

# An inexact multi-objective programming model for water resources management in industrial parks of Binhai New Area, China

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## ABSTRACT

In recent years, Binhai New Area of Tianjin has been suffering severe water shortage due to climate change and industrial activities. Integrated and effective water resources management approaches are urgent for the sustainable development of industrial parks in Binhai New Area. However, uncertainties exist in many aspects of the water resources system and are inevitably problematic for water resources planning and policy-making. To address these uncertainties, an interval multiple-objective programming model was developed here to support the long-term planning of industrial water resources management in Binhai New Area, Tianjin, China. The model incorporated both multiple-objective programming and interval linear programming into a general programming framework. The developed model could handle the uncertainties and complexities of the water management system, and also allowed decision makers to adjust fuzzy objective control decision variables to satisfy multiple holistic and interactive objectives. The solutions are useful for planning adjustments of the existing water allocation patterns in Binhai New Area.

**Key words** | industrial water allocation, interval-parameter programming, multiple objectives, uncertainty, water reuse

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## INTRODUCTION

There is growing concern for water environmental security and the disparity between water demand and supply throughout the world. A general water shortage has been caused by continuous population growth and rapid social and economic development. Extreme weather, water infrastructure failures, and environmental deterioration can further constrict the water supply (Xie *et al.* 2011). Ever-increasing demand in the face of limited supply is compelling governments and institutions to initiate various strategies for water management, including water quality improvement, rational water-saving technologies, and exploring alternative water resources. In China, industry is a particular burden on water resources, being both a dominant consumer and source of pollution. For example, in 2012, industrial water consumption in China was  $142.39 \times 10^9 \text{ m}^3$ , while wastewater discharge was  $22.16 \times 10^9 \text{ m}^3$ ; total industrial chemical oxygen demand (COD) for that year was  $3.39 \times 10^6$  metric tons, which contributed to serious pollution. In addition, industrial parks have many uncertainties in their water supply and demand processes;

modeling their systems involves estimating the errors in the modeling parameters of the various complex processes (e.g., fresh water transfer and water recycling) (Huang 1996; Maqsood *et al.* 2005; Li *et al.* 2011). These uncertainties would influence attempts to stabilize the balance between water supply and consumption processes. Therefore, to relieve the water crises that can occur under such complexities and uncertainties, it is extremely important to develop integrated management tools, particularly with regard to industrial parks with high water consumption.

Various optimization methods have been developed to describe and handle the elements of uncertainty related to water resource management problems, which include water availability, water demand, system operations, and environmental requirements (Zhu & ReVelle 1988; Morgan *et al.* 1993; Ferrero *et al.* 1998; Luo *et al.* 2003; Maqsood *et al.* 2005; Rehana & Mujumdar 2009; Xu & Qin 2010). For example, Huang & Loucks (2000) proposed an inexact two-stage stochastic water resources management model for regional industrial, agricultural, and municipal water

allocation problems, where uncertainties were expressed as probability density functions and discrete intervals. Li *et al.* (2009) advanced a multistage fuzzy-stochastic programming model for water resources allocation and management, which expressed uncertainties as probability distributions and allowed fuzzy sets to be considered. To manage the water systems of industrial parks or zones, water allocation methods have been developed to handle the associated uncertainties by integrating materials exchange, discharge, and waste treatment among multiple processing facilities (Yue *et al.* 2014). For example, Côté & Cohen-Rosenthal (1998) optimized the systems of a North American eco-industrial park using mathematical programming to solve industrial water management problems. Bagajewicz *et al.* (2002) addressed the optimal design of water utilization systems in industrial plants using linear models, each considering a single contaminant. Liu *et al.* (2010) proposed an interactive fuzzy approach for planning an industrial water resources management system with the aim of sustainably using the regional water resources.

The previously proposed models can effectively deal with uncertainties expressed as intervals and probability distributions in water management problems. However, the global challenges of additional water management objectives have limited the applicability of single-objective optimization to water resource systems (Erbe & Schtze 2005). Therefore, multiple-objective methods have been proposed to balance the functions of the various objectives in water resource systems and to comprehensively unify the different elements. For example, Slowinski (1986) proposed an interactive fuzzy multi-objective linear programming method for application to water supply planning. Mendoza *et al.* (1993) addressed fuzzy multiple-objective linear programming techniques in forestry planning. Wu *et al.* (1997) proposed an interactive inexact-fuzzy multiple-objective programming (MOP) model for planning water resource systems; the associated uncertainties were presented in terms of discrete intervals and fuzzy sets. Lavric *et al.* (2005) adopted a strategy to resolve problems of water allocation that employed multiple-objective optimization using a genetic algorithm. Özelkan *et al.* (1997) studied multi-purpose functions, and used dynamic programming to introduce many sample purposes such as flood control, hydroelectricity, and water demand. Creaco *et al.* (2015) expressed uncertainty in the multi-objective programming, and optimized the network performed by considering two objective functions. Conventional MOP approaches generally require uncertain parameters in the optimization models to be expressed as probability distributions, and

cannot directly reflect non-probability-distribution information. However, many real-world problems involve parameters with insufficient information quality to be presented as probabilistic distributions. Interval-parameter programming (IPP) is an alternative method for handling uncertainties in a model's left- and/or right-hand side, as well as those that cannot be quantified via distribution functions (Huang 1996). Therefore, one potential approach for better reflecting uncertainties is to incorporate IPP within a MOP framework when interval numbers are used as uncertain inputs.

However, few studies have focused on developing an inexact multiple-objective optimization model for solving water resource allocation problems in industrial parks of a water shortage city. The water issues of industrial parks are characterized by high water consumption, low water efficiency, and high effluent discharge. The lack of both a unified water resource management mechanism and supervisory measures leads to serious water wastage and unregulated wastewater discharge, which exacerbate the problems already associated with limited water resources. Therefore, as an extension of the previous studies, this study aims to develop an inexact multiple-objective programming model (IMOP) for the management of water resources in a typical industrial city. The model incorporates the optimization techniques of IPP into MOP to handle the multiple uncertainties of the water resources system. The developed model was applied to Binhai New Area, Tianjin, China, to support the planning of water utilization in industrial parks. The model considered multiple water users and water sources, as well as taking environmental issues and economic factors into consideration. The results can assist water resource managers to establish effective water exploitation and allocation policies and also to better understand the tradeoffs between environmental and economic objectives.

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## WATER RESOURCES MANAGEMENT IN BINHAI NEW AREA

### The study area

The municipality of Tianjin is located in the east part of the North China Plain. As of the end of 2013, it had an administrative area of  $11.95 \times 10^5$  km<sup>2</sup>, a population of approximately 14 million, and gross domestic product (GDP) of 1,437 billion yuan. The study area (Binhai New Area) is situated in eastern Tianjin, close to the Bohai Sea (Figure 1). In the past decade,

Binhai New Area has become the most dynamic economic center of Tianjin; for example, its 2013 GDP of 802.4 billion yuan constituted about 56% of the total production of the entire city. By 2010, more than 285 companies had set up bases in the area. Industry in the study area is concentrated in five main industrial clusters, including electronic information, petrochemical and marine chemical industry, metallurgy, and optical-electronic-machinery integration. The industrial structure accelerates economic growth of the area, but also places a burden on its resources.

### Water resources and shortages

Tianjin has a warm temperate continental monsoon climate with an annual rainfall of 574.9 mm. It has an abundance of natural resources (e.g., salt, wetlands, petroleum, and gas), but suffers severe water shortages. The total available water resources are only  $1.724 \times 10^9 \text{ m}^3$ , including surface water ( $1.065 \times 10^9 \text{ m}^3$ ) and groundwater ( $0.73 \times 10^9 \text{ m}^3$ ). The per capita water availability is only  $160 \text{ m}^3$ , which is far below the internationally accepted warning limit of

$1,000 \text{ m}^3$ . Binhai New Area compares unfavorably with other areas of the city, having a per capita water availability ranging from 130 to  $150 \text{ m}^3$ . Its main water sources are imported water from the Luan River and the Yellow River, which supplement groundwater and water from seawater desalination. Industrial expansion and economic development are suffering owing to the water scarcity in this region. For example, total water demand in 2020 is predicted to be  $0.945 \times 10^9 \text{ m}^3$ , while the supply capacity is only  $0.801 \times 10^9 \text{ m}^3$ , indicating a serious water shortage. This would limit the development and prosperity of the industrial parks.

### Water utilization and recycling

Traditional water use ignores the natural water cycle, and so exacerbates problems in the aquatic ecosystem as well as increasing water shortages. The prospect of severe water scarcity incentivizes the use of water from non-conventional sources such as industrial or municipal wastewater, which can be restored to a quality suitable for various reuses, and

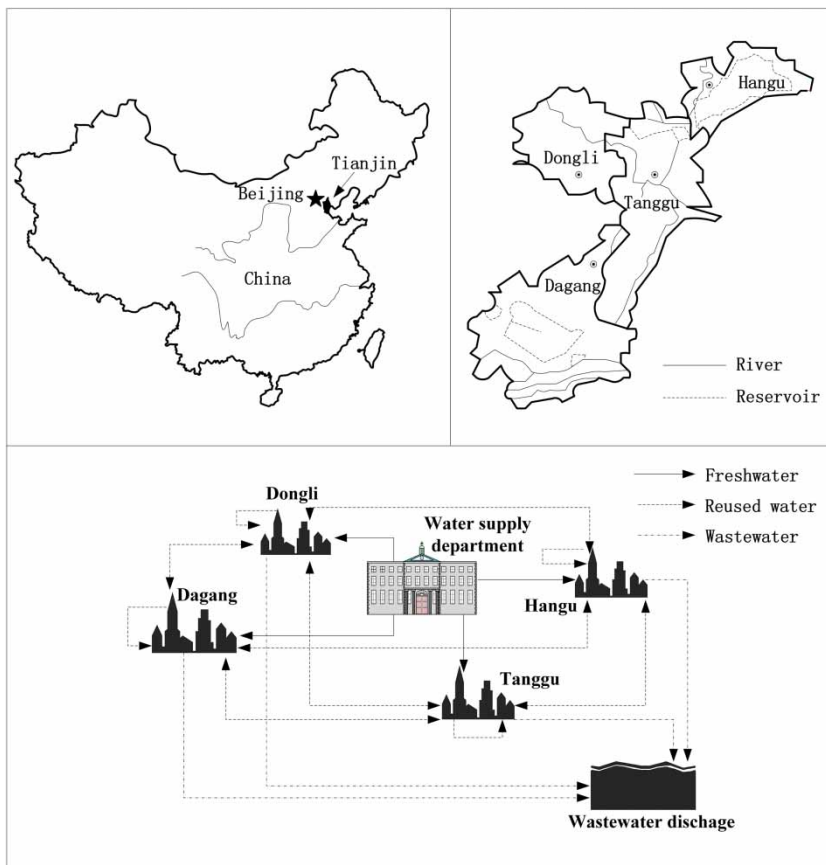


Figure 1 | The study area and its water resources network.

so relieve urban water shortages. By 2013, the study area possessed eight water reclamation plants with treatment capacities ranging from  $50 \times 10^3$  to  $230 \times 10^3$  m<sup>3</sup>/d. The treated water is allocated to sectors such as irrigation, river supply, industry, and domestic use. For example, in the Meijiang community of Binhai New Area, the treated water is used for flushing toilets and for filling artificial lakes.

### Water environmental protection

Numerous chemical plants within the study area discharge wastewater into receiving waters, thus deteriorating the aquatic environment. All of the rivers in the study area are subject to pollution due to the low capacity of the wastewater treatment plants. For example, in 2012 there were 30 sewage treatment plants with a total treatment capacity of  $149.05 \times 10^6$  ton in Binhai New Area, but there were  $171.83 \times 10^6$  ton of wastewater. A large proportion of the wastewater was directly discharged without centralized treatment, causing most of the rivers in Binhai New Area to suffer serious pollution of grade V (or worse) of the national water quality standard.

COD, NH<sub>3</sub>-N, biochemical oxygen demand, and permanganate are the main water pollutants in the study area. NH<sub>3</sub>-N pollution mainly originates from the industrial sector, especially chemical industries, and its level in surface water is a primary indicator of water quality. For example, in 2010, 71% of the total NH<sub>3</sub>-N emissions in Tianjin were from Binhai New Area. Wastewater from this area includes outflows from petrochemical, coal chemical, and marine chemical industries. The pollutants are widely distributed, and are highly concentrated, toxic, and flammable. Although many measures have been implemented (e.g., environmental regulations and laws, restrictions of fertilizer application, and soil/water conservation), the river water quality remains significantly impaired.

### Problem statement

Based on the data presented above, decision making around the supply and demand sides in Binhai New Area should take a variety of complex processes, such as industrial production, water resources utilization, recycling capacity, and pollutant emissions into consideration. Moreover, the system parameters, such as economic efficiency, levels of wastewater discharge, and system cost would be presented as uncertainties (Zhu *et al.* 2011). The complexities and uncertainties could affect the related optimization processes and consequent decision schemes. Therefore, the problem

under consideration is how to coordinate the multiple objectives to optimize the overall system. However, many previous studies have focused on the development of single-objective methods. Although considering a single objective is sufficient for some decision-making processes, many situations involve decisions with multiple objectives. The problems associated with the water management systems of Binhai New Area include: (a) how to allocate effectively the limited water resources to multiple departments, (b) how to deal with the uncertainties expressed as functional intervals in the objective function and constraints, and (c) how to generate optimal results in the situation of multiple objectives.

## MODEL FORMULATION

### Model development

An IMOP method is developed to support the long-term water management planning of Binhai New Area. Various users can obtain water from public water sources, recycled water from other users, and water reclaimed by a regenerator; such water users could be regarded as sinks. By explicitly considering a number of water sources, the method can help to obtain a desired water allocation plan that appropriately balances the various water supply goals. Meanwhile, wastewater could be directly used by other factories, transferred to the regenerator for water reclamation, or otherwise discharged to the sewage treatment plant; such water suppliers could be regarded as sources. A conceptual framework of the developed system is shown in Figure 2.

The objective functions in this study are designed with three aspects in mind: (1) the maximization of net economic benefit, (2) the minimization of wastewater discharge, and (3) the minimization of total system costs, all for four regions in Tianjin. The objective functions are represented below.

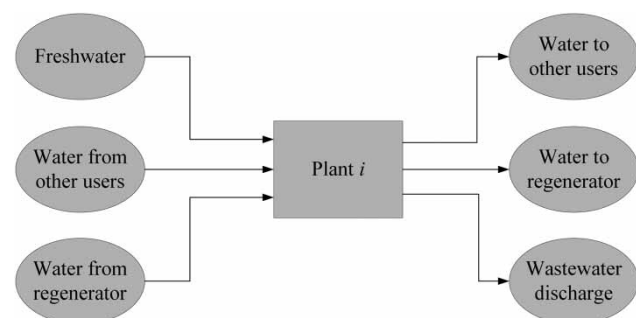


Figure 2 | Input and output water streams for an industrial plant.

### Economic objective function

The objective of the economic model is to maximize the overall benefits. The benefits are earned from the manufacture produced by water action including freshwater, reused water and reclaimed water. The fuzzy goal is given by (1):

$$\text{Max } f_1^\pm = \sum_j^J (FW_j^\pm + RW_j^\pm + RCW_j^\pm) \cdot NA_j^\pm \quad (1)$$

where  $FW_j^\pm$ ,  $RW_j^\pm$ , and  $RCW_j^\pm$  denote the consumption of freshwater, recycled water, and reclaimed water for sink  $j$  (ton/year);  $NA_j^\pm$  is the net benefit per unit water (RMB/ton).

### Environmental objective function

The objective of the environment model is to minimize the total pollutant emissions. The discharge quantity of each area equals the flow in the plant exempting the flow from this sector to the other sectors (including to the other three areas and to regeneration plant). The fuzzy goal is given by Equation (2):

$$\text{Min } f_2^\pm = \sum_i^I W_i^\pm = \sum_i^I M_i^\pm - \sum_i^I \left( \sum_j^J r_{ij}^\pm - \sum_t^T r_{it}^\pm \right) \quad (2)$$

where  $W_i^\pm$  is the wastewater discharge from source  $i$  (ton/year);  $M_i^\pm$  is the flow rates of water in source  $i$  (ton/year);  $r_{ij}^\pm$  is the water flow rate from source  $i$  to sink  $j$  (ton/year);  $r_{it}^\pm$  is the water flow rate from source  $i$  to regenerator  $t$  (ton/year).

### Resource consumption objective function

The objective of the resource model is to minimize the total cost for freshwater, wastewater treatment, regeneration and reused water. The fuzzy goal is given by Equation (3):

$$\text{Min } f_3^\pm = \sum_j^J \text{Cost } 1_j^\pm + \sum_i^I \text{Cost } 2_i^\pm + \sum_i^I \text{Cost } 3_i^\pm + \sum_i^I \text{Cost } 4_i^\pm \quad (3)$$

$\text{Cost } 1_j^\pm$ ,  $\text{Cost } 2_i^\pm$ ,  $\text{Cost } 3_i^\pm$ , and  $\text{Cost } 4_i^\pm$  are the related costs of total freshwater consumption, wastewater

discharge, reclaimed water consumption and reused water consumption by source  $i$  or sink  $j$  (RMB/year). The models can be formulated as follows:

$$\text{Cost } 1_j^\pm = FW_j^\pm \cdot CFW, \quad (3a)$$

$$\text{Cost } 2_i^\pm = W_i^\pm \cdot CW, \quad (3b)$$

$$\text{Cost } 3_i^\pm = \sum_t^T r_{it}^\pm (CNout_i^\pm - CNout_t^\pm) \cdot CR_t, \quad (3c)$$

$$\text{Cost } 4_i^\pm = \sum_j^J r_{ij}^\pm \cdot C_{ij}. \quad (3d)$$

where  $CFW^\pm$ ,  $CW^\pm$ ,  $CR_t^\pm$  and  $C_{ij}^\pm$  are the costs of freshwater, wastewater discharge, reclaimed water and reused water (RMB/ton);  $CNout_i^\pm$  and  $CNout_t^\pm$  are the outlet concentrations of  $\text{NH}_3\text{-N}$  from source  $i$  and regenerator  $t$  (ton/ton).

The objective is subject to the following constraints.

### Available water quantity constraints

In the water resources management system, the total water amount allocated to all water users should not be more than the available water flows of the reservoir in order to balance the relationship between water supply and demand.

$$\sum_j^J FW_j^\pm \leq WP^\pm. \quad (4)$$

where  $WP^\pm$  is the available quantity of freshwater resources (ton/year).

### Recycled water constraints

In the water recycle system, the total amount of reused water equals the sum of water flow between every two plants, or we could also say the flow from source  $i$  to sink  $j$ .

$$RW_j^\pm = \sum_i^I r_{ij}^\pm. \quad (5)$$

### Reclaimed water constraints

The total amount of reclaimed water equals the sum of water flow from regenerator  $t$  to each plant (sink  $j$ ).

$$RCW_j^\pm = \sum_t^T r_{tj}^\pm. \quad (6)$$

where  $r_{ij}^\pm$  is the water flow rate from regenerator  $t$  to sink  $j$  (ton/year).

### Water demand constraints

As a role of water user, each plant plays the part of sink in the system. In order to meet the production requirements and to achieve economic efficiency, water demand by different users should be satisfied by various sources, namely from the reservoir, other users and the regenerator.

$$\sum_i r_{ij}^\pm + \sum_t r_{ij}^\pm + FW_j^\pm = N_j^\pm. \quad (7)$$

where  $N_j^\pm$  is the demand of water in sink  $j$  (ton/year).

### Water quality restriction constraints

According to the principle of water saving and safety supply, the inlet concentration of pollutants should not exceed the maximum allowable concentration restriction. The inlet pollutants are mainly from freshwater, outlet water flow from other users and the reclaimed water from regenerator.

$$\begin{aligned} \sum_i r_{ij}^\pm \cdot CN_{out_i}^\pm + \sum_t r_{ij}^\pm \cdot CN_{out_t}^\pm + FW_j^\pm \cdot CN_f \\ \leq N_j^\pm \cdot CN_{in_u_j}^\pm. \end{aligned} \quad (8)$$

where  $CN_{in_u_j}^\pm$  is the inlet concentration of  $\text{NH}_3\text{-N}$  limits of sink  $j$  (ton/ton);  $CN_f^\pm$  is the concentration of  $\text{NH}_3\text{-N}$  in fresh water (ton/ton).

### The constraint of water quantity balance in each source

As a role of water supplier, each plant plays the part of source in the system. Flow rate in a plant includes the water supplied to other plants, water to regeneration plant and the discharging part.

$$\sum_j r_{ij}^\pm + \sum_t r_{it}^\pm + W_i^\pm = M_i^\pm. \quad (9)$$

where  $M_i^\pm$  is the available water flow in source  $i$  (ton/year).

### The water quality restriction for the inlet of each regeneration process

$$\sum_i r_{it}^\pm \cdot CN_{out_i}^\pm \leq \sum_i r_{it}^\pm \cdot CN_{in_u_t}^\pm. \quad (10)$$

where  $CN_{in_u_t}^\pm$  is the inlet concentration of  $\text{NH}_3\text{-N}$  limits of regenerator  $t$  (ton/ton).

### The water balance for each regeneration process

$$\sum_i r_{it}^\pm = \sum_j r_{ij}^\pm. \quad (11)$$

### Solution process of the IMOP model

According to Huang et al. (1993), the  $\lambda^\pm$  value was incorporated to the developed model and different values correspond to the various membership grades of satisfaction. Therefore, the proposed model can be formulated as:

$$\max \lambda^\pm \quad (12a)$$

$$\begin{aligned} s.t. f_k^\pm(X^\pm) &\geq f_{kg}^- + (1 - 2\lambda^\pm) \cdot (f_{kg}^+ - f_{kg}^-), \\ k &= 1, 2, \dots, p, \end{aligned} \quad (12b)$$

$$\begin{aligned} f_l^\pm(X^\pm) &\geq f_{lg}^- + (1 - 2\lambda^\pm) \cdot (f_{lg}^+ - f_{lg}^-), \\ l &= p + 1, p + 2, \dots, q, \end{aligned} \quad (12c)$$

$$\begin{aligned} A_i^\pm X^\pm &\geq b_i^- + (1 - 2\lambda^\pm) \cdot (b_i^+ - b_i^-), \\ i &= n + 1, n + 2, \dots, m, \end{aligned} \quad (12d)$$

$$X^\pm \geq 0, \quad (12e)$$

$$0 \leq \lambda^\pm \leq 1, \quad (12f)$$

where  $\lambda^\pm$  is the control decision variable corresponding to the degree (membership grade) to which  $X^\pm$  solutions fulfill the fuzzy objective or constraints.  $f_g^+$  and  $f_g^-$  are the lower and upper bounds respectively of the objectives' aspiration level as designated by the decision makers. The fuzzy goal is shown graphically in Figure 3.

### Data collection

The study area is divided into four geographical regions: the districts of Tanggu, Hangu, Dagang, and Dongli. Economic and environmental data were collected over two typical years (2009 and 2010). Table 1 lists the flow volumes in the four districts, and Table 2 shows the pollutant production coefficient, draining concentration, and inlet concentration limit in each area.



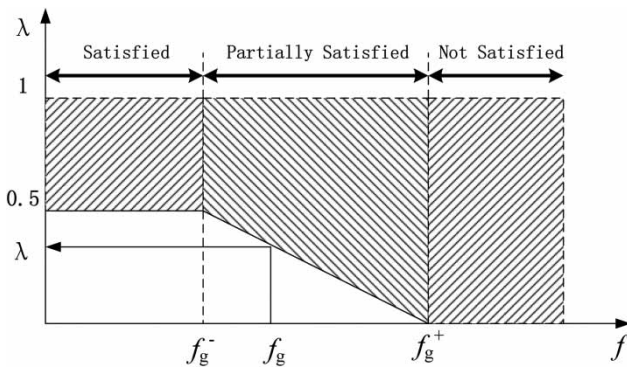


Figure 3 | Fuzzy linear membership function for goals.

### RESULTS, ANALYSIS, AND DISCUSSION

The optimization problems in this study are operated with the modeling language running on the Lingo11 solver. Problem instances are solved on a 32-bit Lenovo workstation running on Windows 7 with two dual-core 2.60 GHz CPU, 4.0 GB of RAM, and 500 G of hard disk space. In this study, reported CPU times are in seconds and the software of Lingo11 is terminated when the prescribed CPU time limit of 150 s is reached.

#### Water allocation schemes and water recycling

Figure 4 presents the results obtained from the IMOP model. The incorporation of an IPP model leads the solutions of the water allocation schemes and wastewater discharges to be interval numbers. For example, the amount of freshwater allocated to Hangu district would be [1134, 1190] ton. The results indicate that the

corresponding decisions and policies should be sensitive to the uncertain modeling inputs. The demands placed on water resources should influence planning decisions; there will be excess water resources if the available water resources fully meet the demand during the considered period of planning. To avoid wasting resources, the exchange of water resources between districts is considered here. For example, Hangu district could provide [0, 103] ton excess water to Tanggu district to ensure regional development. Dagang district would require water from the other districts: for example, [0, 823] ton of water resources from Dongli district and [0, 7] ton of water resources from Hangu district would be allocated to Dagang to satisfy its requirements for low-quality-water.

Figure 5 shows the allocation schemes and wastewater discharges for the different districts. The maintainance of economic and social development relies on fresh water as the main water source. For example, the amounts of freshwater allocated to Tanggu, Hangu, Dagang, and Dongli from public water sources would be [2864, 3007], [1134, 1190], [2069, 2172], and [1187, 1884] ton, respectively, thus accounting for more than 50% of the total water allocation (Figure 5(a)). Reused water would constitute an important source to satisfy the increasing demand. Its allocation is presented in Figure 5(b). Most of the reused water would be allocated to Tanggu district, while Dagang would receive the least amount. As the cradle of industry in the north of China, Tanggu consumes the most water among these four districts; most of the water resources are allocated to the industrial sector, including the Bohai oilfield and the Tianjin soda plant. Hangu district is allocated the least freshwater. As it is located near the Bohai Sea, Hangu’s rich marine resources are more suitable

Table 1 | Water inflows and demand of Binhai New Area (ton/year)

	Tanggu	Hangu	Dagang	Dongli
Available water inflow	[6301, 6636]	[2490, 2614]	[4552, 4779]	[2487, 2625]
Water demand	[5728, 6014]	[2268, 2381]	[4139, 4345]	[2261, 2374]

Table 2 | The related coefficients of pollutants for each district

	Tanggu	Hangu	Dagang	Dongli
Pollutant production coefficient	[0.678, 0.712]	[0.784, 0.823]	[0.568, 0.597]	[0.710, 0.746]
Outlet concentration (ton/ton)	[0.022, 0.024]	[0.024, 0.025]	[0.023, 0.024]	[0.167, 0.175]
Inlet concentration (ton/ton)	[0.080, 0.084]	[0.086, 0.090]	[0.080, 0.084]	[0.586, 0.615]

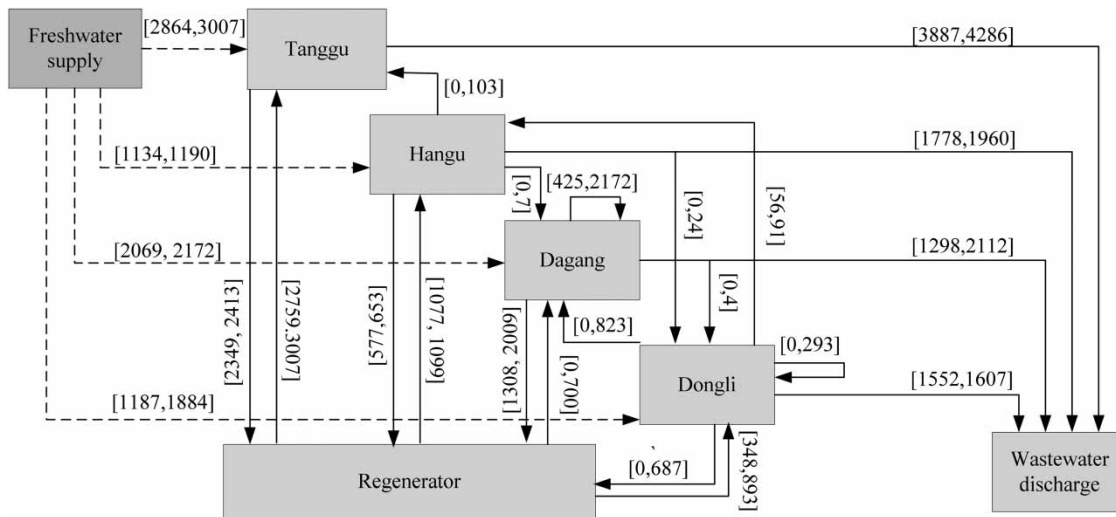


Figure 4 | Solutions of water allocation schemes and wastewater discharge.

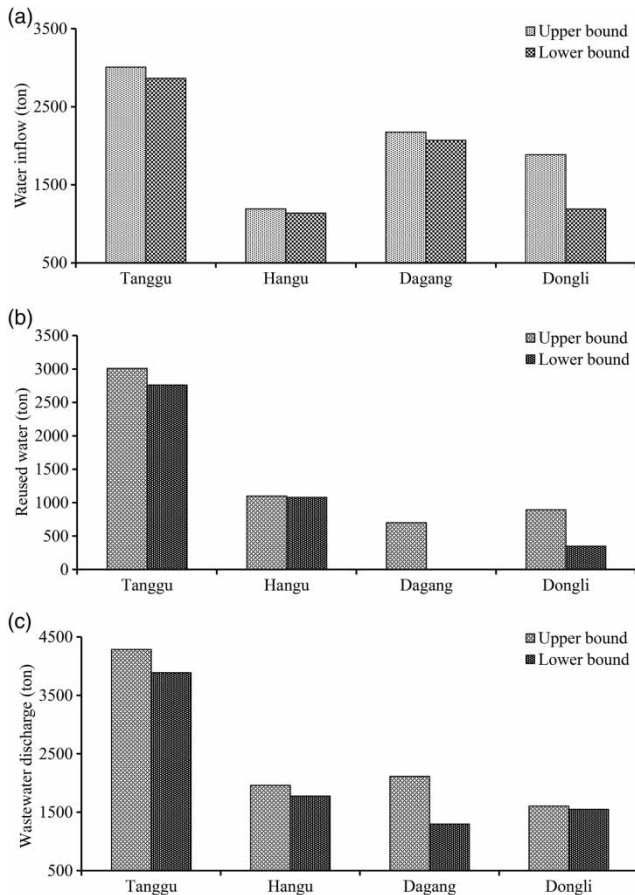


Figure 5 | Solutions of water allocation and wastewater discharge. (a) Solutions of water inflow. (b) Solutions of reused water flow. (c) Solutions of wastewater discharge.

for leisure and tourism than for industrialization. Thus, Hangu district requires less water than the more industrialized districts to ensure its sustained development. The salt

industry is the main constituent of the region's secondary industries, and could be supplied with reused water.

### Wastewater discharge and pollutants

According to the solution of the IMOP model, the discharged wastewater would be [3887, 4286], [1778, 1960], [1298, 2112] and [1552, 1607] ton from Tanggu, Hangu, Dagang, and Dongli, respectively (Figure 5(c)). High water consumption generally correlates with high wastewater discharge. For example, Tanggu district has the highest water allocations, and correspondingly discharges the largest quantity of wastewater. Dagang and Dongli district follow a similar trend. The emissions of NH<sub>3</sub>-N are [94, 98], [45, 48], [30, 51], and [260, 282] ton from each district, respectively. Water pollution is particularly severe in Dongli district, as a large amount of NH<sub>3</sub>-N is discharged into the aquatic environment due to the high concentration of NH<sub>3</sub>-N present in the industrial wastewater from heavy machinery and automobile factories. Therefore, a series of rigorous regulatory measures is needed to standardize the management of wastewater discharge.

### System benefit and cost

Table 3 shows the solutions for benefits and costs of the system. The calculated system benefit of [1.508, 1.575] × 10<sup>9</sup> RMB is associated with the profits from freshwater, recycled water, and reclaimed water. The net benefits would be [497.58, 544.18] × 10<sup>6</sup>, [45.59, 49.80] × 10<sup>6</sup>, [703.75, 763.89] × 10<sup>6</sup>, and [211.64, 278.23] × 10<sup>6</sup> RMB for



**Table 3** | Net system benefit and cost for each user district during the planning period

District	System benefit (10 <sup>6</sup> RMB)	Related cost (10 <sup>3</sup> RMB)
Tanggu	[497.58, 544.18]	[21.37, 23.47]
Hangu	[45.59, 49.80]	[8.74, 9.67]
Dagang	[703.75, 763.89]	[15.15, 15.39]
Dongli	[211.64, 278.23]	[12.95, 17.04]

Tanggu, Hangu, Dagang, and Dongli district, respectively. Dagang, an important petrochemical base, possesses a comprehensive production system that dominates its characteristics in the analysis. Its increased net water consumption would lead to a higher economic benefit. However, less benefit would be obtained in Hangu district due to its traditional industrial structure. The system cost associated with the freshwater supply, wastewater, and reused water treatment is  $[47.70, 48.44] \times 10^3$  RMB. The costs for the four districts would be  $[21.37, 23.47] \times 10^3$ ,  $[8.74, 9.67] \times 10^3$ ,  $[15.15, 15.39] \times 10^3$ , and  $[12.95, 17.04] \times 10^3$  RMB, respectively. The results indicate that a higher benefit could be obtained if the water demands are satisfied, but at a correspondingly high cost.

## CONCLUSIONS

The developed model was applied to industrial water-resources management in Binhai New Area, Tianjin, China. The model allows uncertainties presented as interval values to be incorporated within a general multi-objective optimization framework. Net system benefits, pollutant emissions, and system costs were analyzed. Complexities associated with water quality management can be systematically reflected in the model. To generate solutions, the model is transformed into two deterministic sub-models, which correspond to the lower and upper bounds of the objective-function value. Interval solutions can then be generated by sequentially solving the two sub-models. The results are useful for guiding the adjustment or justification of the existing water allocation schemes within a complicated and uncertain water resources system.

The proposed method could assist water resource managers to identify desired management policies under various considerations. However, the model includes some limitations. For example, the distances between the industrial plants and the regenerator are not taken into account, and the study period of 2 years is short. These limitations

could lead to weak system stability and unbalanced allocation patterns. More-complex models and hybrid approaches should be developed, over a longer study period, to obtain more-applicable results. In addition, only four water use sectors are considered here. To obtain a detailed water allocation plan, more water users should be taken into account. Moreover, the model considers the situation of industrial plants; other models (such as agricultural, municipal, and environmental) should also be considered in future research efforts.

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