. (2021) took the Guanzhong Plain, a typical semi-humid and drought-prone area in China, as the research area, used the Copula function to model the joint distribution of effective precipitation and crop water requirements, and evaluated the agricultural water shortage risk under the condition of natural precipitation supply. Zhang and Guo (2018) combined interval parameter programming (IPP), two-stage stochastic programming (TSP), CVaR, and integer programming (IP) methods to establish an imprecise CVaR two-stage mixed integer linear programming model for agricultural water management under uncertain conditions considering ecological water requirements, which could generate more flexible solutions under different risk aversion levels. Zhang et al. (2019) established an interval linear fractional bi-level programming model and used a satisfaction-based interactive fuzzy coordination algorithm to solve the model for irrigation water resource management under uncertain conditions. They integrated the interval analytic hierarchy process and the technique for order preference by similarity to an ideal solution to evaluate the applicability of the optimization schemes.

As an effective probabilistic graphical model, the Bayesian network (BN) plays a unique role in dealing with the uncertainty of agricultural water use under climate change (Zhang et al., 2024). It constructs a network structure that includes various factors affecting agricultural water use, clearly presents the interrelationships among these factors in a graphical way, and uses probability distributions to describe the uncertainty of each factor (Dang et al., 2019; Liu et al., 2023). Based on Bayes' theorem, it can update and predict the probability distribution of other related factors through probabilistic reasoning according to the known partial information (Rohmer, 2020). In the context of rising temperatures, the BN can integrate historical data on temperature, precipitation, soil moisture and crop water requirements, thereby establishing a probabilistic correlation model between temperature and other factors. This model enables the inference of the potential range of crop water requirements in future periods, even in the presence of uncertain temperature changes, based on existing meteorological data. It provides a scientific basis for adjusting the irrigation strategy and effectively coping with the challenges brought by the changes in evaporation and crop water requirements caused by rising temperatures (Schauberger et al., 2017; Tao et al., 2018; Minhas et al., 2020).

2.2. Research progress on multi-objective models

Although the BN performs excellently in dealing with uncertainties, agricultural water management is a complex systematic project involving multiple levels of objectives and decisions (Radmehr et al., 2022; Uhlenbrook et al., 2022). Besides dealing with the uncertainties brought about by climate change, it is also necessary to consider how to achieve multiple objectives such as maximizing agricultural economic benefits, improving the utilization efficiency of water resources, and protecting the ecological environment (Yang and Solangi, 2024). Therefore, the bi-level multi-objective programming model (BLMOP) has been introduced into the agricultural water management system (Chen et al., 2023; Cheng et al., 2022). The BLMOP model bifurcates the agricultural water decision-making process into two distinct tiers: the upper-level serves as the macro decision-making stratum, predominantly originating from a comprehensive regional or basin-wide perspective. This level considers high-level objectives, including the equitable distribution of water resources, the optimization of the agricultural industrial framework, and the maintenance of ecological equilibrium (Yue et al., 2021). It steers agricultural water management towards a sustainable trajectory through the implementation of pertinent policies and strategic blueprints. The lower-level represents the micro-operational stratum, which zeroes in on the particular production choices made by individual farms or farmers, aimed at enhancing both economic returns and water utilization efficiency at the most granular level.

Through the hierarchical structure and the coordinated optimization of multiple objectives, the BLMOP model can coordinate the interests of all parties at different scales and achieve the overall optimization of the agricultural water management system (Hu et al., 2016). In recent years, the BLMOP model has received increasing attention and application in the allocation of agricultural water resources and has shown good prospects. Chen et al. (2023) quantified the fairness of water resource regulation using the Gini coefficient (GI) and water supply efficiency, introduced welfare economics based on the principles of welfare economics to establish a water resource regulation function, and constructed an optimized operation model for a hierarchical water supply cascade reservoir group. Tu et al. (2024) proposed a bi-level multi-objective interval-bi-stochastic programming (BLMOIBSP) model based on the joint operation of multiple water sources. They used the interval two-stage stochastic programming (ITSP) method to handle the interval parameters of water demand and combined the Chaotic Aquila Optimizer (CAO) algorithm and the satisfaction-based bi-level interactive method to solve the BLMOIBSP model. Wu et al. (2022) integrated interval parameter programming, fuzzy credibility-constrained programming, BLMOP, and the GI to establish a BLMOP model for inter-basin water transfer. Ren et al. (2023) established a fuzzy max min decision bi-level multi-objective interval programming model, with the fairness of water resource allocation and agricultural economic benefits as the planning objectives, and obtained the optimal water resource allocation schemes for different representative hydrological years.

To address above issues, the main objectives of this study is to propose an agricultural water management method using BN, IPP, and BLMOP models. This approach aims to address the challenges posed by climate change and achieve scientific management and sustainable utilization of agricultural water. The hydrological uncertainties are characterized using BN probabilistic reasoning. The optimization of water allocation across hierarchical scales is achieved by means of multi-objective trade-offs. The utilization efficiency of water resources is improved, the sustainable utilization and the balance between supply and demand of water resources in the irrigation district are ensured, and it is expected to provide an effective decision making support tool for agricultural water managers.

Compared with previous studies, the scientific contributions of this study are mainly reflected in the following. Firstly, the paper introduces BN into the irrigation diversion analysis to quantify the non-linear probabilistic impacts of climate factors on water diversion. Rather than dividing into high, normal, and low flow years, multiple scenarios are screened. This enables the analysis to encompass a more comprehensive range of climatic risks and to address water diversion needs under various climatic conditions. Secondly, the establishment of a dual objective system of economy and equity is imperative. The GI assesses the equitable distribution of water resources among channels, thereby providing a numerical approach for resolving disputes over water allocation in a regional context. Thirdly, the scenario parameters output from BN are directly inputted into the BLMOP model, thereby ensuring that both macro-decision and micro-dispatch are capable of responding to climate fluctuations. Fourthly, the BLMOP model addresses interval parameters, including canal water loss and diversion volume, with the objective of enhancing the robustness of the scenario. Fifthly, the Shaanxi Jiaokou Irrigation District is utilized as a practical illustration. In the context of climate change, the quantification of uncertainty, hierarchical decision-making processes, and multi-objective equilibrium in agricultural water resource management are achieved through multi-model coupling. This approach serves to verify the applicability and superiority of the framework proposed in this study.

3. Study area and data

3.1. Study area

In this study, the Jiaokou Irrigation District in Shaanxi Province is selected as the case study area (Fig. 1). This region exhibits distinctive agricultural production characteristics and a variety of water resource utilization scenarios, which collectively reflect the intricate problems and challenges confronting agricultural water management in the context of climate change. The total area of the irrigation district is

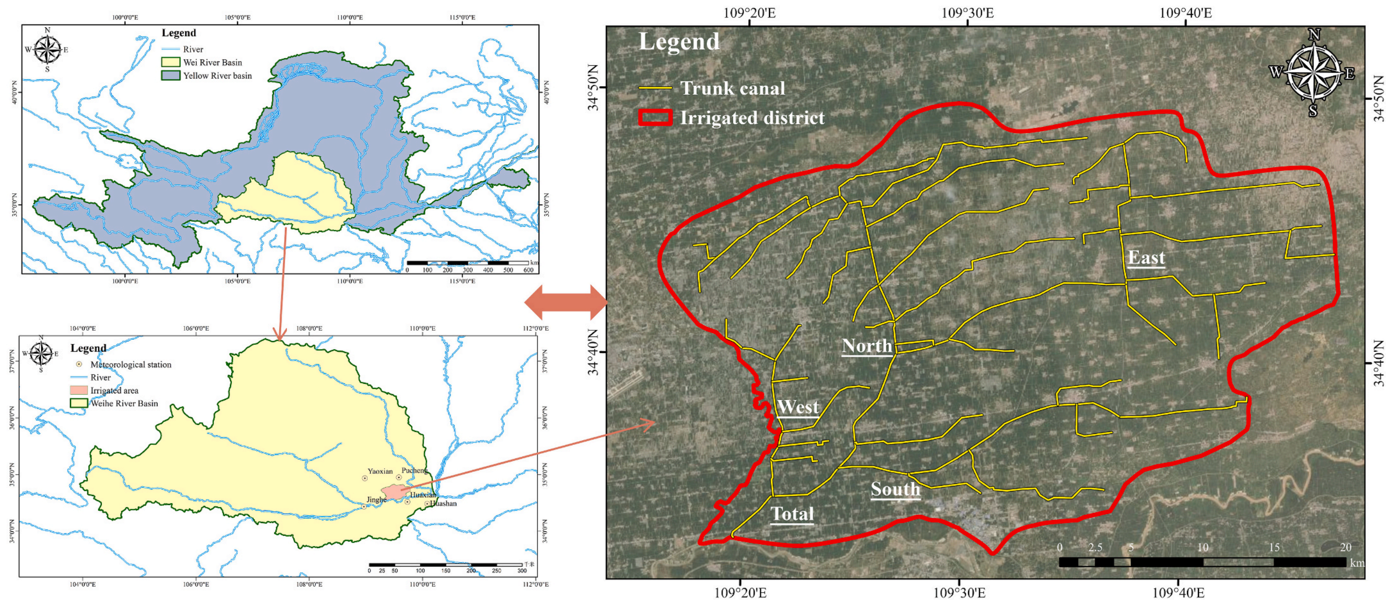

Fig. 1. Study area.

approximately 1024.81 km^2. The region falls within the temperate and semiarid monsoon climate zone. The annual mean precipitation is 569.4 mm, the mean daily sunshine duration is 2218.5 h, the annual evaporation is 1208 mm, and the annual mean relative humidity is about 71 %. The Wei River supplies surface water, with an allocated water volume quota of 3.8×10^8 m^3. The primary crops cultivated in the irrigation district encompass wheat, corn, cotton, and cash crops. The existing irrigation canal network in the area is relatively complex, comprising 1 main canal, 4 trunk canals, and 35 branch canals. However, the process of water conveyance through these canals inevitably results in a certain degree of water loss. The ongoing climate change and the increasing demand for agricultural water have exacerbated the existing disparity between water supply and demand. This underscores the pressing need to refine and enhance agricultural water management strategies, with the overarching objective being the sustainable advancement of the agricultural sector and the judicious utilization of water resources (Zhang et al., 2024).

3.2. Data sources

Considering the diverse meteorological conditions around the irrigation area, this study collected the daily meteorological data of five representative meteorological stations around the irrigation district from 1959 to 2020 and used the Thiessen polygon interpolation method to obtain the average data of the irrigation area. The data were obtained from the National Meteorological Information Center of the China Meteorological Administration (http://data.cma.cn/), including latitude, longitude, average temperature, precipitation and evaporation. A small amount of data was missing, and linear interpolation was used for supplementation and the average values within a certain period were adopted. The data including irrigation water use, crop planting area, crop yield, and economic benefits can be obtained by the Jiaokou Irrigation District Administration Bureau, the *Xi'an Statistical Yearbook* (http://tjj.xa.gov), and the *Shaanxi Statistical Yearbook* (http://tjj.shaanxi.gov.cn/tjsj/ndsj/tjnj/), for the period of 2015–2020.

4. Methodology

The BN is utilized to address issues of uncertainty, with consideration given to the alterations in available water supply resulting from climate change in the context of the current water resource scheduling for the irrigation area. Furthermore, the impacts of diverse water inflow scenarios on the available water supply within the irrigation district are deliberated. When combined with the optimization of decisions facilitated by the BLMOP model, this approach enables the comprehensive scientific allocation of water resources in the irrigation area, ranging from the macro to the micro level. The upper-level model commences from a macro perspective and comprehensively considers two key elements, namely economic benefits and social fairness. The lower-level model focuses on the micro level, aiming to reduce the water shortage of lower-level water users caused by the unreasonable allocation of water resources and control the water loss during the process of water conveyance in canals (Fig. 2).

4.1. Bayesian network

4.1.1. Establishment of Bayesian network

A BN comprises a Directed Acyclic Graphical (DAG) and a Conditional Probability Table (CPT) (Kitson et al., 2023). This tool enables the analysis of uncertainty by integrating the principles of graph theory and probability theory. The wide range of applications in fields such as prediction, intelligent reasoning, diagnosis, decision-making, risk analysis, and reliability analysis underscores its versatility (Poppenborg and Koellner, 2014). The joint probability distribution of all variables in a set X is represented by P, then all variables in X are consistent with all nodes in the DAG.

$$P(B_i|B_1, B_2, \ldots, B_{i-1}) = \prod_{i=1} P(B_i|P_a(B_i)), i = 1, 2, \ldots, n \tag{1}$$

Where $Pa(B_i)$ refers to the set of parent nodes of node B_i.

In this study, the target node is set as water diversion. A meticulous examination of the pivotal factors influencing the water resource system within the designated research area has been conducted, leading to the determination of the nodes of the BN. These nodes encompass the Season, precipitation (P), temperature (TEM), and evaporation (EVP) parameters. The seasonal factor has the capacity to affect precipitation, temperature, evaporation, and other variables, and there are intricate correlations among precipitation, temperature, evaporation, and water diversion (Konapala et al., 2020). The season is set as the parent node because crop growth stages change with the seasons, resulting in significant differences in irrigation sensitivity to meteorological factors. This is consistent with the actual growth conditions of the crops.

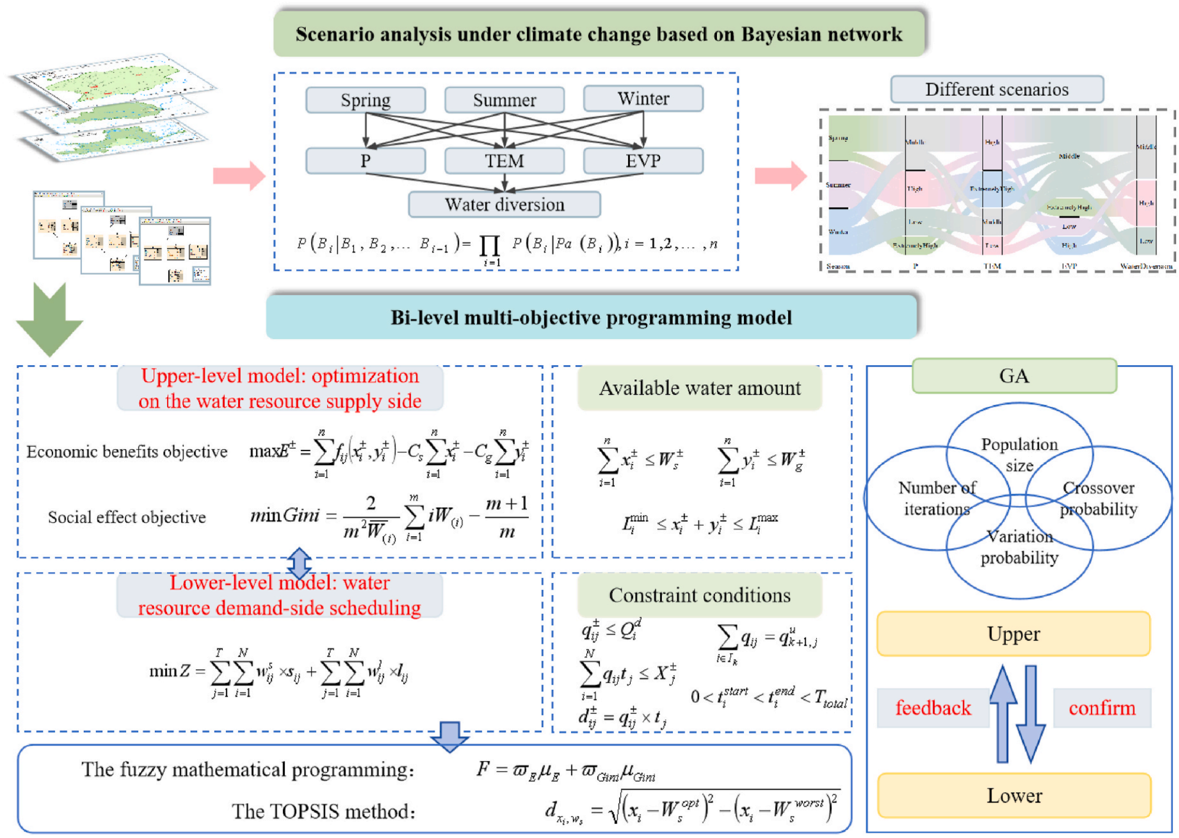

Fig. 2. Framework of this study.

Precipitation directly affects soil moisture conditions and is negatively correlated with irrigation requirements. Evaporation is closely related to temperature and positively correlates with irrigation requirements as it exacerbates water loss. Conversely, the interplay among temperature, evaporation, and water diversion can also influence the allocation of water resources.

The conditional probability relationships among nodes are determined by collecting historical data from the study area over an extended

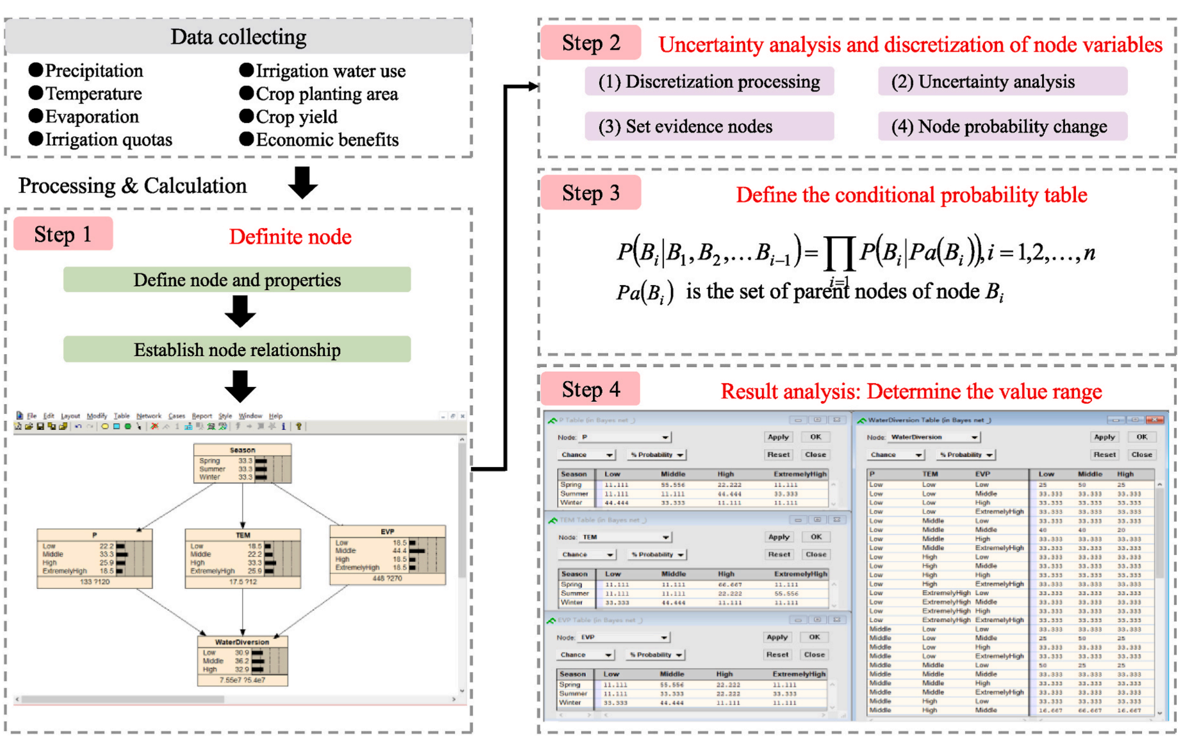

Fig. 3. Flowchart of the Bayesian network.

period (Fig. 3). The utilization of statistical analysis methodologies facilitates the processing of these data, leading to the calculation of the joint probability distribution and the conditional probability distribution between factors such as precipitation, temperature, evaporation, and water diversion over diverse seasonal periods (Amirataee et al., 2023). The CPT reveals a negative correlation between precipitation and the amount of water diversion for spring, summer, and winter irrigation. This indicates that as precipitation levels increase, the amount of water diversion decreases. Evaporation exhibits a positive correlation with the amount of water diversion. When evaporation levels are high, an increased amount of water diversion is necessary to replenish soil moisture. The impact of temperature on the amount of water diversion is relatively complex. An increase in temperature has been shown to accelerate evaporation, thereby increasing the amount of water diversion. However, if precipitation levels are sufficient, this effect can be mitigated. Furthermore, the combined impact of these factors on water diversion varies due to differences in factors such as crop growth stages across seasons.

4.1.2. Scenario analysis of water diversion under climate change

In this study, 11 water diversion scenarios with typical characteristics were constructed by probabilistic inference of meteorological data from 1959 to 2020 using BN (Fig. 4). Four types of drought-dominated scenarios, two types of flood-risk scenarios and three types of normative equilibrium scenarios were systematically screened based on the multidimensional coupling characteristics of precipitation, temperature and evaporation and the intensity of their impacts on agriculture. The precipitation temperature, and other such parameters that are utilized to delineate the scenarios, have been identified as pivotal factors in determining the distribution outcomes. The combined effect of these factors is reflected in the differences in water diversion volumes under different scenarios. Scenario S-I is characterized by moderate precipitation, high temperatures, and significant evaporation in the spring, where diversions are increased to high levels to reflect water stress. In this scenario, spring is more sensitive to water requirements as it is the early stage of crop planting and growth. Scenario S-II is marked by high precipitation, high temperatures, and substantial evaporation, with high diversion during summer months. This scenario poses concerns regarding drought risk and water allocation in the event of uneven precipitation distribution. Scenario S-III is marked by low precipitation, moderate temperature, medium evaporation, and low diversion during winter, leading to a general scarcity of water resources. Scenario S-IV is defined by low precipitation, low temperature, and medium evaporation in winter, with medium diversion. Scenario S-V is characterized by an abundance of summer precipitation, high temperatures, moderate evaporation, and substantial water diversion. It is noteworthy that the volume of precipitation may exceed the natural drainage and water storage capacity, necessitating flood prevention measures. Scenario S-VI is characterized by an abundance of precipitation, high temperatures, substantial evaporation, minimal surface water diversion during summer months, significant drainage pressure, and a high risk of flooding. Scenario S-VII is characterized by medium precipitation, high temperature, medium evaporation, and a medium amount of water diversion in the spring, with a relative balance between precipitation and evaporation. The overall situation is considered normal. Scenario S-VIII is marked by abundant precipitation, high temperature, medium evaporation, medium water diversion in the spring, and adequate water resources. Scenario S-IX is a normal condition with moderate winter precipitation, low temperatures, moderate evaporation, moderate water diversion.

4.2. Bi-level multi-objective programming model

The BLMOP model established in this study has an upper-level model that commences from a macro perspective and comprehensively considers two key elements, namely economic benefits and social fairness. The lower-level model focuses on the micro level, aiming to reduce the water shortage of lower-level water users caused by the unreasonable allocation of water resources and control the water loss during the process of water conveyance in canals. The model's primary objective is to optimize the allocation of water resources within the irrigation district and the canal system, thereby enhancing the utilization of these resources, both economically and socially. This approach ensures the sustainable utilization of water resources, maintaining a balance between supply and demand within the irrigation area (Zhang et al., 2020, 2023; Li et al., 2021).

4.2.1. Upper-level model: water resource supply side optimizing

The upper-level model considers the objectives of economic benefits and social effects. Utilizing the functions associated with the irrigation benefits and irrigation water consumption of the key canals in the irrigation area, as outlined in the lower-level model, the objectives of the irrigation district canal bi-level model are to achieve effective constraints. The bi-level model incorporates a range of factors, including the available water volume and the scale of canal projects, to facilitate interval optimization and allocation for surface water diversion and groundwater exploitation across different key canals. This approach is designed to ensure the optimal allocation of limited water resources

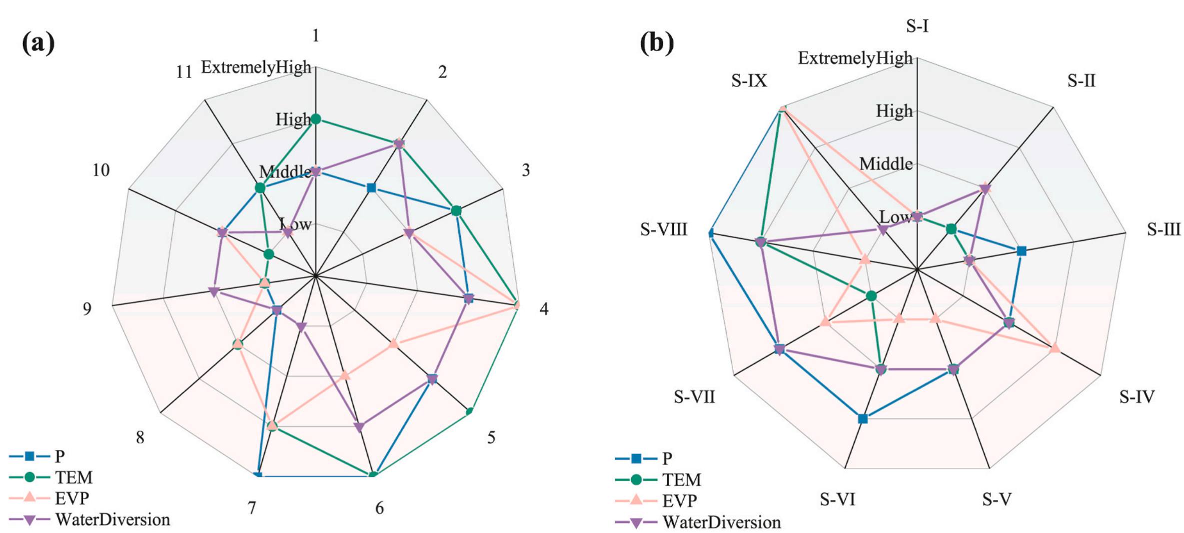

Fig. 4. Different water diversion scenarios (a) 11 scenarios, (b) 9 typical scenarios.

among various canals, thereby maximizing economic output and social benefits within the irrigation area.

The objective of economic benefits is to maximize the overall irrigation benefits of the irrigation area. This calculation is derived by subtracting the management cost of the irrigation district from the sum of the irrigation benefits of each canal. The irrigation benefit of each canal is related to the irrigation water amount, and the calculation formula is as follows.

$$\max E^{\pm} = \sum_{i=1}^{n} f_{ij}\left(x_i^{\pm}, y_i^{\pm}\right) - C_s \sum_{i=1}^{n} x_i^{\pm} - C_g \sum_{i=1}^{n} y_i^{\pm} \tag{2}$$

Where $x_i^{\pm}$ refers to the surface water diversion amount of the canal (m^3). $y_i^{\pm}$ refers to the groundwater exploitation amount of the canal (m^3). $f_{ij}\left(x_i^{\pm}, y_i^{\pm}\right)$ refers to the function related to the irrigation benefits and irrigation water amount of each canal system. C_s refers to the surface water management cost of the irrigation district (yuan/m^3). C_g refers to the groundwater management cost of the irrigation district (yuan/m^3).

The social effect objective is reflected by the GI to embody the fairness of water resource allocation among different canals. The value range of the GI is between 0 and 1. The larger the value, the more unequal the allocation is, and the greater the difference in water resource allocation. The calculation of the GI is based on the Lorenz curve. For water resource allocation, the calculation method is as follows.

$$min\mathrm{GI} = \frac{2}{m^2 \overline{W}_{(i)}} \sum_{i=1}^{m} iW_{(i)} - \frac{m+1}{m} \tag{3}$$

Where m refers to the number of canals. the water allocation data of canal i is arranged in ascending order, W_{ij} refers to the i data after sorting. $\overline{W}_{(i)}$ refers to the mean value (m^3).

Constraints include surface water availability, groundwater availability, and trunk canal project size constraints.

$$\sum_{i=1}^{n} x_i^{\pm} \leq W_s^{\pm} \tag{4}$$

$$\sum_{i=1}^{n} y_i^{\pm} \leq W_g^{\pm} \tag{5}$$

$$L_i^{\min} \leq x_i^{\pm} + y_i^{\pm} \leq L_i^{\max} \tag{6}$$

Where $W_s^{\pm}$ refers to the total interval of available surface water for agricultural use in the irrigation district (m^3). $W_g^{\pm}$ refers to the total interval of available groundwater for agricultural use (m^3). $L_i^{\max}$ refers to the upper limit of the water conveyance capacity of the canals within the superior canal system i (m^3), which is deduced by increasing the flow rate of the canals. $L_i^{\min}$ refers to the lower limit of the water conveyance capacity of the canals within the superior canal system i (m^3), which is deduced by the minimum flow rate of the canals.

4.2.2. Lower-level model: water resource demand side scheduling

The lower-level model takes the water allocation flow rate q_{it} at the head of the N canal in T period as the decision variable. The objective function is set to minimize the water shortage experienced by lower-level water users and the water loss during canal water conveyance.

$$\min Z = \sum_{j=1}^{T} \sum_{i=1}^{N} w_{ij}^{s} \times s_{ij} + \sum_{j=1}^{T} \sum_{i=1}^{N} w_{ij}^{l} \times l_{ij} \tag{7}$$

Constraint on the water conveyance capacity of canals: To ensure the safe and stable operation of canals, the water conveyance flow rate of canals shall not exceed the designed flow rate.

$$q_{ij}^{\pm} \leq Q_i^{d} \tag{8}$$

Water quantity constraint: Limited by the incoming water, the water diversion amount at the head of the superior canal shall not exceed the allocated water amount of this main canal. The product of the water allocation flow rate of each inferior canal and the water diversion time is equal to the water allocation amount of this canal.

$$\sum_{i=1}^{N} q_{ij} t_j \leq X_j^{\pm} \tag{9}$$

$$d_{ij}^{\pm} = q_{ij}^{\pm} \times t_j \tag{10}$$

Water balance constraint of canal sections: The flow rate at the end of the i canal section of the superior canal should be equal to the sum of the flow rates at the heads of the inferior canals connected to the end of this canal section and the flow rate at the head of the *(i+1)* canal section of the superior canal.

$$\sum_{i \in I_k} q_{ij} = q_{k+1,j}^{u} \tag{11}$$

Rotation period constraint: The start time and end time of water allocation for each inferior canal should be within the rotation period, and the start time should be greater than zero.

$$0 < t_i^{start} < t_i^{end} < T_{total} \tag{12}$$

Where Q_i^d refers to the designed flow rate of the inferior canal (m^3/s). t_j refers to the duration of the j period (s). $X_j^{\pm}$ refers to the total water amount interval allocated by the superior canal to the inferior canal in the j period (m^3). $d_{ij}^{\pm}$ refers to the water allocation amount of the i canal in the j period (m^3). $i \in I_k$ refers to the set of inferior canals connected to the end of the k canal section of the superior canal. $q_{k+1,j}^{u}$ refers to the flow rate at the head of the *(k+1)* canal section of the superior canal in the j period (m^3).

4.2.3. Model solution

The model in this study is a complex interval multi-level multi-objective programming model. The proposed solution involves a transformation of complexity into simplicity, multi-level into single-level, multi-objective into single-objective, and interval into deterministic. The decomposition and coordination method is employed to divide the multi-level system, while the fuzzy mathematical programming is adopted to convert multi-objective into single objective. Finally, the best worst method interval model is transformed into a deterministic model (Fu et al., 2016; Nematian, 2023; Li et al., 2024). The interval parameters are determined on the basis of historical and field survey data. For agriculture-related parameters, the data are primarily derived from field surveys. The determination of these boundaries is achieved through the statistical analysis of their fluctuation ranges. The calculation of the water diversion interval is performed by a BN, which utilizes historical meteorological data and historical water diversion data to determine.

The fuzzy mathematical programming uses the membership function method to transform the multi-objective model into a single objective model. For the economic benefit objective function $E^{\pm}$, the membership function μ_E is defined according to its value range and the expected satisfaction level. For the social effect objective function GI, the membership function μ_{GI} is also defined according to the reasonable value range of the GI and the expected fairness degree. By determining the weights ω_E and ω_{GI} of the importance attached to the economic benefit and social effect objectives, a comprehensive fuzzy objective function is constructed to transform the multi-objective optimization problem of the upper-level model into a single objective optimization problem.

$$F = \varpi_E \mu_E + \varpi_{GI} \mu_{GI} \tag{13}$$

The TOPSIS method can be used to deal with the interval parameters contained in the model. In the case of constraints containing interval parameters, the following expressions can be used to eliminate uncertainties.

$$x_j \times \sum_{j=1}^{n}\left[a_{ij}^{-} + s_{ij}\left(a_{ij}^{+} - a_{ij}^{-}\right)\right] \leq b^{-} + t_j(b^{+} - b^{-}) \tag{14}$$

Where s_{ij} and t_j refer to auxiliary variables, which are used to transform the interval numbers $a_{ij}^{\pm}$ and $b^{\pm}$ into corresponding deterministic expressions. When $s_{ij} = 0$ and t_j=1, the model is transformed into the optimal model. When $s_{ij} = 1$ and t_j=0, the model is transformed into the worst model. Previous studies have used expert consultation, the analytic hierarchy process, or other decision analysis methods to determine the weightings that decision-makers assign to economic benefit and social effect objectives. For instance, if an irrigation district prioritizes economic development, the weighting for that objective may be higher. Conversely, if the district prioritizes social equity, the weighting for that objective may be higher. The sum of the weightings should equal one. This study assumes that the weights of the importance attached to the economic benefit objective and the social effect objective are both 0.5. The weighting of 0.5 is derived from the initial equity-efficiency balance assumption and is subject to optimization in future iterations, in conjunction with stakeholder research.

The genetic algorithm is used to solve the constructed BLMOP model. For different scenarios, the corresponding parameters and conditional probability relationships are input respectively to obtain the water resource allocation schemes under each scenario (Habibi Davijani et al., 2016). During the solution process, the upper and lower level models are linked and coordinated through data interaction, and iterative optimization is performed using a genetic algorithm. Subsequent to the generation of the preliminary configuration plan by the upper-level model, the lower-level model performs a resolution of the issue in accordance with the aforementioned plan, thereby yielding feedback on matters such as water shortage and water loss. The upper-level model adjusts the plan and iterates again until convergence. The stability of the solution process is ensured through a clear upper and lower level feedback mechanism and algorithm convergence criteria. Since the groundwater in the Jiaokou Irrigation District is only used as an emergency water source, the groundwater allocation interval is ignored in this study.

5. Results

5.1. Canal flow rate and water distribution period

The trunk canal flow shows a significant variation pattern (Fig. 5). When under a similar high temperature and strong evaporation scenario, the flow rate of the north trunk canal diminishes from an initial 12 m^3/s to 7.2 m^3/s, representing a decline of about 40 %. This phenomenon is primarily attributed to the high ambient temperatures, which expedite the process of water evaporation, consequently diminishing the overall water resources. The allocation of water to the north trunk canal has been adjusted accordingly. The flow rate of the east trunk canal fluctuated between 4.9 and 8.28 m^3/s in the previous period, which reflects the frequent redeployment of water resources to meet the water demand of different regions during the unstable period. In scenarios characterized by exceedingly high precipitation levels, the flow rate of the west trunk canal is maintained at a consistent level ranging from 2.79 to 4.65 m^3/s. The flow rate of the south trunk canal is maintained at approximately 4.8 m^3/s, which is about 60 % lower than the flow rate in the water shortage scenario. The considerable amount of precipitation increases total water resources; however, it concomitantly increases the risk of flood occurrence. In the event of a state of equilibrium between precipitation and evaporation, the north trunk canal is subject to minimal fluctuations in flow, attributable to disparities in precipitation. The remaining canals exhibit a consistent flow rate ranging from 3.5 to 5.2 m^3/s, with a standard deviation of less than 0.5 m^3/s. The supply and demand of water resources have been balanced to a sufficient extent to adequately address fundamental water requirements across various regions. Analysis of the various scenarios above indicates that precipitation and evaporation emerge as the predominant factors influencing the outcomes of water resource allocation. These two factors have the capacity to alter the total volume of water resources and regulate the supply-demand relationship. This directly determines the magnitude and stability of trunk canal flows, as well as water allocation strategies.

In the context of climate change, the water distribution period of the canal shows a certain degree of flexibility (Fig. 6). In scenarios of water stress or scarcity, the duration of a single distribution is generally less than 500 h, and the distribution periods are relatively scattered. A high-frequency distribution pattern over a brief period facilitates the precise and flexible allocation of limited water resources to various areas. This mode fits the water demand characteristics of crops at different growth

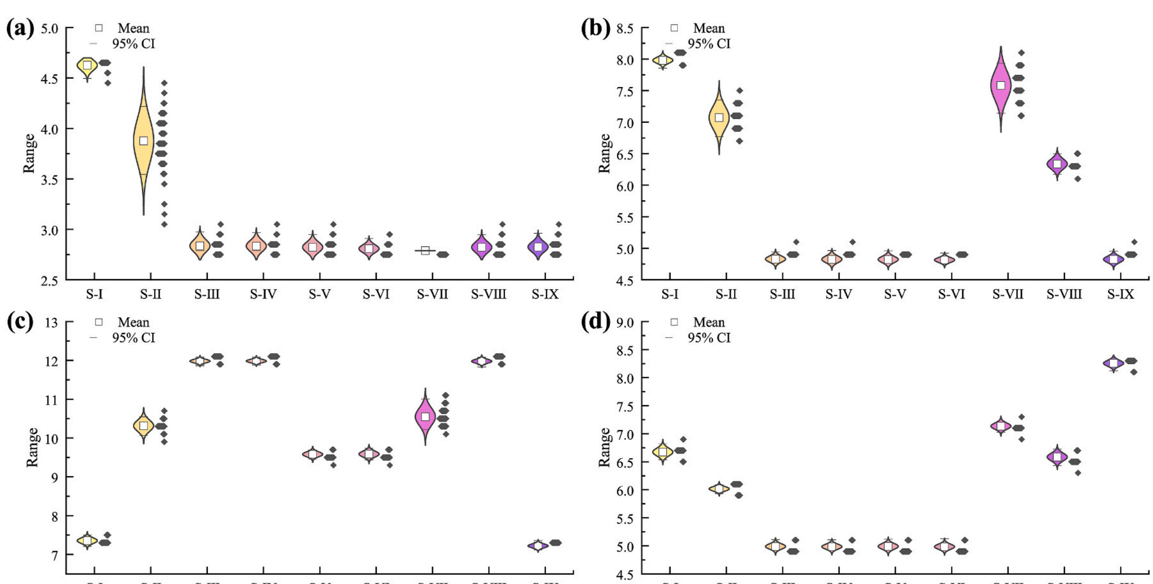

Fig. 5. Canal flow rate under different scenarios (a) west trunk canal, (b) south trunk canal, (c) north trunk canal, (d) east trunk canal.

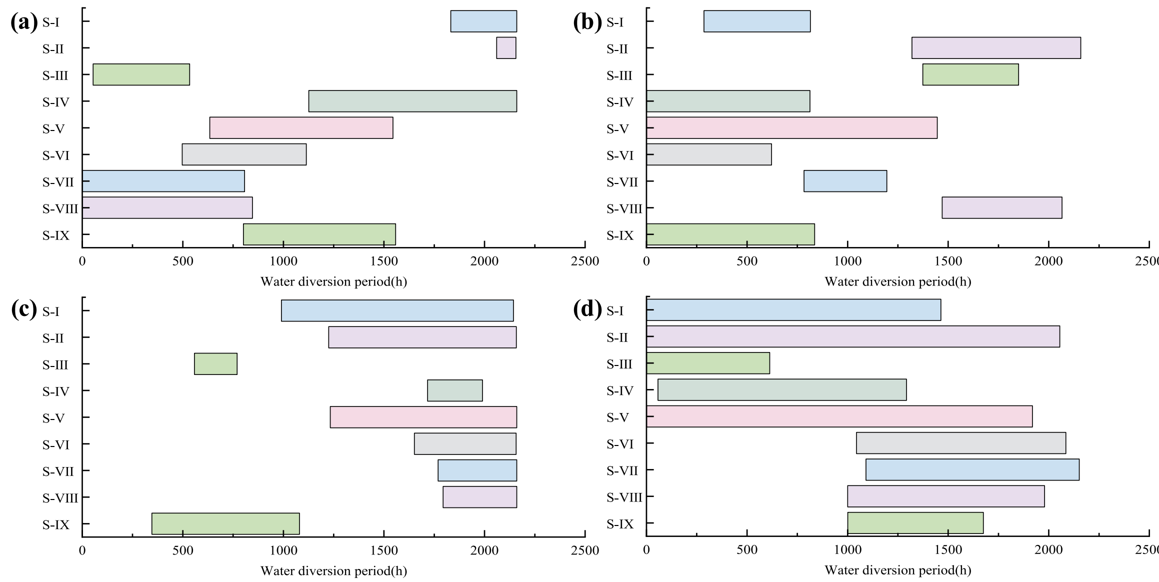

Fig. 6. Water distribution periods under different scenarios (a) west trunk canal, (b) south trunk canal, (c) north trunk canal, (d) east trunk canal.

stages. Localized water shortages due to long periods of centralized water supply can be avoided. Under the scenario of abundant precipitation, about 70 % of the water distribution period is concentrated within the range of 1 to 1500 h. The south t canal accomplished about 85 % of the water distribution in 1 to 1446 h. Centralized water rationing in advance not only makes full use of abundant water resources, but also reduces the risk of later impacts on the water supply due to unexpected conditions such as flooding. In scenarios where water resources are stable or plentiful, the distribution period is continuous and can extend from 1000 to 1500 h. The continuous distribution of water in accordance with crop water demand patterns provides a strong guarantee of stable crop growth. This flexibility is indicative of the capacity of the water allocation strategy to be adapted to climatic conditions, thereby enhancing the efficiency of water utilization. The overall

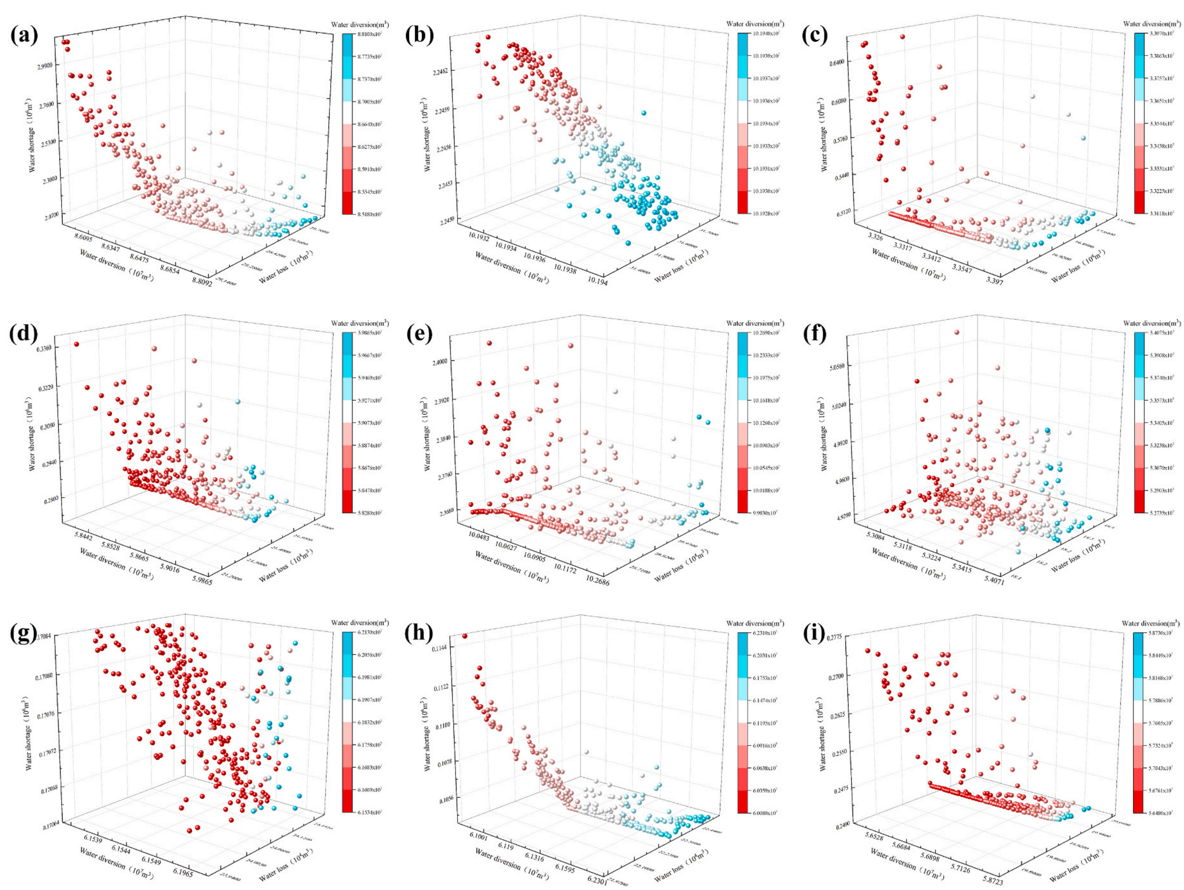

Fig. 7. Water shortage and water conveyance loss under different scenarios (a) S-I, (b) S-II, (c) S-III, (d) S-IV, (e) S-V, (f) S-VI, (g) S-VII, (h) S-VIII, (i) S-IX.

supply-demand status of water resources is directly regulated by water distribution periods, as evidenced by scenario analysis. The demand patterns for crop water determine the alignment of distribution schedules with actual water requirements, thereby directly impacting the efficiency of water resource utilization.

5.2. Water shortage and water conveyance loss

The water shortage and water conveyance loss in the lower-level model vary significantly among different scenarios (Fig. 7). Under the circumstances of high evaporation, relatively insufficient precipitation and substantial water demand by crops, the water shortage is estimated to range from 2.12 to 2.84 × 10^5 m^3. As the seasons transition and winter sets in, precipitation levels decline, and temperatures drop, resulting in a slowdown in crop growth and a concomitant decrease in water demand. The water shortage drops to below 2.12 × 10^5 m^3. In conditions of extreme precipitation, the water shortage is recorded at 1.02 to 1.21 × 10^5 m^3, representing about 60 % decrease compared to the average during periods of water resource scarcity. A substantial quantity of precipitation exerts a substantial replenishing effect on water resources, thereby ensuring sufficient supply to meet demand and significantly mitigating water scarcity. When precipitation and evaporation are balanced or water resources are abundant, the shortage of water tends to be relatively stable. The supply and demand of water resources are relatively balanced, enabling the maintenance of a low water shortage.

At higher temperatures, the rate of soil moisture evaporation is accelerated, leading to an increase in soil looseness around the channel and a significant increase in the risk of seepage. The larger canal flow produces a stronger scouring effect on the canal wall, which brings the amount of water loss in the range of 2.02–3.11 × 10^6 m^3. As temperature declines, soil gradually tightens, seepage is reduced, and the channel flow decreases. The scouring effect is weakened, and the amount of water conveyance loss decreases. In scenarios characterized by substantial precipitation and a consequent rise in canal flow, the magnitude of water conveyance loss increases to 2.40 × 10^6 m^3 due to the high flow. This phenomenon can be attributed to the superfluity of flow rate in relation to the canal's carrying capacity, which results in spillover losses as some of the water overflows. When the water resources are stabilized while the canal flow is stabilized, the scouring and seepage on the canal due to flow variations are reduced. The water loss was stabilized at 1.71 × 10^5 m^3, which is about 94.5 % lower than the peak water loss and effectively improves the utilization of water resources in the conveyance process. The water shortage and water conveyance loss in the lower-level model are influenced by meteorological factors, crop water requirements, and trunk canal flows.

5.3. Canal water diversion volumes

The amount of water diversion under different scenarios showed significant differentiation characteristics (Fig. 8). In scenarios involving water stress or scarcity, the lower limit of diversion ranges from 4.57 × 10^5 to 1.03 × 10^6 m^3. The lower limit of total diversion is only about 40 % of that in the water stabilization scenario. The lower limit is established to ensure the fulfillment of the fundamental water demand. The lower limit values for each canal diversion are at a low level, indicating that water resources are allocated with extreme caution in times of drought. The upper limit is relatively elevated and more constraining than the other scenarios, reflecting the substantial limitations imposed on the allocation of water during periods of drought. In circumstances where precipitation levels are exceedingly high, the upper limit value of overall canal diversion tends to be elevated, while the lower limit value

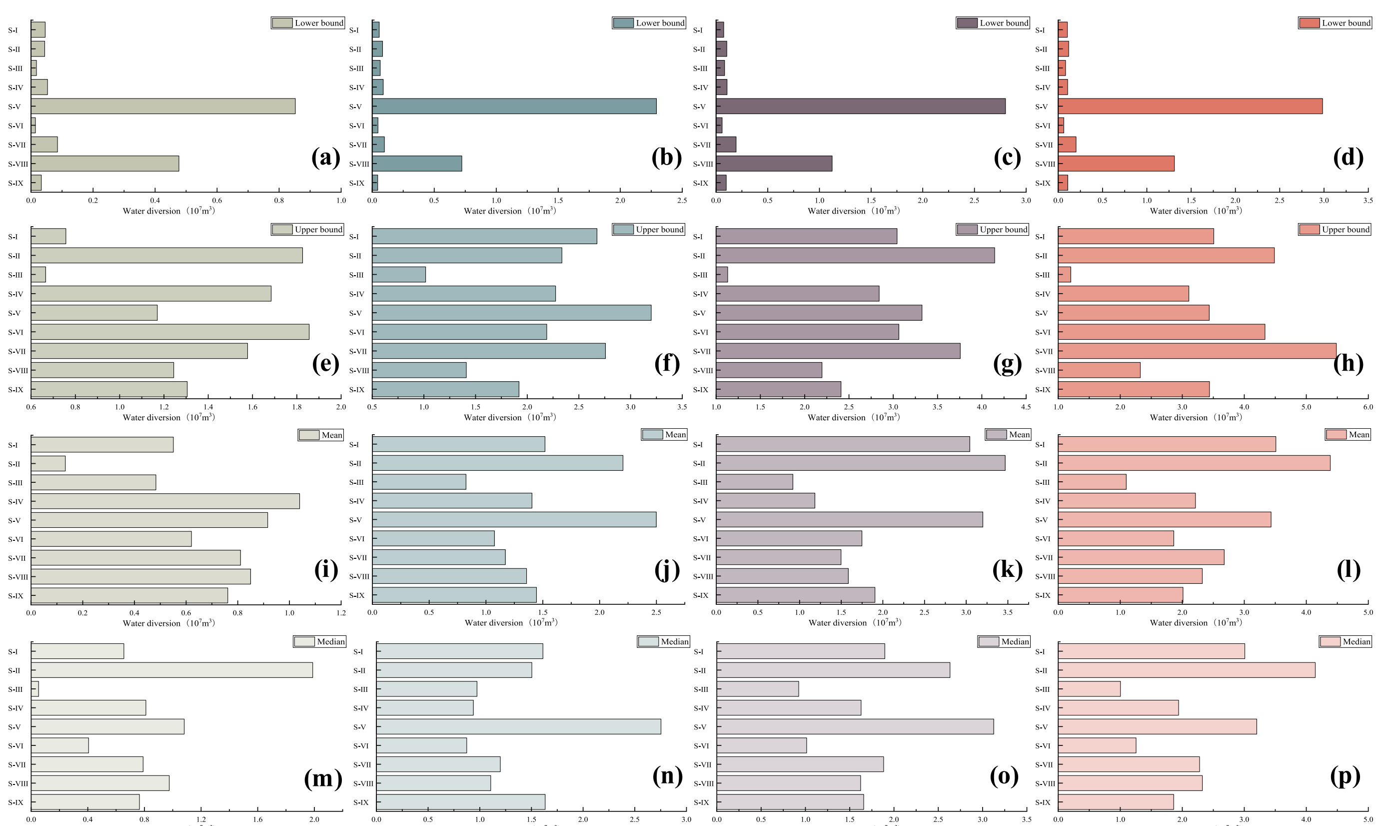

Fig. 8. Water diversion volume of all canals (a ~ d) Lower limits of the trunk canals: (a) west, (b) south, (c) north, (d) east. (e ~ h) Upper limits of the trunk canals: (e) west, (f) south, (g) north, (h) east. (i ~ l) Mean values of the trunk canals: (i) west, (j) south, (k) north, (l) east. (m ~ p) Median values of the trunk canals: (m) west, (n) south, (o) north, (p) east.

exhibits significant variability. This phenomenon is indicative of the flexibility and uncertainty in canal diversion regulation during periods of flooding. The upper limit of water diversion in the west trunk canal is 1.86×10^7 m^3, and the lower limit is reduced to 1.41×10^5 m^3. The discrepancy between the upper and lower limits exhibits a marked increase. It is plausible that the drainage conditions in the area surrounding the canal have undergone a shift. The volume of water that is diverted must be modified in a substantial manner in accordance with the prevailing circumstances to align with the flood control and drainage of the entire irrigation area. When water resources are stable or sufficient, the difference between the lower and upper limit values is relatively small, indicating that the distribution of water resources is regular and certain in normal climate. The lower limit of water diversion from the north trunk canal is 9.91×10^5 m^3, and the upper limit is 2.41 $\times$ 10^7 m^3. The decline in the lower limit of water diversion is associated with the distribution of precipitation in the region during the time period. Precipitation replenished soil moisture to a certain degree, thereby reducing the dependence on canal diversion. The upper limit diversion volume is determined in accordance with long-term water supply and demand balance considerations. This approach is designed to guarantee the availability of sufficient water reserves to address the potential for short-term droughts or periods of elevated water use under typical conditions.

The mean value of water diversion decreased from 1.17×10^7 to 3.31×10^6 m^3, concurrent with a synchronized decrease in the median value as water resources gradually decreased (Fig. 9). As water stress escalates, the majority of regional water diversions are concentrated at lower levels. In instances where precipitation levels are high yet regional water utilization exhibits significant variation, the mean value experiences substantial fluctuations within the range of 1.06–2.75 $\times$ 10^7 m^3. The utilization of water resources and the degree of demand in different regions result in significant variations in the mean value of water diversion. In instances where the water resource supply remains relatively stable, the fluctuation of the mean value of water diversion is less than about 15 %, and the median stability is higher. This aligns with the established crop water demand law. The distribution of water resources is deemed to be both reasonable and sustainable, ensuring that the water requirements for crop growth are adequately met.

5.4. Analysis of economic benefits and fairness of water allocation

The economic benefits demonstrate a discernible shift (Fig. 10). Economic benefits demonstrate a downward trend during periods of water stress. The value increased from 9.52×10^8 yuan in S-I to 1.06×10^9 yuan in S-II, then decreased to 8.76×10^8 yuan in S-III, and subsequently rebounded to 1.07×10^9 yuan in S-IV. This discrepancy may be attributable to variations in drought severity and the diverse coping strategies employed by the irrigation districts. During periods of severe water scarcity, agricultural production experienced a decline, resulting in a decrease in economic efficiency. Adopting effective water-saving irrigation and crop adjustment measures by irrigation districts has been demonstrated to improve economic benefits to a certain extent. The economic benefit exhibits significant variability in periods of extreme precipitation. The economic benefit reaches 4.85×10^9 yuan at S-V, while it drops sharply to 7.58×10^8 yuan at S-VI. This phenomenon may be attributed to the effective utilization of water resources by the irrigation district at S-V, despite the presence of flood risk. For instance, the implementation of water storage facilities has proven to be a strategy for the collection and storage of excess water, which can subsequently be utilized for irrigation or other production activities. This approach has yielded substantial economic benefits. In contrast, the flooding experienced in S-VI has resulted in a more significant impact on agricultural production facilities and crops. This dynamic precipitated a precipitous decline in economic benefits. In typical circumstances, the economic benefit is characterized by its stability and considerable magnitude. The economic benefit exhibited an increase from 1.35×10^9 yuan at S-VII to

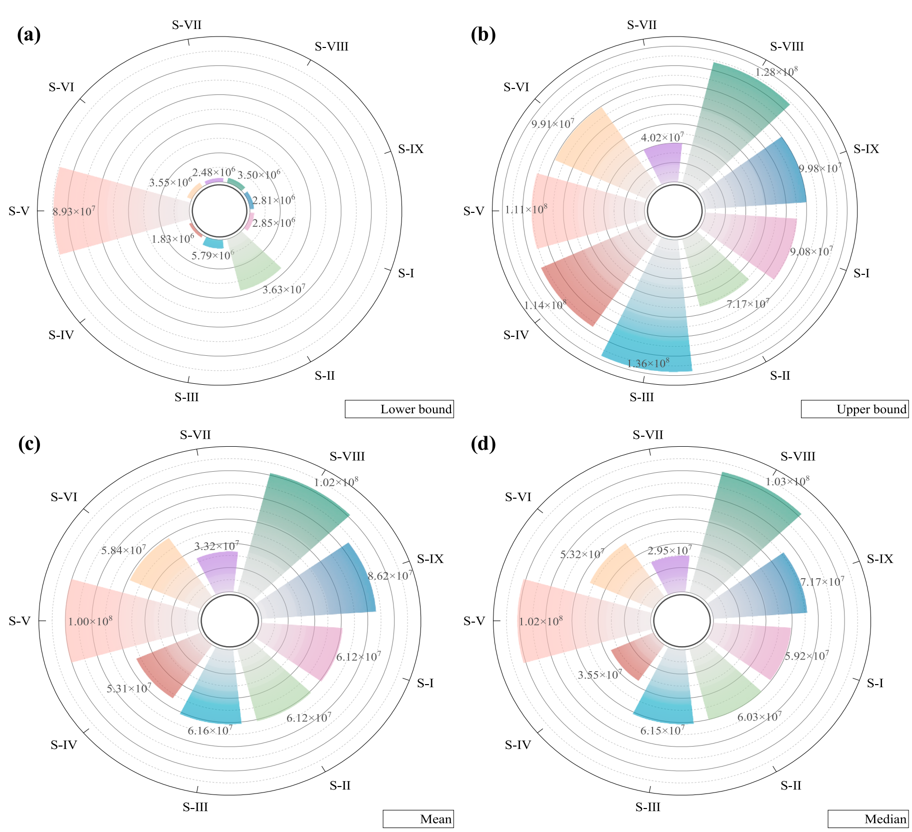

Fig. 9. Total water diversion volume (a) lower bound, (b)upper bound, (c)mean value, (d) median value.

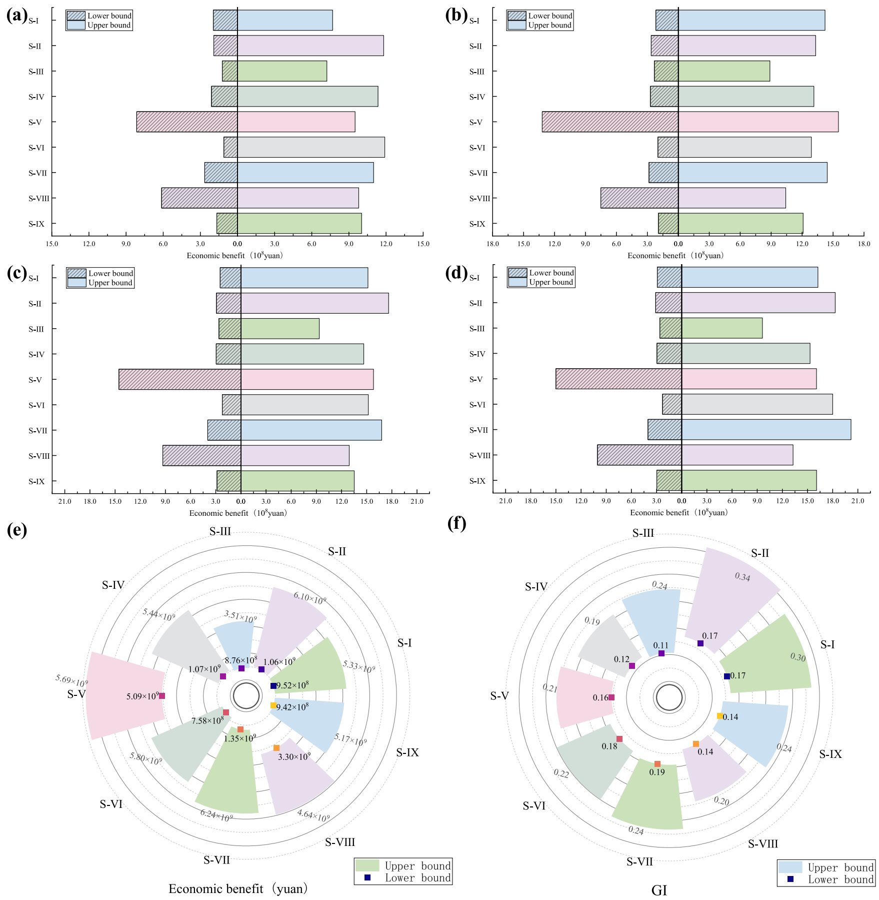

Fig. 10. Economic benefits and GI (a) economic benefits of the west trunk canal, (b) economic benefits of the south trunk canal, (c) economic benefits of the north trunk canal, (d) economic benefits of the east trunk canal, (e) total economic benefits, (f) GI.

3.30×10^9 yuan at S-VIII, followed by a decline to 9.42×10^8 yuan at S-IX. This phenomenon may be associated with stable crop growth under normal climatic conditions and adequate availability and rational allocation of water resources. A substantial enhancement in economic efficiency was observed at S-VIII, attributable to a confluence of factors. These factors include enhanced market prices for crops, refined agricultural production techniques, and augmented water use efficiency.

The GI is a metric of fairness in the distribution of water resources among the canals. The range of GI is between 0.02 and 0.29 from S-I to S-IV, which is relatively low overall. This indicates that the distribution of water resources is relatively fair under drought conditions. The GI of S-IV is only 0.02, indicating that the difference in water resource allocation among the canals is negligible at this time. The irrigation district has adopted a strict equitable allocation strategy, prioritizing the basic survival water needs of each region to reduce the impact of drought on the whole irrigation district. The GI ranges from 0.16 to 0.22 in instances where precipitation abundance necessitates the rational allocation of water resources. It is imperative to consider the water requirements of key regions and other regions to ensure equitable distribution and promote coordinated regional development. In instances where water

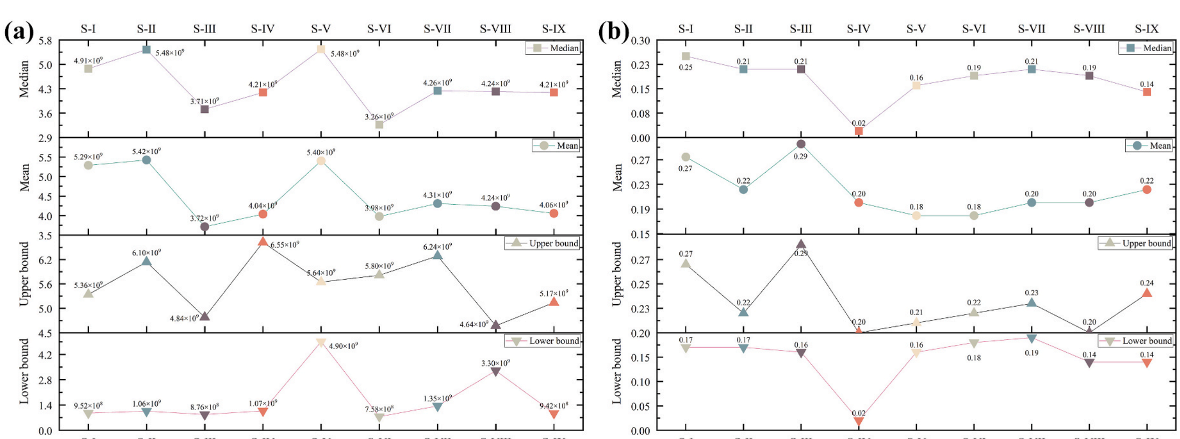

Fig. 11. Comprehensive analysis of the calculation results of the BLMOP model (a) economic benefits, (b) GI.

resources are stable or sufficient, the GI typically ranges from 0.14 to 0.24, falling below 0.3. This approach ensures that the fundamental water rights and interests of each region are safeguarded, while simultaneously facilitating the prioritization and allocation of water resources to regions or industries that can generate higher economic benefits. An effective balance between efficiency and equity is achieved.

The comprehensive results of BLMOP model calculations are analyzed (Fig. 11). The alterations in canal flow, water deficit, and water diversion are influenced by a multitude of factors, including climate, crop water demand patterns, and project scheduling. Water resources allocation must be informed by the findings of a scenario simulation, thereby facilitating the development of diversified strategies. In circumstances where water resources are limited, it is imperative to reinforce water conservation measures to ensure the prioritization of critical water needs. When precipitation is abundant, it is imperative to optimize flood control measures and the scheduling of flood discharges. In the typical case, a balanced water allocation pattern is maintained, and a buffer is set aside. This study offers a quantitative foundation for the management of water resources under various scenarios within the irrigation area. Subsequent studies could deepen the analysis of scenario-driven mechanisms in conjunction with long-term monitoring data to improve the efficiency and science of water allocation.

6. Discussion

6.1. Performance of the framework

The BN, IPP, and BLMOP model coupling framework constructed in this study with reference to SDG2, SDG6, and SDG13 provides a flexible framework for agricultural water management in irrigation districts. The BN constructs dynamic associations between climate factors and water diversion through a probabilistic graphical model and identifies multiple types of typical scenarios based on historical meteorological data (Shi et al., 2020). This model quantifies the nonlinear effects of precipitation, temperature, evaporation, and other factors on water diversions. The BN is responsible for providing scenario inputs that are characterized by an element of uncertainty. These inputs are subsequently utilized for the purpose of optimization. This data-driven scenario analysis overcomes the limitations of traditional models that rely on historical averages. It is able to capture the fluctuating characteristics of water diversion under multi-factor interactions (Bozorgi et al., 2021). The water diversion range, as determined by the BN, can be directly embedded in the range parameters of the BLMOP model. This approach ensures that the range boundaries align more closely with the actual uncertainty distribution. The propagation of uncertainty from variable correlation to parameter distribution is facilitated by probabilistic inference within the BN. Subsequently, the model is to be solved and subsequently passed to the objective function and constraint conditions. Ultimately, this transfer is reflected in the interval range of the output results. The incorporation of BN into the BLMOP model serves to augment the capacity to manage uncertainty, correlation, and dynamics. This augmentation is complementary to the interval planning and fuzzy decision-making processes inherent to the BLMOP model. This approach ensures that the propagation of uncertainty from the source parameters to the final decision-making plan is both more accurate and more in line with the actual system characteristics.

The BLMOP model demonstrates the organic unity of the macro and micro decision-making through a hierarchical structure. The upper-level model commences with the entire irrigation area, with economic efficiency and distribution equity serving as its primary objectives. When considered in conjunction with the total water resources constraints and the limitations of the canal project scale, it establishes the interval of water diversion for trunk canals. It has the potential to optimize the efficiency and equity of regional development. The lower-level model emphasizes canal-scale scheduling and is oriented to minimizing water shortage and water transmission loss. By dynamically optimizing the distribution flow and time period, the efficiency and reliability of water use at the grassroots level are enhanced. This objective is consistent with the SDG6, which aims to ensure equitable distribution of water resources. It also establishes the foundation for the allocation of water resources, ensuring the agricultural production in each region of the irrigation districts and thereby enabling the realization of SDG2. In comparison with the conventional single-objective optimization model, this hierarchical structure possesses the capacity to address the demands of agricultural production and social equity in a holistic manner through the multi-objective synergistic optimization mechanism. The decision-making mechanism is characterized by increased systematicity and comprehensiveness, thereby fostering favorable conditions for the synergistic realization of SDGs within the irrigation districts (Dong et al., 2016; Chen et al., 2023).

6.2. Comparison among models

From the available research, it appears that conventional deterministic models frequently determine outcomes by referencing historical mean data, such as the allocation of farmland irrigation based on predetermined irrigation quotas and scheduling (Li et al., 2010). In the face of uncertainties such as temperature fluctuations and uneven precipitation, attributable to climate change, the efficacy of these models is frequently called into question. A comparison of stochastic programming with simple stochastic programming models reveals that, while stochastic programming also attempts to handle uncertainties, it still has limitations in constructing complex variable relationships and multi-objective trade-offs. The stochastic planning model attempts to address the uncertainty problem to a certain extent. However, there are evident deficiencies in the model's design, particularly in the establishment of the relationship between complex variables and the synergistic optimization of multiple objectives. It is challenging to delve more profoundly into the intricate causal relationships between variables. Furthermore, it is incapable of achieving scientific and rational trade-offs between numerous objectives, which hinders the fulfillment of the genuine demand for synergistic promotion of multi-dimensional sustainable development objectives in irrigation districts.

This paper combines the probabilistic reasoning of the BN with the structured decision-making advantages of the BLMOP model, organically integrating these factors and optimizing decisions from macro to micro. This approach is instrumental in guaranteeing the judicious utilization of water resources while concurrently facilitating adaptable responses to contingencies (Wang et al., 2022). During the water resource allocation process, the BLMOP model has the capacity to formulate risk response strategies based on the uncertainty information provided by the BN (Zhou et al., 2023). In the event of alterations to the external conditions of the irrigation area, the model has the capacity to swiftly adapt to the novel circumstances. By modifying the network structure, adjusting parameters, or optimizing the objective function, it is possible to reformulate water resource allocation strategies that meet the new requirements. To illustrate, in instances where a decline in precipitation is predicted, accompanied by an escalation in demand for water diversion within a designated time frame, the model has the capacity to proactively optimize the allocation of water volume among primary canals and secondary canals. The primary objective of this initiative is to ensure the adequate hydration of pivotal areas and crops. This flexibility will assist irrigation districts in optimizing their water resources management in the long-term development process and in coping with the challenges posed by various internal and external changes. It offers a novel and efficacious approach to implementing the SDGs in irrigation districts.

A comparison of this research framework with other current emerging models reveals its distinct advantages. A subset of emerging models prioritize the optimization of a singular objective, such as the maximization of economic benefits, while disregarding the equity objective (Habibi Davijani et al., 2016). The model's inability to optimize the comprehensive benefits of water allocation is a salient issue. In the context of addressing uncertainty, alternative models have been observed to employ elementary stochastic simulation methodologies. The inability to thoroughly analyze the probabilistic relationships between variables, as facilitated by Bayesian networks, hinders the effective management of the intricate impacts of climate change on water resources systems within irrigation districts. The framework of this study realizes the comprehensive optimization of multi-objectives and the in-depth treatment of uncertainty through the deep coupling of multi-models, which provides scientific decision support for irrigation district water resources management.

6.3. Practical implications

The empirical application of the framework has shown that it is able to effectively address the challenges of water use under different climatic conditions. The model under consideration in this paper takes into account the uncertainties associated with precipitation and temperature due to climate change. It also allocates a certain degree of elasticity in the optimization process. The upper-level model prioritizes the maximization of economic benefits. The utilization of indicators such as the GI serves to regulate the equitable distribution of water resources. This measure is intended to prevent the over-occupation of water resources by certain canals or regions, which has the potential to result in the harm of other regions' interests due to the over-pursuit of economic interests. When addressing grassroots water demands, the lower-level model enhances the fairness of water resource allocation (Sjah and Baldwin, 2014). This approach is designed to ensure that each lower-level canal and water user can access a satisfactory water supply at different times. The collaborative optimization of the upper and lower models has been demonstrated to significantly enhance water resource utilization efficiency (Cai et al., 2021). The upper-level model reasonably allocates different water sources to each backbone canal. This strategy has been demonstrated to effectively mitigate the risk of over-concentration and the subsequent inefficient usage of water resources within the canals. The lower-level model meticulously regulates the water distribution flow of each canal during distinct periods. This approach has been demonstrated to reduce water conveyance losses and minimize ineffective evaporation and seepage in agricultural fields.

In response to a range of climate-related circumstances, the present framework is designed to implement the application of multidimensional optimization mechanisms. Its configuration schemes for different scenarios can support policies that control regional water consumption. It also provides data references for managing agricultural water under uncertainty. In the context of drought scenarios, the upper- and lower-level models collaborate to function in unison, thereby enabling the irrigation district to prioritize meeting the fundamental water requirements of key crops and critical areas (Multsch et al., 2017). By implementing a strategic adjustment to the water resource allocation structure, there is potential to enhance the efficiency of water resource utilization, thereby mitigating the adverse impact of drought on agricultural production (Kahil et al., 2015). For instance, an increase in the water supply to areas where drought-tolerant crops are cultivated is recommended. The optimization of irrigation methods is crucial, encompassing the implementation of water-saving techniques such as drip and sprinkler irrigation. It is imperative to curtail water usage per unit area to ensure the preservation of elevated agricultural yield while confronting the constraints imposed by limited water resources. In scenarios involving flooding, the model exhibits a remarkable capacity for rapid adaptation. It has been demonstrated to modulate the water diversion volume of canals, thereby ensuring optimal drainage strategies are in place. This proactive adjustment has been shown to effectively enhance the flood control and drainage capabilities of the region. By taking this action, the occurrence of canal overflow and water logging in farmland is prevented. Consequently, the water conservancy facilities within the irrigation district and the ecological environment of the farmland are safeguarded. Specifically, certain canals are designated as flood discharge canals for the expeditious drainage of excess water. In the aftermath of the recession of the flood, water resources are allocated with meticulous care for the purpose of post-disaster recovery irrigation. The objective of this allocation scheme is to promote the growth and restoration of crops. In typical circumstances, the model demonstrates a commitment to preserving the long-term, stable equilibrium of water resource supply and demand within the designated irrigation area. While ensuring economic benefits, it also places significant emphasis on the fairness and sustainability aspects of water resource allocation. This comprehensive approach facilitates the attainment of a balanced equilibrium among the various factors involved in the management of water resources.

7. Conclusions

In this study, an agricultural water management framework coupling BN, IPP, and BLMOP models is constructed to address the uncertainty challenges of water allocation in irrigation districts under climate change. The BN identifies nine types of typical scenarios by integrating seasonal, precipitation, temperature, evaporation, and other multi-source data. The upper-level model places emphasis on the optimization of economic efficiency and equity in irrigation districts. The lower-level model focuses on canal water use efficiency and loss control. In various scenarios, the model is capable of making rational adjustments to the water allocation strategy in accordance with the actual situation. This approach has the potential to effectively address the challenges posed by climate change while ensuring the preservation of economic efficiency and social equity. The main conclusions of this study are summarized as follows.

(1) A multi-scenario water diversion analysis was conducted based on the BN. It is employed to quantify the probabilistic impact of multi-climatic factors on water diversions by integrating multi-source data, including season, precipitation, temperature, and evaporation. Eleven scenarios are constructed and nine types of typical scenarios are screened. In light of the numerous uncertainties associated with climate change, the BN has been developed for probabilistic prediction of key variables based on limited observational data and prior knowledge. This analysis is essential for the subsequent construction of models, as it provides a significant database.

(2) The BLMOP model has been demonstrated to achieve cross-scale optimization and multi-objective equilibrium. The upper-level model encompasses economic and social effect objectives. The primary objective of the lower-level model is to minimize water shortages and canal delivery water loss. Multi-objective functions are converted to single-objective functions through the application of fuzzy mathematical planning. The TOPSIS method has been demonstrated to be a viable approach for addressing the interval parameters inherent within the model. The constructed model was solved using a genetic algorithm. The model demonstrates an aptitude for the rational allocation of water resources under various scenarios. For instance, in S-I, the lower limit of water diversion of the west trunk canal is 4.57×10^5 m^3 which decreases to 3.31×10^6 m^3 in S-III. It reflects the dynamic adjustment of water resources allocation in response to variations in drought severity, thereby adapting to different water resources conditions.

(3) The scenario-driven strategy ensures the dynamic adaptability of water allocation. The BLMOP model for optimal allocation of regional water resources can ensure the fairness while ensuring the rationality of the water allocation scheme. The integration of macro and micro levels is achieved through the interaction of data between the lower-level model and the upper-level model. The upper-level is responsible for implementing a water

allocation scheme based on overall efficiency. The lower-level components are responsible for the detection of water shortages and losses during operation. This enables the system to respond quickly to changes in precipitation fluctuations, planting structure adjustment, etc., and maintains the rationality and adaptability of the water allocation scheme. The findings indicate that the aggregate benefit of the irrigation district under the normal scenario can reach 3.30×10^9 yuan. The fluctuation in the mean value of water diversion is less than about 15 %. The GI is maintained within the range of 0.02–0.29 to ensure distributional equity at the regional scale.

The findings of this study offer novel methodologies and tangible illustrations for the management of water resources in agricultural contexts. In the long term, the optimized allocation scheme of the upper and lower models contributes to the sustainable use of water resources in the irrigation district. Nevertheless, the model exhibits certain limitations. For instance, the determination of conditional probability relationships in the BN may contain some inaccuracies, and the efficiency of the solution algorithm for the BLMOP model could be enhanced. Future research could further optimize the methods for determining model parameters and explore more efficient solution algorithms. Concurrently, a more comprehensive consideration of influential factors is imperative to ensure the continuous enhancement of the water resource allocation model for irrigation areas and the augmentation of the level of water resource management in these areas.

CRediT authorship contribution statement

Lingzi Wang: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Rengui Jiang:** Writing – review & editing, Supervision, Funding acquisition. **Yong Zhao:** Writing – review & editing, Formal analysis, Conceptualization. **Jiancang Xie:** Writing – review & editing, Conceptualization. **Xiao Zhang:** Writing – review & editing, Methodology. **Ganggang Zuo:** Writing – review & editing. **Simin Wang:** Writing – review & editing, Formal analysis. **Xixi Lu:** Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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