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Conjunctive use of Inter-Basin Transferred and Desalinated Water in a Multi-Source Water Supply System Based on Cost-Benefit Analysis

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Abstract Water shortage has forced coastal cities to seek multi-source water supply with a focus on inter-basin water and desalinated seawater. The differences of water supply costs pose a challenge in the optimal use of multiple water resources. This paper aims to understand the impact of desalinated seawater's variable costs on multi-source water supply through a cost-benefit analysis method based on a multi-objective optimization model, considering different combination scenarios of desalination yield, streamflow condition, seawater desalting plant (SDP) scheme, water shortage index and utilization ratio of the SDP. The application in the coastal city Tianjin, China shows that the desalination yield has an impact on the tradeoff between the water shortage index and the total water supply cost and an optimal desalination yield can be determined at a turning point. And where the turning point appears is influenced by the utilization ratio of the SDP and streamflow conditions of inter-basin water. Moreover, a single centralized SDP is found to have an overall lower water supply cost than several decentralized small-sized SDPs. Lower water shortage index leads to higher cost, and the unit decrease of shortage index will need more added cost when the shortage index is very low. This method is proven to be effective in identifying the best conjunctive use of inter-basin water and desalinated seawater, which can contribute to relieve urban water shortage.

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1 Introduction

With growing economy and population, sustainable water supply has become a serious problem in many cities across the world. Multiple water sources such as inter-basin transferred water and desalinated seawater have been increasingly used in water-scarce coastal cities. Inter-basin water transfer has become an important means to meet the allocation mismatch between natural water resources and human demand (Zhang et al. 2012). Many water transfer schemes have been constructed in the world, for instance, the West to East Water Transfer Project in Pakistan, the California State Water Project, and the South to North Water Transfer Project in China. Seawater desalination for industrial and municipal uses is another promising solution (Ziolkowska 2015; Crisp and Swinton 2008; Ghaffour 2009). For example, in Israel, desalinated seawater is supplied continuously and reliably into the regional and national grids from three large seawater desalting plants (SDPs), at the rate of about 300 million $m^3 \cdot a^{-1}$ in 2011, accounting for about 21% of total potable water supply in the country (Tenne et al. 2013). In recent decades, continuous progress in desalination technologies makes it a prime, if not the only, candidate for alleviating severe water shortages across the globe (Ettouney et al. 2002).

The combined use of multiple water sources brings new challenges to water resources management. Due to varying water supply costs from different water sources, finding the optimal water supply solution is generally a multi-objective optimization problem that needs to consider the costs and benefits arising from the uses of different water sources and many different formulations have been used in the literature. For example, Tabari and Soltani (2013) developed a multi-objective model for the management of conjunctive use of surface and ground water, maximizing the minimum reliability of system as well as minimizing the costs due to water supply, aquifer reclamation and violation of the reservoir capacity in operation and allocation priority. Vieira et al. (2014) described an optimization model for large-scale multisource water-supply systems, taking economic, environmental, technical, and legal criteria into account. Gaivoronski et al. (2012) developed a cost–risk balanced management model for multisource water-supply systems management to meet various users' demands using a multistage stochastic programming approach. Al-Zahrani et al. (2016) proposed a multi-objective programming model for water distribution from multiple sources to multiple users, considering five objectives: satisfy domestic, agricultural and industrial water demands from 2015 through 2050; satisfy water quality for these sectors; maximize treated wastewater reuse in the agriculture; minimize groundwater extraction; minimize overproduction of desalinated water; and minimize overall cost of water consumption.

However, previous research paid little attention to non-conventional water sources such as desalinated seawater which has become more and more important in reducing urban water shortage. What's more, previous multi-objective optimization problem formulations with regard to cost and benefit usually take a simplified way to calculate water supply costs. Actually, differing from conventional water resources, the cost of desalinated seawater is associated with the production yield and the SDP capacity instead of a fixed value due to economies of scale (Hsu and Li 2009). On one hand, the unit production cost would decrease with the increase of the production yield when the SDP capacity is stable. On the other hand, a SDP with a large capacity is able to operate more economically than a small-sized SDP. Therefore, the water supply cost of desalinated seawater is variable, which should be considered in the optimization process.

This paper proposes a cost-benefit analysis method for analyzing the effect of variable costs of desalinated seawater on the conjunctive use of urban multiple water resources. Firstly, the study area Tianjin of China and its water supply system are introduced. Secondly, based on the assumptions about varying costs of desalinated seawater, a multi-objective optimization model for multi-source water supply is formulated. Finally, this model is applied to the case study under different combination scenarios of desalinated seawater yields, SDP schemes, shortage indexes and utilization ratios of the SDP, and their impacts on total water supply cost are analyzed and discussed.

2 Case Study

2.1 Study Area

Tianjin, a coastal city in China, is chosen because it has high economy and population growth rates but limited local freshwater resources and relies on multiple water sources to reduce the huge supply and demand gap. The annual average available local water resources of Tianjin city is only 160 m^3 per person, which is only 1/13 of the average level of China (2100 m^3 per person). In order to relieve water shortage, Tianjin has been diverting water from other river basins of abundant water resources, including Luan River and Hanjiang River (Mid-route of South-to-North Water Diversion Project, MSNWDP). Even so, the annual average per capita water of Tianjin city is still far below the world's recommended warning line for water scarcity (1000 m^3 per person). Therefore, Tianjin has been using desalinated seawater and by 2015, the capacity of desalinated seawater in Tianjin is 0.31 million m^3 per day, accounting for 34% of total desalination capacity in China. However, the use of desalinated seawater in Tianjin is still far below its full potential because the utilization ratios (yield / SDP capacity) of most SDPs are less than 50%. There is a need to improve the efficiency of desalinated seawater in conjunction with other water sources available in Tianjin.

2.2 The Water Supply System

The water supply system of Tianjin as of 2015 is shown in Fig. S1. There are 3 main types of water sources supplying for 11 regions of 4 plates, including water transferred through the MSNWDP, water transferred from Luan River and desalinated seawater. The two types of inter-basin water sources are diverted to 19 water treatment works (WTWs). It's worth noting that the streamflow from Luan River comes into YQ reservoir, providing water for Tianjin together with the natural inflow of YQ reservoir. Because the regulating storage of YQ reservoir and the capacity of supply pipes are large, it could decide when to divert water from Luan River and how much water will be diverted every month. The streamflow from the Mid-route of South-to-North Water Diversion Project (MSNWDP) comes into Tianjin from WQT reservoir, which cannot be stored and regulated due to the small available storage of WQT reservoir and BT reservoir. Desalinated seawater is mainly provided to coastal regions where it is produced, so its transportation costs could be neglected.

3 Methodology

3.1 Variable Costs of Desalinated Seawater

The production cost of desalinated seawater consists of capital and operating costs. The capital cost is mainly affected by the SDP capacity, and the operating cost varies with the facility capacity and utilization ratio. The unit production cost of desalinated seawater (Druetta et al. 2014) is calculated as

$$c = \frac{a \times c_1(v) \times v + c_2(v,q) \times q}{q} \tag{1}$$

where a (yr^{-1}) represents amortization factor; v (m^3/d) is the SDP capacity and q (m^3) is the annual production yield of SDP; $c_1(v)$ ($) represents the unit capital cost which is the function of v; $c_2(v,q)$ ($) represents the unit operating cost which is the function of v and q. The experience range of the unit production cost is \$0.45–\$2.51/m^3 (Ziolkowska 2015; Bennett 2011).

The amortization factor is calculated as

$$a = \frac{i(1+\mathrm{i})^n}{(1+\mathrm{i})^n - 1} \tag{2}$$

where i is the annual interest rate and n is SDP life (in years). It is indicated from references (Ettouney et al. 2002; Mabrouk et al. 2010) that an amortization life of 20–30 years is adequate and an interest rate in the range of 5–10% is common for economic analysis. So i and n are set as 25 and 5% respectively.

The unit capital cost $c_1(v)$ is calculated through curve fitting using the data collecting from references (Lapuente 2012), and its formulation is as below.

$$c_1(v) = \alpha_1 c_1^0 \beta_1^{(v-v_0)} + \gamma_1 \tag{3}$$

where c_1^0($) represents the capital cost of the SDP with capacity v_0 (10^4 m^3/d) and γ_1($) represents the lowest unit capital cost. The value of c_1^0, v_0 and γ_1 are 1666, 3 and 1004 respectively. The fixed coefficients α_1 and β_1 are 0.37 and 0.95 respectively.

When the SDP capacity is fixed, the unit operating cost $c_2(v,q)$ would decrease with the increase of production yield due to economies of scale. The experience formulation of $c_2(v,q)$ is shown as below.

$$c_2(v,q) = c_1(v)\mu^q \tag{4}$$

Through considering several factors including energy cost, chemical cost, labor cost, etc. (Ettouney et al. 2002; Mabrouk et al. 2010), μ is set as 0.975 to make the unit production cost of desalinated seawater (including capital cost and operating cost) in the experience range.

Moreover, considering the fact that the SDP rarely operates at full capacity and the utilization ratio generally remains between 50%–80%, another assumption is proposed that the unit cost remains unchanged after the utilization ratio of the SDP reaches 50% because the SDP has entered into a stable operation state.

Figure 1 shows the unit cost of desalinated water calculated using above equations under different SDP capacity. The unit cost decreases with the increasing production yield and then remains the same after the production yield reaches a half of the SDP capacity. The decline rate of unit cost reduces rapidly before it becomes stable. When the production yield is low, the larger the SDP capacity, the higher the unit water supply cost will be. This is because the
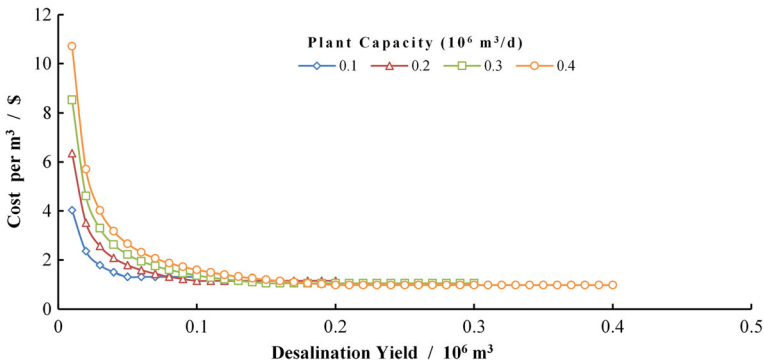
Fig. 1 The unit cost of desalinated seawater under different SDP capacity

amortization of the capital cost of a large-sized SDP is much higher than that of a small-sized one. On the contrary, the unit water supply cost of a large-sized SDP is lower than that of a small-sized one when the production yield is large enough that the SDP has remained a stable operation. This is because the efficiency of a large-sized SDP is higher than that of a small-sized one under the state of stable operation.

3.2 Problem Formulation

The raw water cost of inter-basin water from Hanjiang River is much higher than that from Luan River for its longer water delivery distance, and the two sources are diverted to different WTWs. The longer the distance from the diversion main point to WTW, the higher the water supply cost will be. Thus, this paper considers the optimal distribution of two inter-basin water sources under different scenarios of desalination yield, aiming at analyzing the impact of the variable cost of desalinated seawater on the tradeoff between benefit and cost.

3.2.1 Optimization Model

To achieve the optimal operation of two kinds of inter-basin water, a model based on the topology network of "Source-WTW-RegionUser" water-supply system (as shown in Fig. S2) is formulated. Topological relationship matrices are established to reveal topology information. The topological relationship matrix of the inter-basin water distributed to WTWs is represented by X, where $x_{i,j}$ represents the supply relationship between inter-basin water source i and WTW j. If WTW j is supplied by inter-basin water source i, then $x_{i,j} = 1$, otherwise $x_{i,j} = 0$. The topological relationship matrix of WTWs and users of each region is defined as Y, where $y_{j,kl}$ represents the supply relationship of WTW j and user l of region k. If user l of region k is supplied by WTW j, $y_{j,kl} = 1$, otherwise $y_{j,kl} = 0$.

(1)   Objective functions

One objective is minimizing the water supply system's water shortage:

$$\text{Min Shortage Index} = \frac{\sum \text{water deficit in } a \text{ period}}{\sum \text{water demand in } a \text{ period}} \tag{5}$$

$$\sum water \quad deficit \quad in \ a \ period = \sum_{k=1}^{K} \sum_{l=1}^{L} \sum_{t=1}^{T} D_{kl,t} - \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{l=1}^{L} \sum_{t=1}^{T} S_{j,kl,t} \times y_{j,kl} \qquad (6)$$

$$\sum water \quad demand \quad in \ a \ period = \sum_{k=1}^{K} \sum_{l=1}^{L} \sum_{t=1}^{T} D_{kl,t} \qquad (7)$$

The other objective is minimizing annual water supply cost of two kinds of inter-basin water:

$$Min \ \ Cost = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} W_{i,j,t} \times x_{i,j} \times C_{i,j} \qquad (8)$$

where $D_{kl,t}$ (m^3) represents inter-basin water demand (total water demand deducts the desalination yield of other water sources) of user l of region k at period t; $S_{j,kl,t}$ (m^3) represents the inter-basin water diverted to user l of region k through WTW j at period t; $W_{i,j,t}$ (m^3) represents the water diverted to WTW j from inter-basin water source i at period t; $C_{i,j}$ ($) represents the cost of water diverted to WTW j from inter-basin water source i, which is calculated and provided by Tianjin government through considering several factors, including capital costs (e.g., Land, Water conveyance project, Buildings) and operation and maintenance costs (e.g., Energy consumption, Labor, Insurance); L、K、J、I、T represent the number of users, regions, WTWs, inter-basin water sources and periods, respectively.

(2) Constraint conditions
1) Supply and demand balance. The inter-basin water diverted to user l of region k should be equal to or less than its inter-basin water demand in every period.

$$d_{kl,t} = \sum_{j=1}^{J} S_{j,kl,t} \times y_{j,kl} \leq D_{kl,t} \qquad (9)$$

2) Water balance at WTW node. The water yield diverted to WTW j from all the inter-basin water sources should be equal to the water yield of all the users of regions supplied by WTW j in every period.

$$\sum_{i=1}^{I} W_{i,j,t} \times x_{i,j} = \sum_{k=1}^{K} \sum_{l=1}^{L} S_{j,kl,t} \times y_{j,kl} \qquad (10)$$

3) The capacity of water source. Because the inter-basin water from Hanjiang River could not be stored, so its water supply yield should not exceed its planning water supply capacity in every period. On the opposite, the inter-basin water from Luan River could be stored and regulated, so only annual capacity limitation should be considered. The capacity at each period

$$q_{i,t} = \sum_{j=1}^{J} W_{i,j,t} \times x_{i,j} \leq Q_{i,t} \qquad (11)$$

The annual capacity

$$\sum_{t=1}^{T} q_{i,t} \leq Q_{i,\max} \tag{12}$$

4) The capacity of WTW. The water yield should not exceed the treatment capacity of WTW in every period.

$$p_{j,t} = \sum_{i=1}^{I} W_{i,j,t} \times x_{i,j} \leq P_{j,t} \tag{13}$$

5) The capacity of water supply pipe

In the real water supply system, water is firstly diverted through trunk pipes, then diverted to WTWs through branch pipes, and finally diverted to users of every region. Both water supply capacity of trunk pipes and branch pipes should be taken into account as below.

The capacity of trunk pipe is

$$g_{im,t} = \sum_{j=1}^{J} W_{i,j,t} \times a_{im,j} \leq G_{im,t} \tag{14}$$

and the capacity of branch pipe is

$$W_{i,j,t} \leq B_{i,j,t} \tag{15}$$

$$S_{j,kl,t} \leq B'_{j,kl,t} \tag{16}$$

6) Nonnegative variable

$$W_{i,j,t} \geq 0; S_{j,kl,t} \geq 0 \tag{17}$$

In Eqs. (9) ~ (17), $d_{kl,t}$ (m^3) represents the received water of user l of region k at period t; $q_{i,t}$ (m^3), $Q_{i,t}$ (m^3) represent the water supply and the capacity of inter-basin water source i at period t respectively while $Q_{i,max}$ (m^3) represents the annual capacity of inter-basin water source i; $p_{j,t}$ (m^3), $P_{j,t}$ (m^3) represent the water supply and the capacity of WTW j at period t respectively; $g_{im,t}$ (m^3), $G_{im,t}$ (m^3) represent the water supply and the capacity of trunk pipe im at period t respectively; $a_{im,j}$ represents the supply relationship of trunk pipe im and WTW j. If WTW j is supplied by trunk pipe im, $a_{im,j} = 1$, otherwise $a_{im,j} = 0$. $B_{i,j,t}$ represents the capacity of branch pipe connecting inter-basin water source i and WTW j; $B'_{j,kl,t}$ represents the capacity of branch pipe connecting WTW j and user l of region k.

3.2.2 Solution Method

The NSGA-II algorithm proposed by Deb et al. (2002) is applied to solve this multi-objective optimization problem. NSGA-II is a non-dominated sorting GA approach, which uses a fast non-dominated sorting procedure, an elitist-preserving approach, and a parameterless niching operator. This technique has been proven effective in solving the wide range of water management problems such as water allocation and water quality management (Fu et al. 2008, 2010; Bazargan-Lari et al. 2009; Sweetapple et al. 2014).

The input data of the model include inter-basin water demands, historical streamflow series of the two inter-basin water transfer sources from Luan River and MSNWDP, the unit production cost of desalinated seawater, and the unit cost of inter-basin transferred water to each WTW. It's worth noting that yearly streamflow series from Luan River and monthly streamflow series from MSNWDP are used in the model. The decision variables are inter-basin water diversion $S_{j,kl,t}$ (the inter-basin water supplied by WTW j to user l of region k at period t) and $W_{i,j,t}$ (the water diverted to WTW j from inter-basin water source i at period t). There are 2 inter-basin water sources, 19 WTWs, 11 regions and 3 users, resulting in a total of $(2 \times 19 + 19 \times 11 \times 3) \times 12 = 7980$ decision variables where 12 represents the time step, 12 months in a year. The population and generation sizes of NSGA-II in this study are set to 500 and 500,000 respectively.

3.3 Optimization Scenarios

To understand the impacts of the variable costs of desalinated seawater on the conjunctive use of multiple water sources in Tianjin, the cost-benefit analysis process based on the optimization model proposed above is demonstrated as follows.

(1) According to Tianjin's development plans of seawater desalination, 10 scenarios of desalination yield are set (as shown in Table 1), aiming at analyzing the impact of different desalination yield on water distribution and total water supply cost.

(2) Using the optimization model for two kinds of inter-basin water, calculate the Pareto front of two objectives including the water supply cost of inter-basin water and the water shortage index under each desalination yield scenario.

(3) Under a specified water shortage index, choose the corresponding water supply cost of inter-basin water from the Pareto front of each desalination yield scenario, and then analyze the changes of these chosen costs along with the increase of desalination yield. Then calculate the total water supply cost of inter-basin water and desalinated seawater under different desalination yield scenario, determining the optimal desalination yield which makes total cost lowest.

(4) According to the different combinations of wetness-dryness conditions of the inter-basin water sources (as shown in Fig. S3 of supplemental materials), we have chosen four typical years to evaluate the impact of the uncertainties of streamflow on the total water supply cost through repeating step (1) to step (3). The typical years are described as follows:

   A. The streamflow from the MSNWDP is low while the streamflow from Luan River is high, and 1978 when the streamflow from the MSNWDP is the lowest in history is chosen as the typical year A.

   B. The streamflow from the MSNWDP is high while the streamflow from Luan River is low, and 1984 when the streamflow from Luan River is the lowest in history is chosen as the typical year B.

Table 1 Desalination yield scenarios (10^6 m³/d)

Scenario	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10
Yield	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1

C. The streamflow from the MSNWDP and from Luan River is both high, and 1986 is chosen as the typical year C.

D. The streamflow from the MSNWDP and Luan River is both low. Although this condition didn't happen in the history, it would have adverse effects on the water supply once it appears. So we also take this condition into consideration, and the lowest streamflow ever appeared of two kinds of inter-basin water (The lowest streamflow from MSNWDP appears in 1978 while the lowest streamflow from Luan River appears in 1984) are chosen as the streamflow of the typical year D.

(5) The distribution and the capacity of SDPs will have effects on the total water supply cost of inter-basin water and desalinated seawater, leading to different water allocation schemes. In order to choose reasonable distribution plan and capacity of SDPs, 8 planning schemes of SDPs including single-SDP schemes, two-SDP schemes and three-SDP schemes are proposed, as shown in Table 2. Under each SDPs scheme, analyze the changes of total water supply cost along with the increase of desalination yield through repeating step (1) to step (3).

(6) Three water shortage indexes (0.05, 0.10, 0.15) are set to assess the impacts of different water shortage to total water supply cost through repeating step (1) to step (3).

(7) Three utilization ratios (40%, 50% and 60%) of the SDP are respectively set to discuss the sensitivity of the results to the utilization ratio of the SDP through repeating step (1) to step (3).

4 Results and Discussion

4.1 Pareto Fronts

Taking the result of typical year A as an example(the streamflow from the MSNWDP is low while the streamflow from Luan River is high), the Pareto fronts under ten desalination yield scenarios are shown in Fig. 2a. When the desalination yield is fixed, the water supply cost of inter-basin water increases with the decrease of water shortage index, indicating that the two objectives are competing. With the increase of desalination yield, the minimize water shortage index of the corresponding Pareto front is closer to 0. For example, the minimize water shortage index of the Pareto front under scenario L1 is 0.05 while the minimize water shortage index of the Pareto front under scenario L10 is 0.005. This is because the increase of desalination yield contributes to alleviating the water supply pressure of fresh water and reducing water shortage. Additionally, when the water shortage index is fixed, the increase of desalination yield will lead to the decrease of water supply cost of inter-basin water because of the reduction of inter-basin water. The Pareto fronts under another three typical years (typical year B, C, D) are shown in Fig. S4 of the supplementary materials.

Table 2 Seawater desalinating plants (SDPs) schemes

Type	Single SDP	Two SDPs					Three SDPs	
Scheme	S1	S2	S3	S4	S5	S6	S7	S8
SDP	1	0.5	0.6	0.7	0.8	0.9	0.4	0.6
Capacity	-	0.5	0.4	0.3	0.2	0.1	0.3	0.2
(10^6 m^3/d)	-	-	-	-	-	-	0.3	0.2

Fig. 2 **a** Pareto fronts under different desalination yield scenario (Typical year: *A*); **b** Total water supply costs (Typical year: *A*; Shortage Index: 0.05; SDP Scheme: S1)
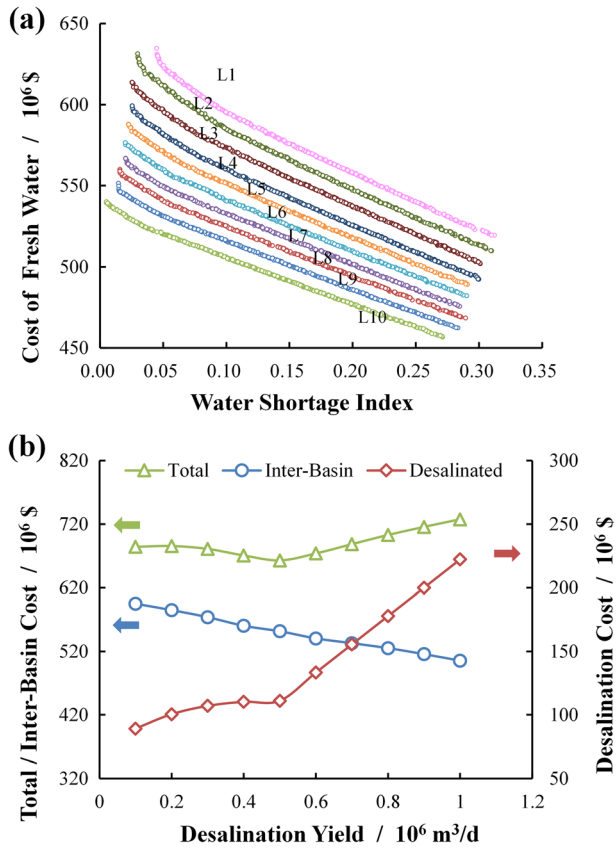
Figure 2b shows the relationship between water supply cost and desalination yield when the shortage index is 0.05 and the SDP scheme is S1 (a SDP of 100 million m³ per day), where those circular symbols represent the water supply cost of inter-basin water, and those diamond symbols represent the water supply cost of desalinated seawater, and those triangular symbols represent the total water supply cost.

With desalination yield increasing, the water supply cost of desalinated seawater firstly increases at a gradually reduced rate before the desalination yield reaches 0.5 million m³ (the corresponding scenario, L5) and then increases linearly. This is because the unit water supply cost of desalinated seawater consists of unit fixed cost and unit operating cost (Eq. (1)), which will be influenced by desalination yield when the capacity of SDP is fixed. According to Eq. (1) and the assumption that the unit cost remain unchanged after the utilization ratio of SDP reaches 50% for the SDP has entered into a stable operation state, the unit water supply cost of desalinated seawater will decrease at a gradually reduced rate before the utilization ratio of SDP reaches 50% and then maintains constant (as shown in Fig. 1).

With desalination yield increasing, the cost of inter-basin water decreases at an almost uniform rate. The reason is that Tianjin mainly relies on the inter-basin water from Luan River under typical year *A* due to the water source of MSNWDP encounters dry year. The inter-basin water from Luan River for four coastal regions (regions R5, R8, R10, R11) is replaced by the

same desalination yield and the difference between the unit inter-basin water supply costs for these coastal regions are very small.

With desalination yield increasing, it's interesting to see the total water supply cost of inter-basin water and desalinated seawater firstly decreases and then increases, resulting in a turning point, where the cost is lowest in the curve and the corresponding desalination yield (L5, 0.5 million m³ per day) is the most optimal yield compromising cost and benefit.

4.2 Impact Analysis

To understand the impact of the uncertainties of streamflow, the capacity of SDPs and the water shortage index on the total water supply cost, eight planning schemes of SDPs (as shown in Table 2), historical streamflow conditions of four typical years (as shown in section 3.3) and three water shortage indexes (0.05, 0.10, 0.15) are set as the input data and boundary conditions of model respectively. The impact analysis results associated with above factors are demonstrated in Fig. 3.

In section 3.1, an assumption is made that the unit cost remains unchanged after the utilization ratio of the SDP reaches 50% because the SDP has entered into a stable operation state. In order to discuss the sensitivity of the results to the utilization ratio of the SDP, three utilization ratios (40%, 50% and 60%) are set as the boundary conditions of model and the impact analysis results are shown in Fig. 4.

4.2.1 The Uncertainties of Streamflow

When the water shortage index is 0.1 and the SDP scheme is S1, the relationships between total water supply cost and desalination yield under the streamflow conditions of 4 typical years proposed above are shown in Fig. 3a. When the streamflow from Luan River is high, it will be used fully and preferentially due to its cheaper cost, and the total water supply cost would be relatively low (such as typical year A and C). The impact of expensive desalinated seawater's variable costs on the total water supply cost is so significant that the turning point determined by the utilization ratio (50%, as shown in Fig. 1) in the desalinated seawater cost curve is exactly the optimal yield (0.5 million m³/d) which makes total cost lowest. When the streamflow from Luan River is low, more expensive water from South-to-North Water Diversion Project has to be used to satisfy water demand (such as typical year B and D), of which the costs for several coastal regions are even higher than desalinated seawater, leading to high total water supply cost. So more desalinated seawater would like to be used to replace the inter-basin water from South-to-North Water Diversion Project and the turning point move backward to 0.7 million m³/d.

4.2.2 The SDP Capacity

When the water shortage index is 0.9 and the typical year is A, the relationships between total water supply cost and desalination yield under 8 SDP schemes proposed above (including single-SDP scheme S1, two-SDP schemes S2-S6 and three-SDP schemes S7-S8) are shown in Fig. 3b. It reveals that the water supply cost of several decentralized small-sized SDPs (S2-S8) is higher than that of a single centralized large-sized SDP (S1) when the desalination yield is fixed, and their gap is getting wider with the increase of desalination yield, which could be explained from two aspects: 1) the unit capital cost of a small-sized SDP is higher than that of a

Fig. 3 **a** Total costs under the streamflow conditions of four typical years (SDP scheme: S1; Shortage Index: 0.1); **b** Total costs under 8 desalination SDP schemes (Shortage Index: 0.1; Typical year: A); **c** Total costs with three shortage indexes (SDP scheme: S1; Typical year: A)
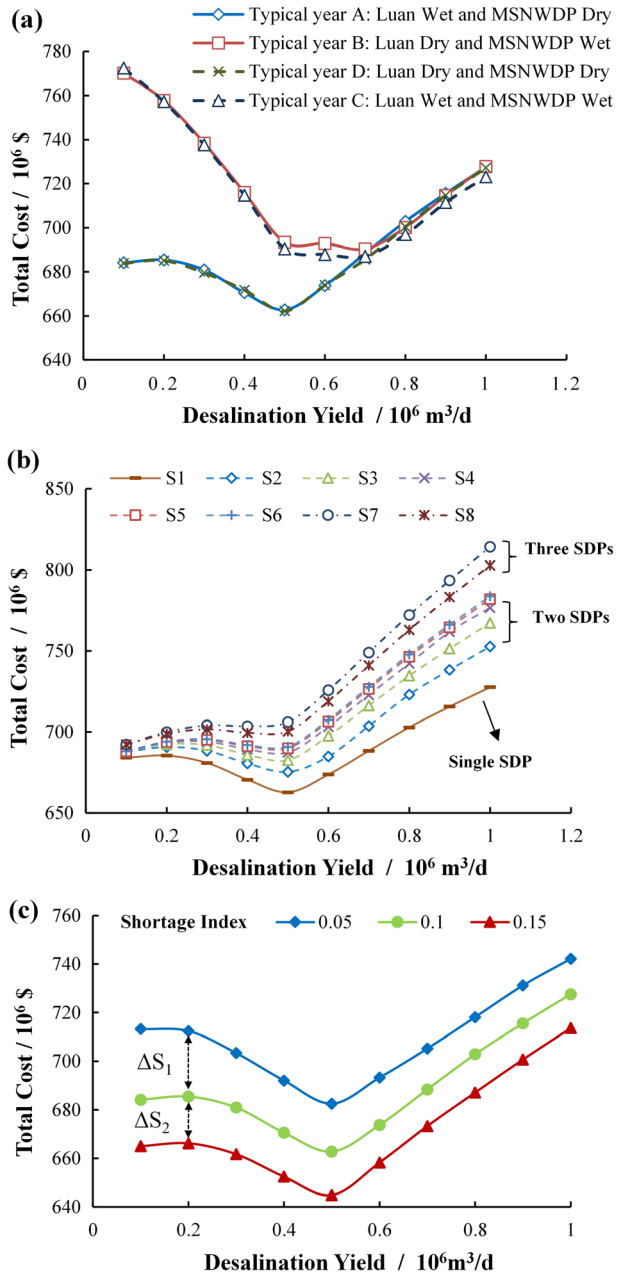
large-sized one, as illustrated in Eq. (3), so these decentralized SDP schemes will have higher unit capital costs than the centralized SDP scheme when the total desalination capacity is fixed; 2) the unit operating cost of a large-sized SDP reduced more substantially than that of a small-sized one with the increase of desalination yield, as illustrated in Eq. (4), so these decentralized SDP schemes will have the lower reduction rates of unit operating cost than the centralized SDP scheme when the total desalination capacity is fixed. Therefore, the centralized SDP

Fig. 4 a The variable costs of desalinated seawater with three utilization ratios of SDP (SDP scheme: S1); **b** The total water supply costs with three utilization ratios of the SDP under the streamflow condition of typical year *A* (SDP scheme: S1; Shortage Index: 0.1); **c** The total water supply costs with three utilization ratios of the SDP under the streamflow condition of typical year *B* (SDP scheme: S1; Shortage Index: 0.1)
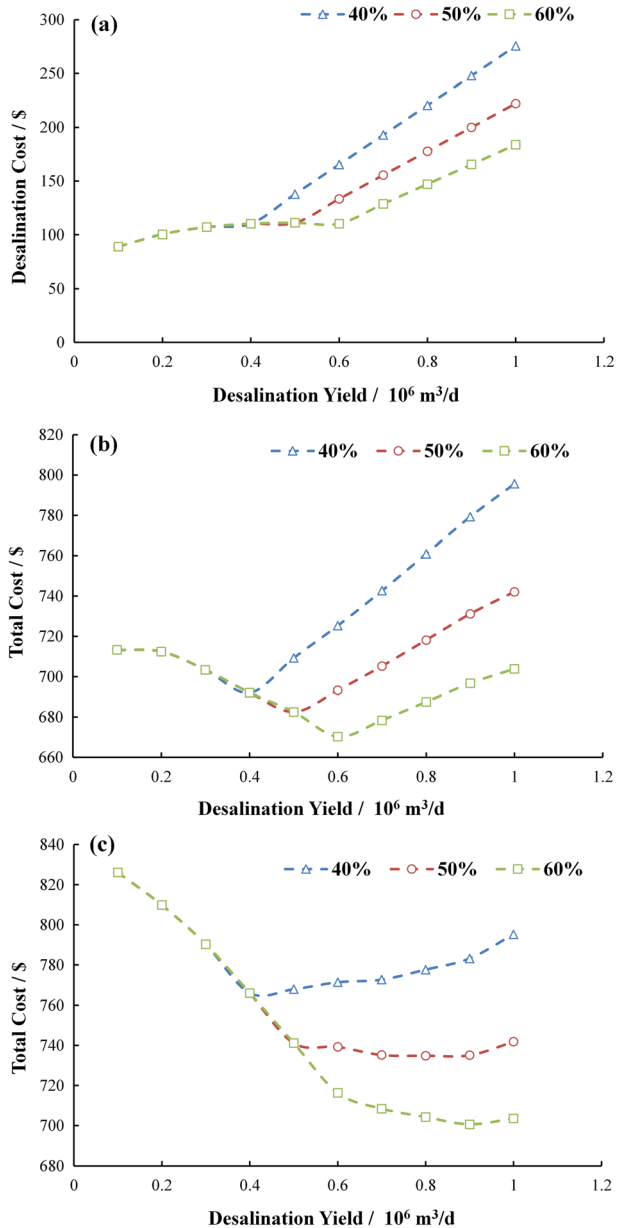
scheme S1 is found to be better than these decentralized SDP schemes (S2- S8). Similarly, two-SDP schemes (S2- S6) are found to be better than three-SDP schemes (S7-S8).

4.2.3 The Water Shortage Index

Figures 2a and S4 shows that the water supply cost of inter-basin water will increase with the water shortage index decreasing, and the cost increases substantially at the higher end of each

Pareto front, leading to a turning point in each Pareto front, after which the Pareto front has bigger slope than before, implying that the unit decrease of water shortage index requires more water supply cost. With the increase of the desalination yield, the turning point will move to the higher end of the Pareto front. For example, in Fig. S4(a), the turning point appears at where the shortage index is 0.1 under the scenario L7 while it appears at where the shortage index is 0.15 under the scenario L5.

Aiming at contrasting the difference of the increased total cost before and after the turning point, three shortage index including 0.05, 0.10 and 0.15 are selected to analyze the impact of shortage index on total water supply cost when the SDP scheme is S1 and the typical year is A. The variation of the total water supply cost under three shortage indexes is shown in Fig. 3c. It reveals that lower shortage index results in higher cost under the fixed desalination yield. If a decision-maker prefers to guarantee urban water supply security, the water supply plan with low shortage index is recommended but at the expense of high cost; on the contrary, the water supply plan with low cost is an economic choice but increasing the water shortage. In addition, when the shortage index is lower than the turning point, the unit decrease of shortage index leads to more increased cost. For example, in Fig. 3c, under the desalination yield scenario L2 (0.2 million m^3 per day), ΔS_1 and ΔS_2 represent the added cost when the shortage index decreases from 0.1 (the turning point) to 0.05 and from 0.15 to 0.1 respectively, and ΔS_1 is greater than ΔS_2 obviously. This is because the cheap water source is used first in the optimization process, and more expense water source has to be used to satisfy the increasing water demand.

4.2.4 The Utilization Ratio of SDP

When the water shortage index is 0.1 and the SDP scheme is S1, Fig. 4a shows the variable costs of desalinated seawater with three utilization ratios of the SDP. With the desalination yield increasing, the water supply cost of desalinated seawater firstly increases at a gradually reduced rate before the desalination yield reaches the utilization ratio and then increases linearly. After the desalination yield reaches the utilization ratio, the higher the utilization ratios is, the lower the cost would be.

Figure 4b shows the total water supply costs with three utilization ratios of the SDP under the streamflow condition of typical year A (The streamflow from the Mid-route of South-to-North Water Diversion Project is low while the streamflow from Luan River is high). When the streamflow from Luan River is high, it will be used fully and preferentially and the total water supply cost would be relatively low due to its cheaper cost. The impact of the expensive desalinated seawater's variable costs on the total water supply cost is so significant that the turning point in the total cost curve is mainly determined by the utilization ratio of the SDP. For instance, as shown in Fig. 4b, the turning point appears at 0.4 million m^3/d, 0.5 million m^3/d and 0.6 million m^3/d when the utilization ratio are 40%, 50% and 60% respectively.

Under the streamflow condition of typical year B (The streamflow from the Mid-route of South-to-North Water Diversion Project is high while the streamflow from Luan River is low), Fig. 4c shows the total water supply costs with three utilization ratios of the SDP. When the streamflow from Luan River is low, more expensive water from South-to-North Water Diversion Project has to be used to satisfy water demand, of which the costs for several coastal regions are even higher than desalinated seawater, leading to the high total water supply cost. So more desalinated seawater would like to be used to replace the inter-basin

water from South-to-North Water Diversion Project and the turning points move backward. For instance, as shown in Fig. 4c, the turning point appears at 0.7 million m^3/d when the utilization ratio is set as 50% while the turning point appears at 0.8 million m^3/d when the utilization ratio is set as 60%. Differently, when the utilization ratio is set as 40%, the desalination costs for several coastal regions are still higher than that of the inter-basin water from South-to-North Water Diversion Project, so less desalinated seawater is used and the turning point appears at 0.4 million m^3/d.

Above all, we found that the lowest turning point of the total cost is influenced by the utilization ratio of the SDP and the flow of inter-basin water diverted from the Mid-route of South-to-North Water Diversion Project significantly because they are both expensive.

5 Conclusions

This paper has proposed a cost-benefit analysis method to assess the impacts of the varying costs of desalinated seawater on the multi-source water management in a complex water supply system of Tianjin, China under different scenarios of desalination yield, streamflow condition, seawater desalinating plant (SDP) capacity, water shortage index and utilization ratios of SDP. A summary of the key findings are as follows:

(1) A multi-objective optimization model based on the assumptions about the varying costs of desalinated seawater has been proven effective in finding higher performing solutions on the tradeoff between the water shortage index and the total water supply cost of inter-basin water and desalinated seawater. The variable cost of desalinated seawater is affected by the SDP capacity and production yield. The unit cost would first decrease substantially with the increasing production yield and then remain the same after the SDP enters into a stable operation state. When the production yield is low, the larger the SDP capacity is, the higher the unit water supply cost would be. When the production yield is large enough, the unit water supply cost of a large-sized SDP is lower than that of a small-sized one.

(2) Analysis of costs and benefits from different desalination yield has revealed a turning point where the optimal water supply cost and the optimal desalination yield could be determined. The water supply cost of the turning point is mainly influenced by the shortage index and the SDP capacity: the water supply cost would increase with the shortage index decreasing and the cost grows faster than before after the water shortage decreases to a certain point; the water supply cost of a centralized SDP is lower than several decentralized SDPs due to economies of scale. Additionally, the desalination yield of the turning point is mainly influenced by both the utilization ratio of the SDP and the streamflow condition.

More work needs to be done in the future, such as collecting more data to verify the assumptions on the varying cost of desalinated seawater, and incorporating both the allocation and the variable production cost of desalinated seawater into the optimization process.

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