Water management for industrial development, energy conservation, and subjective attitudes: a comprehensive risk-oriented model to explore the tolerance of unbalanced allocation problem

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ABSTRACT

In this study, a new concept concerning comprehensive characteristics of water resources utilization as an index for risk modeling within the water allocation management model is proposed to explore the tolerance of unbalanced allocation problem under water–energy nexus. The model is integrated with interval two-stage stochastic programming for reflecting system uncertainties. These uncertainties are associated with the industrial production feature and the decision-making process. With respect to water–energy nexus, energy proposed is mainly focused on the consumption intensity of water purification and transportation from different water sources. The developed model is applied for industrial water resources allocation management in Henan province, China. Multiple scenarios related to disparate energy consumption control and the comprehensive risk levels are simulated to obtain a reasonable trade-off among system profit, comprehensive risk, and energy consumption. The results indicated that the strict comprehensive risk management or energy consumption control measures could cause damage to system benefit owing to decreasing the flexibility of industrial water resources distributions, and the preliminary energy consumption or the comprehensive risk control would be beneficial to moderate the conflict between industrial sectors and water resources, and accelerate industrial structure transformation in the future.

Key words: comprehensive risk, energy consumption control, optimization model, unbalanced allocation, water management

HIGHLIGHTS

- A comprehensive risk-oriented industrial water resources management model is proposed.
- Uncertainties are reflected as stochastic and interval information.
- Energy–water nexus is a constraint index for water purification and transportation.
- The tolerance of unbalanced allocation problem is explored.
- Trade-off among system profit, comprehensive risk, and energy consumption is analyzed.

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1. INTRODUCTION

Water and energy resources are the most significant factors in the industrial system, and the related problems with diminishing water resources, a higher consumption and pollution, and a lower production and inefficiency are being challenges for balancing water resources allocation among sectors in industrial system management. Some measures (e.g., multi-period water network management, sustainable industrial water projection, and a multi-hierarchy industrial virtual water network) have been proposed for improving industrial water resources management, perfecting water resources value, and reducing cumulative environmental risk (Liu et al. 2017; Shrestha & Wang 2020; Xie et al. 2020; Yu et al. 2020; Fu et al. 2021; Haque et al. 2021; Tian et al. 2021). However, the complexities and the uncertainties in industrial water resources system, such as the complexities of energy–water nexus and the spatial and temporal variations of system parameters, exacerbate the difficulties in regional industrial water resources management (Qin et al. 2015; Lu & Chen 2016; Guo et al. 2020; Shao et al. 2020; Lee et al. 2021). Faced with increasing water shortage crisis and extensive industrial leviathan development, effective measures/approaches for industrial water resources management are needed to reveal the interaction relationship between energy and water, and balance production benefit and risk control among industrial sectors under uncertainty.

Previously, various of inexact optimization techniques were proposed for industrial water resources management under considering multiple system uncertainties (Huang et al. 2019; Gao et al. 2021; Yu et al. 2021). For example, Aviso et al. (2010) advanced a bi-level fuzzy optimization model to research the influence of water charge and the cost of sewage treatment on the eco-industrial water interchange system. Ren et al. (2013) proposed a stochastic fractional programming to maximize economic benefits related to the efficiency of water resources in industrial system management. Li et al. (2016) advanced an inexact stochastic multiple objective programming to optimize the management structure between industry and water environment under uncertainty. He et al. (2018) developed an industrial water resources management through integrating interval chance-constrained programming for addressing uncertainties as random and interval information. Dadmand et al. (2020) advanced a robust fuzzy stochastic programming model for water resources allocation, where the sustainability index and groundwater resources are integrated.

There are many uncertainties in the industrial water resources management system, such as available water resources and economic or resources income/outcome for industrial sectors. These uncertainties could be expressed in the probability distribution function and discrete interval in the water resources planning system, and that could be associated with the industrial production feature and the decision-making process. Among the proposed methods, interval two-stage stochastic programming (ISTP) could effectively deal with the uncertainty and be widely used for industrial water resources system management. In addition, if the scheduled target is violated, ISTP could solve the recourse action issues, through financial penalties for corrective measures (Maqsood & Huang 2003; Xie et al. 2018; Yin et al. 2021). For example, Xu et al. (2012) advanced an inexact two-stage stochastic programming integrated with the water quality simulation model for
water resources management and water quality improvement among different industries in a river basin. Yue et al. (2017) advanced a two-stage stochastic programming for industrial adjustment under considering sustainable water and energy utilization. From the above analysis, industrial water resources management with different system objectives under uncertain information can be addressed through ISTP.

However, most studies focused on searching the relationship between energy and water in the regional energy system or the water resources system through ecological network analysis (Wang & Chen 2016; Wang et al. 2018; Xu et al. 2021) and input–output analysis (Okadera et al. 2015; Chen et al. 2018; Lin et al. 2019; Tian et al. 2019). Few studies brought energy consumption control for water sources optimization under considering energy–water nexus in water delivery, purification, allocation, and wastewater treatment. Meanwhile, the risk for the unbalanced water resources allocation among industrial sectors has been considered in the previous studies (Gallagher et al. 2016; Hu et al. 2016; Fu et al. 2018; Li et al. 2020). In these studies, the risk is directly expressed through the difference between the water resources requirement and the actual water amount. However, the comprehensive characteristics of water resources utilization in each sector seldom are considered and could weaken the impact of risk on the system. To trade-off above-mentioned impacts, the benefit for industrial water resources utilization, the cyclic utilization of water resources, and the sewage discharge take into consideration as the comprehensive risk in this study. Therefore, the objective of the study is to propose a comprehensive risk-aversion approach through integrated with the traditional risk measurement and the risk-mitigation coefficient as random and interval values in the industrial water resources system. The proposed model is used for solving industrial water resources allocation problem under considering surface water, groundwater, diverted water, and reused water in Henan province, China. The optimized solutions under different scenarios could be used for generating sustainable industrial development plans and water resources allocation schemes.

2. MODEL DEVELOPMENT

2.1. Model framework

To analyze multiple uncertainties and energy–water nexus influence for the industrial water resources allocation system, and search the relationship between unbalanced-allocation risk and system benefit, a comprehensive risk-oriented industrial water resources management model was proposed from the following aspects (Figure 1): (1) Keeping sustainable industrial production development and water resources exploitation is crucial under multiple uncertainties. Therefore, water resources management department needs to confirm water resources allocation amount to each industrial sector before the variables of total water resources are ascertained. And making an adjustment of the pre-allocation schemes is also necessary after the variables of total water resources are ascertained. The inexact two-stage stochastic programming that incorporated with interval-parameter programming (Huang 1996; Xia et al. 1997; Piluso & Huang 2009) and two-stage stochastic programming (Dai et al. 2000; Darby-Dowman et al. 2000; Maqsood et al. 2005) could successfully reflect the decision process of industrial water resources management and effectively handle the interval and random information as the representation of system uncertainties. (2) For making reasonable and balanced water allocation strategies among industrial sectors, a comprehensive risk-aversion approach is proposed through integrated with the traditional risk measurement and the risk-mitigation coefficient that are related with the characteristics of water resources utilization of each sector into a general framework. (3) Considering energy consumption in water delivery, purification, allocation, and wastewater treatment, the total energy consumption control is brought into the optimization model for searching the interaction relationship between energy intensity and water resources allocation, and gaining green and low carbon oriented industrial water resources management schemes.

2.2. Comprehensive risk-aversion approach

The risk of water resources allocation can be defined as the difference between the water resources requirement and the actual supply amount, and the traditional risk measurement can be expressed as follows:

\[
Risk_i = \Omega_i - \tilde{z}_i
\]

(1a)
where $V_i$ denotes the water resources requirement for industrial sector $i$, and $z_i$ denotes the water allocation amount for industrial sector $i$.

To control the risk of each industrial sector, the risk-aversion approach can be expressed by introducing the risk-mitigation coefficient ($d_i$).

$$\text{Risk}_i \leq d_i \cdot \Omega_i, \forall i$$

(1b)

In general, the coefficient was set by the decision-makers with a subjective willingness that would lead to an unbalanced water resources allocation scheme among industrial sectors. Therefore, under considering wastewater production rate, water resources reuse, and the benefit for water resources utilization in the industrial system, a comprehensive risk-mitigation coefficient is proposed as follows:

$$d_i = d_1 \cdot \frac{f_i}{J_{\text{max}}} + d_2 \cdot \frac{R_{\text{max}} - R_i}{R_{\text{max}}} + d_3 \cdot \frac{BNT_{\text{max}} - BNT_i}{BNT_{\text{max}}}$$

(1c)

where $f_i$ is the wastewater producing coefficient of per industrial water consumption for industrial sector $i$; $R_i$ denotes the reuse ratio of per water resources; $BNT_i$ is the benefit of per water resources allocated to industrial sector $i$; $J_{\text{max}}$ denotes the maximum in all $J_i$; $R_{\text{max}}$ denotes the maximum in all $R_i$; $BNT_{\text{max}}$ denotes the maximum in all $BNT_i$; and $d_1$, $d_2$, and $d_3$ are the compensation coefficients.

The comprehensive risk-aversion approach could make a close relationship between water shortage risk and water consumption features for each industrial sector and promote industrial eco-development for improving water efficiency.

### 2.3 Interval two-stage stochastic programming

Considering interval and random information in industrial water resource system management, an inexact two-stage stochastic programming can be described as follows (Birge & Louveaux 1988; Huang & Loucks 2000; Li & Huang 2006; Li &
Huang 2009):

\[
\begin{align*}
\text{max } f^\pm &= \sum_{i=1}^{M} c_i^\pm x_i^\pm - \sum_{i=1}^{M} \sum_{s=1}^{N} p_s Q(y_i^+, \omega_s^+) \\
\text{Subject to:} & \\
\alpha^\pm x_i^\pm &\leq b^\pm \\
T(\omega_s^+) x_i^+ + W(\omega_s^+ ) y_i^+ &= H(\omega_s^+) \\
x_i^+ &\geq 0, y(\omega_s^+) \geq 0
\end{align*}
\] (2a)

where \(i\) denotes the industrial sectors; \(x_i^\pm\) denotes the allocation target of water resources for industrial sector \(i\); \(c_i^\pm\) is the net benefit of per water resources allocated for industrial sector \(i\); \(s\) is the scenario for available water resources; \(p_s\) denotes the popularity of the scenario \(s\) happening; \(\omega_s^\pm\) is the amount water resources of the scenario \(s\); \(Q(y_i^+, \omega_s^+)\) denotes the penalty of the scenario \(s\) happening in the second stage; \(\sum_{s=1}^{N} p_s Q(y_i^+, \omega_s^+)\) is the expected values of penalty in the second stage; and \(T(\omega_s^+), W(\omega_s^+)\), and \(H(\omega_s^+)\) denote the interval parameters and/or the variables of model parameters. Thereinto, superscript ‘\(\pm\)’ denotes the interval parameter/variable; the ‘\(-\)’ and ‘\(+\)’ represent the lower and upper bounds of the interval parameter/variable.

2.4. Model development

Generally, the main water sources are surface water, groundwater, diverted water, and reused water. There is a competitive relationship for water resources allocation among major industrial sectors. Factors related to industries production, water resources consumption, and energy utilization are significant for maximizing system benefits, including (i) benefits acquired from water resources consumption and the penalties under the situation of insatiable pre-target, (ii) cost for water resources purchase and purification, and (iii) cost for reused-water treatment and wastewater treatment. The constraints are closely related to the decision variable and a series of water resources balance, which includes available water resources, wastewater treatment, energy consumption control, and the risk of unbalanced allocation. Meantime, the randomly available precipitation and different risk-aversion policies are considered. Therefore, a comprehensive risk-oriented industrial water resources management model is developed as below:

\[
\begin{align*}
\text{max } f^\pm &= S^\pm - \sum_{j=1}^{n} C_j^\pm \\
(1) \text{ Total benefit of industrial sectors:} & \\
S^\pm &= \sum_{i=1}^{n} \sum_{l=1}^{3} \sum_{h=1}^{3} (S_{il}^\pm - P_h \cdot QSW_{ilh}^\pm + GW_{ilh}^\pm + P_h \cdot RW_{ilh}^\pm) \cdot BNT_{ilh}^\pm \\
(2) \text{ Cost for water resources purchase:} & \\
C^\pm &= \sum_{i=1}^{n} \sum_{l=1}^{3} \sum_{h=1}^{3} (S_{il}^\pm - P_h \cdot QSW_{ilh}^\pm + GW_{ilh}^\pm) \cdot CWS_{ilh}^\pm + \sum_{i=1}^{n} \sum_{l=1}^{3} IW_{ilh}^\pm \cdot CIW_i^\pm \\
(3) \text{ Cost for reused-water purification:} & \\
C_i^\pm &= \sum_{i=1}^{n} \sum_{l=1}^{3} \sum_{h=1}^{3} RW_{ilh}^\pm \cdot P_h \cdot CWR_i^\pm
\end{align*}
\]
(4) Cost for surface water groundwater and diverted-water purification:

\[
C_4^± = \sum_{t=1}^{n} \sum_{i=1}^{n} \sum_{h=1}^{3} (SW_i^{±} - P_h \cdot QSW_{ih}^{±} \cdot SWP_i^± + GW_i^{±} \cdot GWP_i^± + IW_i^{±} \cdot IWP_i^±)
\]  

(5) Cost for wastewater treatment:

\[
C_5^± = \sum_{t=1}^{n} \sum_{i=1}^{n} \sum_{h=1}^{3} (SW_i^{±} - P_h \cdot QSW_{ih}^{±} + GW_i^{±} + IW_i^{±} + P_h \cdot RW_{ih}^{±}) \cdot WTP_i^±
\]  

(6) Penalty for the second-stage:

\[
C_6^± = \sum_{t=1}^{n} \sum_{i=1}^{n} \sum_{h=1}^{3} P_h \cdot QSW_{ih}^{±} \cdot BNT_{ih}^{±} \cdot 0.2
\]

where \(i\) denotes the industrial sectors; \(t\) denotes the planning period; \(h\) is the level of available surface water resources, including medium and high levels; \(SW_i^{±}\) represents the allocation target of surface water resources for industrial sector \(i\) in period \(t\) (10^6 m^3/year); \(GW_i^{±}\) and \(IW_i^{±}\) denote the groundwater and diverted-water allocation amount for industrial sector \(i\) in period \(t\) (10^6 m^3/year); \(P_h\) is the probability of the available surface water resources in each level; \(QSW_{ih}^{±}\) is the water shortage amount for industrial sector \(i\) (the second-stage variable) (10^6 m^3/year); \(RW_{ih}^{±}\) denotes the reused-water amount for industrial sector \(i\) (10^6 m^3/year); \(BNT_{ih}^{±}\) is the benefit of per water resources allocated to industrial sector (10^6 RMB/10^6 m^3); \(CWS_i^{±}\) is the water charge (10^6 RMB/10^6 m^3); \(CWR_i^{±}\) and \(CIW_i^{±}\) denote the cost of per reused-water treatment and of per diverted-water purchased (10^6 RMB/10^6 m^3); \(SWP_i^±\), \(GWP_i^±\), and \(IWP_i^±\) denote the purification cost for surface water, groundwater, and the diverted water (10^6 RMB/10^6 m^3); \(J_{ih}^{±}\) is the wastewater producing the coefficient of per industrial water consumption; and \(WTP_i^±\) is the cost of per wastewater treatment.

Subject to:

(1) Constraints for water supply and demand:

\[
\sum_{i=1}^{n} SW_i^{±} - QSW_{ih}^{±} \leq SWUA_{ih}^{±}, \forall t, h
\]  

\[
\sum_{i=1}^{n} GW_i^{±} \leq GWUA_i^{±}, \forall t
\]  

\[
\sum_{i=1}^{n} IW_i^{±} \leq IWUA_i^{±}, \forall t
\]  

\[
SWW_{ih}^{±} = SW_i^{±} - QSW_{ih}^{±}
\]

where \(SWUA_{ih}^{±}\) is the available water resources during period \(t\) under level \(h\) (10^6 m^3/year); \(GWUA_i^{±}\) denotes the available groundwater resources (10^6 m^3/year); \(IWUA_i^{±}\) represents the available diverted-water resources (10^6 m^3/year); and \(SWW_{ih}^{±}\) denotes the surface water allocation amount for industrial sector \(i\) during period \(t\) under level \(h\) (10^6 m^3/year).
(2) Constraints for energy consumption control:

\[
\sum_{i=1}^{n} (SW_{ih}^+ - P_h \cdot QSW_{ih}^+ + GW_{ih}^+ + IW_{ih}^+ + RW_{ih}^+) \cdot DE_i^+ \geq 0
\]

\[
\sum_{i=1}^{n} (SW_{ih}^- - QSW_{ih}^-) \cdot SE_i^- + GW_{ih}^- \cdot GE_i^- + IW_{ih}^- \cdot IE_i^- + RW_{ih}^- \cdot RE_i^- 
\]

\[
+ \sum_{i=1}^{n} (SW_{ih}^+ - QSW_{ih}^+ + GW_{ih}^+ + IW_{ih}^+ + RW_{ih}^+) \cdot J_i^+ \cdot JE_i^+, \forall t, h
\]

\[
RW_{ih}^+ = (SW_{ih}^+ - QSW_{ih}^+ + GW_{ih}^+ + IW_{ih}^+ + RW_{ih}^+) \cdot R_{ih}^+, \forall t, h
\]

where \(DE_i^+\) is the coefficient of energy consumption constraint for industrial sectors \(i\) in period \(t\); \(SE_i^-\), \(GE_i^-\), and \(RE_i^-\) denote the energy consumption coefficient for surface water, groundwater, and reused-water purification; and \(IE_i^-\) denotes the energy consumption coefficient for diverted-water purification and transportation. \(JE_i^+\) represents the energy consumption coefficient for wastewater treatment; \(R_{ih}^+\) denotes the reuse ratio of per water resources.

(3) Constraints for risk balance of industrial sectors:

\[
RISK_{ih}^+ = DW_{ih}^+ - (SW_{ih}^+ - QSW_{ih}^+ + GW_{ih}^+ + IW_{ih}^+ + RW_{ih}^+), \forall i, t, h
\]

\[
RISK_{ih}^+ \geq \xi \cdot DW_{ih}^+, \forall i, t, h
\]

\[
RISK_{ih}^+ \leq k \cdot \omega_{ih}^+ \cdot DW_{ih}^+, \forall i, t, h; i = 1, 2, \ldots, I
\]

\[
\omega_{ih}^+ = a \cdot \frac{J_i^+}{J_{\text{max}}^+} + b \cdot \frac{R_{ih}^{\text{max}} - R_{ih}^+}{R_{\text{max}}^+} + c \cdot \frac{BNT_{ih}^{\text{max}} - BNT_{ih}^+}{BNT_{\text{max}}^+}, \forall i, t
\]

where \(RISK_{ih}^+\) denotes the risk for industrial sectors \(i\) in period \(t\) under level \(h\) (10^6 m³/year); \(DW_{ih}^+\) denotes the water resources requirement; \(\xi\) is the risk management coefficient; \(\omega_{ih}^+\) is a comprehensive risk-mitigation coefficient; \(J_{\text{max}}^+\) denotes the maximum in all \(J_i^+\); \(R_{\text{max}}^+\) denotes the maximum in all \(R_{ih}^+\); \(BNT_{\text{max}}^+\) denotes the maximum in all \(BNT_{ih}^+\) (10^6 RMB¥/10^6 m³); and \(a, b, c, \) and \(k\) are the compensation coefficients. All nomenclatures for variables and parameters are shown in Supplementary Appendix B.

3. CASE STUDY

3.1. Overview of the study area

Henan province (31°23′–36°22′N, 110°21′–116°39′E) as the significant industrial and agricultural base is located in the middle part of China. As shown in Figure 2, the region contains 17 prefecture-level cities, 20 county-level cities, 54 municipal districts with an area of 167,000 km², and a permanent resident population of 96.4 million in 2019. The annual precipitation was 818.4 × 10³ m³, and 63.9% of the total rainfall was forced principally from June to September (WRBCQ 2019). As an important and powerful province, the total gross domestic product was RMB¥ 5,499.7 × 10³, with an added value of RMB¥ 553.5 × 10³, RMB¥ 2,875.7 × 10³, and RMB¥ 2,676.8 × 10³ of the primary, secondary, and tertiary industry in 2020. Along with the regional economic development and population growth, water shortage and unbalanced water resources distribution are the main water issues. In Henan province, the main water source includes surface water, groundwater, and diverted water. In 2018, the total water resources supply was 234.6 × 10³ m³ from surface water (96.5 × 10³ m³), groundwater (116.0 × 10³ m³), and the diverted water from south to north (16.1 × 10³ m³) (WRBCQ 2018). The total water resources consumption in Henan province was 168.9 × 10³ m³, and the available water resources of per capita was 237.8 m³ that reaches to 60–70% of the national level in 2019 (WRBCQ 2019). In addition, due to agriculture consumed more than 50% of the total water resources consumption amount, industrial production has faced more pressures from water shortage and unbalanced allocation among sectors.

In recent years, the total industrial output value in Henan province ranked 5th in China and 1st in the central and western provinces. The value of industrial enterprises has been showing positive growth since 2010, and the indices of value-added of industrial enterprises above designated still higher than 107.0 (preceding year = 100) (Figure 2) (HNSY 2019). However, high-
speed industrial development has brought intense energy consumption and a large amount of sewage discharge. For the industrial enterprises above designated size, the total energy consumption amount was $129.9 \times 10^6$ tons of standard coal, and the sewage discharge was $51.1 \times 10^6$ m$^3$ that accounted for about 19% of the total amount in the study area in 2019 (HNSY 2020). Faced with water resource shortage, energy consumption overload, and sewage mitigation pressures, to generate a reasonable and balance the industrial water resources allocation structure is more desired.

Besides, many complexities and uncertainties must be considered in industrial water resources management. Especially, the random variations of available precipitation and the uncertainties for benefit and cost of water resources utilization intensely impact the feasibility of water resources management scheme in the industrial system (Long et al. 2018; Ren & Toniolo 2021; Willet et al. 2021). Moreover, the system factors and their relationship are identified unclearly which lead to a series of challenging problems, such as (a) how to generate a plan to acquire the optimal net benefit in industrial water resources allocation under risk-aversion scenarios and energy consumption control scenarios; (b) how to balance water resources allocation for different industrial sectors considering a comprehensive system risk in regional industry system; and (c) how to identify the effect of energy consumption control on the industrial water resources allocation structure.

### 3.2. Data and scenario

To correspond with a regional medium-/long-term development plan, the planning horizon in this study is from 2021 to 2035 that is segmented into three periods, and each planning period lasts 5 years. All industry sectors are divided into 40 varieties as shown in Supplementary Appendix A.
From Henan water resources bulletin (2010–2019), the amount for available surface water resources in the industrial system is divided into three interval values that correspond to the low, medium, and high levels. Table 1 illustrates the available surface water amount with the related probabilities of occurrences. The available amount of groundwater and diverted water is shown in Table 2. In addition, the economic factors and water resources utilization are acquired from Henan Statistics Bureau from 2015–2019, such as benefit of per water consumption, purification cost for water resources, and cost of water resources purchased (HNSY 2015, 2016, 2017, 2018, 2019, 2020; WRBCQ 2015, 2016, 2017, 2018, 2019). Three energy consumption control scenarios as shown in Table 3 are considered for searching the impact of energy intensity on the regional industrial water system that includes a lower-, higher-, and without-energy consumption constraint level corresponding to S0, S1, and S2 scenarios.

Besides, in order to promote the development of advantage industries, the study would research influences of different risk-permission policies (advantage industries would be permitted to allocate more water resources than their water resources requirement) on industrial water resources allocation. Therefore, three comprehensive risk levels (i.e., $\xi = 0$, $-2$, and $-5\%$) in above formula (3o) are designed with corresponding to R1, R2, and R3 scenarios. Moreover, industrial sectors from 1 to 39 are considered in the comprehensive risk management, and industry sector 40 (i.e., Production and Distribution of Water) is not subject to the risk of water shortage in order to avoid water resource supply influence. From the above scenario design, a series of measures are proposed to sustain the reasonable water allocation structure under considering energy consumption and risk with a maximized system benefit.

### 4. RESULT ANALYSIS AND DISCUSSION

Figure 3 presents system cost and net benefits under the comprehensive risk management level (i.e., R1, R2, and R3 scenarios) and energy consumption control level (i.e., S0, S1, and S2 scenarios) during the whole planning horizon. In general, the system cost contains water purification cost, water charge, and wastewater treatment cost. Furthermore, the net benefits

#### Table 1 | Available surface water amount with the related probabilities of occurrences

| Surface water volume level | Probability | Available surface water amount (10^6 m^3/year) |
|---------------------------|-------------|-----------------------------------------------|
| Low                       | 0.2         | $[1,800, 1,860]$                              |
|                           |             | $[1,780, 1,840]$                              |
|                           |             | $[1,760, 1,820]$                              |
| Medium                    | 0.2         | $[1,900, 1,980]$                              |
|                           |             | $[1,880, 1,960]$                              |
|                           |             | $[1,860, 1,940]$                              |
| High                      | 0.6         | $[2,020, 2,100]$                              |
|                           |             | $[2,000, 2,080]$                              |
|                           |             | $[1,980, 2,060]$                              |

#### Table 2 | Available groundwater and diverted-water amount

| Water sources     | Available water resources amount (10^6 m^3/year) |
|-------------------|-----------------------------------------------|
| Groundwater       | $[2,100, 2,200]$                              |
| Diverted water    | $[500, 400]$                                  |

#### Table 3 | Scenarios designed for energy consumption control

| Scenarios | Energy consumption restriction (10^4 kWh/10^6 m^3) |
|-----------|-----------------------------------------------|
| S0        | $[0.8350, 0.8550]$                            |
| S1        | $[0.8365, 0.8553]$                            |
| S2        | /                                             |
would obviously increase as the comprehensive risk management level increasing from R1 to R3 scenarios. For example, under the S0 scenario, the net system benefit would be RMB¥ [19.22, 24.31] x 10^{12}, RMB¥ [19.56, 24.75] x 10^{12}, and RMB¥ [20.06, 25.37] x 10^{12} under R1, R2, and R3 scenarios, respectively; and RMB¥ [19.22, 24.33] x 10^{12}, RMB¥ [19.58, 24.77] x 10^{12}, and RMB¥ [20.09, 25.43] x 10^{12} without-energy consumption control level (S1 scenario), respectively. It indicated that the strict comprehensive risk management measures could cause damage to system benefit owing to decreasing flexibility of industrial water resources distributions. Moreover, as the energy consumption control level decreasing, the system benefit only would be decreasing gradually. For example, under the R1 scenario, the system benefit would be RMB¥ [19.22, 24.31] x 10^{12}, RMB¥ [19.21, 24.38] x 10^{12}, and RMB¥ [19.22, 24.33] x 10^{12} under S0, S1, and S2 scenarios, respectively. From the above analysis, compared with the comprehensive risk management scenarios and the energy consumption control scenarios, the comprehensive risk management would play a more crucial role in system profits.

Tables 4 and 5 describe the optimized surface water, groundwater, and diverted-water resources allocation target for diverse industry sectors in the low level under S1 and R1 scenarios. In general, surface water and groundwater resources would occupy most of the total water resources to sustain industrial water resources supply, and the diverted water would become supplement water sources. The main reasons that lead to such phenomenon are summarized as follows: (i) as a severe water shortage area in the midland of China, groundwater is as crucial as surface water and in Henan province; (ii) the transportation expenses for diverted-water resources are higher than other water resources utilization. According to the difference of water resources consumption, all of the industries are segmented into water-dependent industries (e.g., \(i = 2, 3, 5, 6, 10, 11, 12, 13, 14, 15, 17, 18, 27, 28, 31, 32, 34, 35, 36, 37, \) and 39) and water-independent industries (e.g., \(i = 1, 4, 7, 8, 9, 16, 19, 20, 21, 22, 23, 24, 25, 26, 29, 30, 33, 38, \) and 40). For instance, under period 3, water resources allocation for mining and processing of ferrous metal ores (\(i = 3\)) would be [5.96, 6.41] x 10^6 m^3/year with 2.6 x 10^6 m^3/year (surface water), [3.36, 3.81] x 10^6 m^3/year (groundwater), and 0 (diverted water); and for smelting and pressing of non-ferrous metals (\(i = 26\)), the amount would be [155.74, 172.80] x 10^6 m^3/year with 68.64 m^3/year (surface water), 17.16 x 10^6 m^3/year (groundwater), and [67.94, 87.00] x 10^6 m^3/year (diverted-water).
Figures 4 and 5 show the optimized water resources allocation schemes for industrial sectors in period 1 and the R1 scenario under the medium level. The results show that industrial sectors, particularly the water-dependent industries, would have a great potential for improving profits of the industrial system in Henan province. Faced with the persistently increasing cost of water utilization, water-dependent industries should take more measures for improving the water utilization rate and the return of per water consumption in order to avoid being a high-risk industry. Moreover, high-risk industries should promote industrial upgrading for reducing sewage discharge in order to obtain the permission of more industrial water resources. In addition, in order to protect groundwater resources, the total development and utilization amount should gradually decrease during the whole planning period that increases the replenishment of above and below groundwater resources and leads to more severe water shortage pressure.

Obviously, the maximum water resources amount would be allocated to mining and washing of coal, manufacture of raw chemical material and chemical products, production and supply of electric power and heat power, and production and distribution of water (i = 1, 20, 38, and 40); and support activities for mining, utilization of waste resources, repair services of metal products, machinery and equipment, and production and distribution of gas (i = 6, 36, 37, and 39) would be the minimum water resources users. For example, the allocation amount from surface water, groundwater, and diverted water to production and distribution of water (i = 40) would be 907.94 × 10^6, [1,126.85, 1,280.40] × 10^6 m³/year, and 0 in S0; and [890.72, 916.38] × 10^6, [1,138.07, 1,325.97] × 10^6 m³/year, and 0 in S2, respectively.

In general, groundwater allocation would be higher than surface water for most industries. The main reason is that although the available resources of the latter are less than the former, the different cost for water production from various water sources could have no effect on water resources allocation schemes. In addition, the diverted-water resources would be concentrated on several industries, such as manufacture of paper and paper products, manufacture of raw chemical material and chemical products, manufacture of medicines, smelting and pressing of ferrous metals, manufacture of computer communication and others, and manufacture of measuring instrument and machinery (e.g., i = 16, 20, 25, 33, 34, and 38).

| Table 4 | Optimized surface water resources allocation under low-level and higher-energy control in the S1 scenario |
|---------|---------------------------------------------------------------|
| **Surface water allocation target (10^6 m³/year)** | |
| Industry | t - 1 | t - 2 | t - 3 | Industry | t - 1 | t - 2 | t - 3 |
| i = 1   | 105.67 | 105.55 | 101.48 | i = 21 | 21.63 | 21.2 | 20.78 |
| i = 2   | 6.86   | 6.72   | 6.58   | i = 22 | 14.36 | 14.08 | 13.79 |
| i = 3   | 2.7    | 2.65   | 2.6    | i = 23 | 6.4   | 6.28 | 6.15  |
| i = 4   | 7.89   | 7.73   | 7.58   | i = 24 | 51.36 | 50.33 | 49.32 |
| i = 5   | 2.52   | 2.47   | 2.42   | i = 25 | 42.98 | 42.12 | 41.27 |
| i = 6   | 0.13   | 0.13   | 0.12   | i = 26 | 68.64 | 67.27 | 65.92 |
| i = 7   | 36     | 35.28  | 34.58  | i = 27 | 4.42  | 4.33 | 4.24  |
| i = 8   | 21.57  | 21.14  | 20.71  | i = 28 | 6.29  | 6.16 | 6.04  |
| i = 9   | 23.88  | 23.4   | 22.94  | i = 29 | 6.06  | 5.94 | 5.82  |
| i = 10  | 0.88   | 0.86   | 0.84   | i = 30 | 5.95  | 5.83 | 5.71  |
| i = 11  | 15.42  | 15.11  | 14.81  | i = 31 | 0.9   | 0.88 | 0.86  |
| i = 12  | 2.67   | 2.61   | 2.56   | i = 32 | 8.41  | 8.24 | 8.08  |
| i = 13  | 7.51   | 7.36   | 7.21   | i = 33 | 12.4  | 12.15 | 11.91 |
| i = 14  | 1.94   | 1.9    | 1.86   | i = 34 | 0.96  | 0.94 | 0.92  |
| i = 15  | 1.03   | 1.01   | 0.99   | i = 35 | 0.95  | 0.93 | 0.92  |
| i = 16  | 30.32  | 29.71  | 29.12  | i = 36 | 0.15  | 0.15 | 0.15  |
| i = 17  | 1.01   | 0.99   | 0.97   | i = 37 | 0.16  | 0.16 | 0.16  |
| i = 18  | 3      | 2.94   | 2.88   | i = 38 | [240.58, 75.72] | [258.8, 276.61] | [269.22, 270.93] |
| i = 19  | 24.13  | 23.65  | 23.17  | i = 39 | 0.41  | 0.4  | 0.39  |
| i = 20  | 113.97 | 111.69 | 109.45 | i = 40 | [897.9, 922.75] | [872.91, 915.24] | [855.45, 913.74] |
Table 5 | Optimized groundwater and diverted-water allocation schemes under low-level and higher-energy control in the S1 scenario

| Industry | Water allocation target (10^6 m³/year) | Diverted-water |
|----------|---------------------------------------|----------------|
|          | Groundwater  | t – 1 | t – 2 | t – 3 | t – 1 | t – 2 | t – 3 |
| i = 1    | [96.62, 136.86] | 0     | 8.9  | 0     | [133.6, 152.1] | [123, 141.2] |
| i = 2    | [5.85, 8.88]   | [8.9, 10.36] | [9.03, 10.49] | 0   | 0   | 0   |
| i = 3    | [3.45, 4.1]    | [3.41, 3.87] | [3.36, 3.81] | 0   | 0   | 0   |
| i = 4    | [10.08, 11.97] | [9.27, 9.79] | [8.44, 8.84] | 0   | 0   | 0   |
| i = 5    | [3.22, 3.82]   | [3.26, 3.8]  | [3.31, 3.85] | 0   | 0   | 0   |
| i = 6    | [0.17, 0.2]    | [0.17, 0.2]  | [0.17, 0.2]  | 0   | 0   | 0   |
| i = 7    | 0              | [46.69, 54.39] | 0 | [46, 54.63] | 0   | [47.36, 55] |
| i = 8    | [27.56, 32.73] | [27.97, 32.59] | 0 | 0 | 0 | [28.4, 33] |
| i = 9    | [30.51, 36.24] | [30.9, 35.92] | 0 | 0 | 0 | [31.3, 36.3] |
| i = 10   | [1.12, 1.33]   | [1.13, 1.32]  | [1.15, 1.33] | 0 | 0 | 0 |
| i = 11   | [19.7, 23.4]   | [19.92, 23.11] | 0 | 0 | 0 | [20.1, 23.3] |
| i = 12   | [3.41, 4.04]   | [3.46, 4.03]  | [3.51, 4.07] | 0 | 0 | 0 |
| i = 13   | [9.6, 11.4]    | [9.74, 11.34] | [9.88, 11.48] | 0 | 0 | 0 |
| i = 14   | [2.48, 2.94]   | [2.51, 2.93]  | [2.55, 2.97] | 0 | 0 | 0 |
| i = 15   | [1.32, 1.57]   | [1.34, 1.56]  | [1.36, 1.58] | 0 | 0 | 0 |
| i = 16   | [38.74, 46.01] | [39.07, 45.23] | [39.37, 45.49] | 0 | 0 | 0 |
| i = 17   | [1.29, 1.53]   | [1.31, 1.52]  | [1.33, 1.54] | 0 | 0 | 0 |
| i = 18   | [3.84, 4.56]   | [3.9, 4.54]   | [3.95, 4.6]  | 0 | 0 | 0 |
| i = 19   | [23.59, 31.25] | 20.09 | 12.1 | 0 | 0 | 0 |
| i = 20   | 0              | 0     | 155.34, 183.2 | 122.6, 173 | 150.5, 178 | 0 |
| i = 21   | [27.64, 32.83] | [27.26, 30.92] | [26.85, 30.41] | 0 | 0 | 0 |
| i = 22   | [13.86, 18.6]  | [17.41, 19]  | [16.43, 17.88] | 0 | 0 | 0 |
| i = 23   | [8.18, 9.72]   | [7.44, 7.76]  | [6.67, 6.89]  | 0 | 0 | 0 |
| i = 24   | [65.62, 77.93] | [65.21, 74.49] | 0 | 0 | 0 | [64.7, 73.8] |
| i = 25   | 0              | [56.75, 67.15] | 58.58, 69.09 | [54.9, 65.2] | 0 | 0 |
| i = 26   | 17.16          | 66.86 | 49.15 | [67.94, 87] | 0 | 0 |
| i = 27   | [5.65, 6.7]    | [5.73, 6.66]  | [5.8, 6.74]   | 0 | 0 | 0 |
| i = 28   | [8.04, 9.54]   | [8.14, 9.47]  | 0 | 0 | 0 | [8.24, 9.56] |
| i = 29   | [7.75, 9.2]    | [7.47, 8.28]  | [7.17, 7.94]  | 0 | 0 | 0 |
| i = 30   | 0              | 6.21  | 4.89 | [7.6, 9.02] | 0 | 0 |
| i = 31   | [1.15, 1.37]   | [1.17, 1.36]  | [1.18, 1.38]  | 0 | 0 | 0 |
| i = 32   | [10.74, 12.76] | [10.88, 12.66] | [11.02, 12.79] | 0 | 0 | 0 |
| i = 33   | [15.84, 18.81] | [15.88, 18.28] | [15.9, 18.28] | 0 | 0 | 0 |
| i = 34   | [1.23, 1.46]   | [1.21, 1.37]  | [1.19, 1.35]  | 0 | 0 | 0 |
| i = 35   | [1.22, 1.45]   | [1.24, 1.44]  | [1.25, 1.46]  | 0 | 0 | 0 |
| i = 36   | [0.2, 0.23]    | [0.2, 0.23]   | [0.2, 0.23]   | 0 | 0 | 0 |
| i = 37   | [0.21, 0.25]   | [0.21, 0.24]  | [0.21, 0.24]  | 0 | 0 | 0 |
| i = 38   | [243.6, 298.95] | [272.2, 276.24] | [267.06, 321.8] | 0 | 0 | 0 |
| i = 39   | [0.52, 0.62]   | [0.51, 0.57]  | 0 | 0 | 0 | [0.5, 0.56] |
| i = 40   | [1.131, 1.319.6] | [1.155.7, 1.304] | [1.172.7, 1.305] | 0 | 0 | 0 |
Obviously, the above-mentioned industrial sectors are mostly water-dependent industries except for the manufacture of measuring instrument and machinery industry ($i = 34$). From this point, the profit of per water resources utilization would be relatively less for the majority of water-dependent industries, and surface water and groundwater resources would preferentially be allocated to industries with a higher return of per water resources consumption. Therefore, the former could not obtain enough surface water and groundwater resources to satisfy production demand, and the expensive diverted water would become a supplement for these industries.

Compared with water allocation schemes under different energy consumption control constraints (i.e., $S0$ and $S2$ scenarios), it indicated that the total water consumption amount and the water utilization structure would be changed, and the strict energy consumption control would limit the available energy of per unit of water resources generation. Furthermore,
the energy consumption during the transport process of the diverted water are high. For example, the energy consumption amount would be [0.42, 0.43], [0.77, 0.78], and [1.13, 1.14] kWh/m³ for surface water, groundwater, and the diverted-water in period 1. Therefore, energy consumption control would have a deep impact on in the diverted-water utilization. The total allocation amount of the diverted water would have an obvious decrease trend as energy consumption control level increasing, and surface water allocation amount would slightly increase. For example, under the medium level of available surface water resources in period 1, the allocation amount of surface water, groundwater, and the diverted water would be [1,823.91, 1,888.19] × 10⁶, [1,908.21, 2,200.00] × 10⁶, and [300.00, 400.00] × 10⁶ m³/year under the S2 scenario, respectively; and [1,880.09, 1,954.74] × 10⁶, [1,893.24, 2,200.00] × 10⁶, and [251.85, 311.31] × 10⁶ m³/year under the S0 scenario, respectively.

Figure 5 | Optimized water allocation schemes for water-independent industry sectors under the medium level during the R1 scenario in period 1 (Note: SWW, GW, and IW denote the surface water, groundwater, and diverted-water allocation amount, respectively).
Based on the above-mentioned reasoning, the optimal allocation amount of surface water would be ensured in diverse energy consumption control policies. A reasonable water resources allocation scheme not only could keep industries development, but also could limit energy waste in the production process. From the comprehensive risk analysis through the water utilization index, each industrial sector can be divided into low-risk industry and high-risk industry.

Figure 6 shows the comprehensive risk for the low-risk industries with different risk control in the S1 scenario under the medium level. First, the risk values under the R1 scenario would be 0, and the risk control level would lead to a moderate and neutralizing attitude on industrial water resources allocation management. In addition, under R2 and R3 scenarios, the comprehensive risk value would be a negative number that indicated that water shortage would not occur for low-risk industries under considering the comprehensive risk framework into industrial system management. For instance, the comprehensive risk value would be $[-1.11, -1] \times 10^6$ m$^3$/year for the manufacture of foods ($i = 8$) under the R2 scenario; and $[-2.7, -2.44] \times 10^6$ m$^3$/year for the manufacture of computer communication and other electronic equipment ($i = 33$) under the R3 scenario and the medium level in period 1. For the low-risk industries, a lower water resources demand and a higher return of per water utilization could directly lead to a preferential water allocation. Especially, under R2 and R3 scenarios, the low-risk industries would obtain more water resources than the demand targets, and that could promote industrial productivity and make a higher system benefit.

Figure 7 presents the comprehensive risk for high-risk industries with different risk control in the S1 scenario under the medium level during the planning periods. Obviously, all risk values of the high-risk industrial sectors would be positive in the R1 scenario, and some values would be negative in R2 and R3 scenarios. For example, the comprehensive risk for Smelting and Pressing of Ferrous Metals ($i = 25$) would be 0, $[-68.11, -61.63] \times 10^6$, and $[-170.28, -65.06] \times 10^6$ m$^3$/year under R1, R2, and R3 scenarios in period 1, respectively. Compared with the low-risk industrial sectors, the high-risk industries would have a higher water resources requirement with a lower profit of per water resource consumption, and that would be greatly related to positive water resources shortage risk for some high-risk industries. For example, the industrial water resources requirement for mining
and washing of coal \( (i = 1) \) would be \([583.34, 644.75] \times 10^6 \text{ m}^3/\text{year}\) and the profit of per water resource utilization is \([13.47, 15.60] \text{ RMB/m}^3\) in period 1, and the related risk would be \([0, 36.15] \times 10^6, [36.15, 44.8] \times 10^6, \text{ and } [44.8, 93.06] \times 10^6 \text{ m}^3/\text{year}\) under R1, R2, and R3 scenarios, respectively. Furthermore, risk management coefficient would determine the maximum risk value for industrial sectors, and a higher recycle rate of water resources and a lower sewage discharging measure would be beneficial to reduce the comprehensive risk. As the water recycle rate increasing from periods 1 to 3, the comprehensive risk values for high-risk industries would have a decreasing trend. For example, the risk values for mining and washing of coal \( (i = 1) \) would be \([36.15, 44.8], [13.02, 36.02], \text{ and } [13.15, 11.9] \) in R2 under higher-energy consumption control from periods 1 to 3.

In general, the preliminary energy consumption or the comprehensive risk control would be beneficial to moderate the conflict between industrial sectors and water resources, and accelerate industrial structure transformation in the future. Under the framework for achieving a maximum system return, the comprehensive risk measure is introduced into the industrial water resources system optimization model, and that could effectively keep reasonable profits and avoid the unbalanced
risk for regional water resources allocation. Moreover, energy consumption control policy would have a direct impact on the industrial water resources allocation structure. The comprehensive risk of water utilization management and energy consumption control would play a crucial part in regional industrial development in the future.

5. CONCLUSIONS

In this study, a new concept concerning comprehensive characteristics of water resources utilization as an index for risk modeling within the water allocation management model is proposed to explore the tolerance of unbalanced allocation problem under water–energy nexus. The model is integrated with ISTP for reflecting system uncertainties that could be associated with the industrial production feature and the decision-making process. With respect to water–energy nexus, energy proposed is mainly focused on the consumption intensity of water purification and transportation from different water sources. The developed model is used in planning industrial water resources allocation under considering the randomly available surface water resources, the limited groundwater and diverted-water resources, and 40 industrial sectors in Henan province. Through discussing the variation for net system benefit, industrial water resources allocation schemes, and the comprehensive risk, the following conclusions are known: (i) the strict comprehensive risk or energy consumption control measures could cause damage to system benefit owing to decreasing flexibility of industrial water resources distributions; (ii) the reasonable water resources allocation scheme from the proposed model could not only keep industries development, but also limit energy waste in the production process; and (iii) the preliminary energy consumption or the comprehensive risk control would be beneficial to moderate the conflict between industrial sectors and water resources, and accelerate industrial structure transformation in the future. The results could provide an effective management framework to reflect the complexities and uncertainties in system, and the model could be used for regulating sustainable industrial water resources utilization by decision-makers.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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