Water Resour Manage (2008) 22:911–923
DOI 10.1007/s11269-007-9201-0

Modeling Multisource Multiuser Water Resources Allocation

Yan Han · Shi-guo Xu · Xiang-zhou Xu

Received: 15 April 2006 / Accepted: 22 June 2007 /
Published online: 25 July 2007

Abstract Water shortage emerges and restricts the urban construction and the socio-economy development due to the rapid expansion of the cities throughout the world. Recently treated wastewater reuse, including rainwater collection and utilization, and seawater desalination, etc., has been put in practice in some cities. This paper presents the characteristics of urban multisource water and multiuser and a multi-objective optimization model of reasonable allocation on multisource water for multiuser under sufficiently considering the harmonious development among economy, society and environment. As a case study this model had been applied to the reasonable allocation of water supply and demand in Dalian City in 2010, 2015 and 2020, in which the maximal benefit of economy, society and environment was regarded as the multi-objectives and the step method was adopted to solve the model. The result indicates that the proportion of the reused water to the total water consumption is gradually increasing, but the proportion of the high quality water to the total water consumption is decreasing. In other words, as a secondary water resource, the reused water has replaced partial high quality water gradually. Consequently, the reasonable allocation of urban multisource water for multiuser is the available approach to alleviate urban water crisis and achieve the sustainable utilization of urban water resources.

Keywords Urban water resources · Reasonable allocation · Optimization model · Multi-objective · Sustainability

1 Introduction

Water, a limited resource, is vital for the life existence on earth, and is also the integral part of the urban society. When cities are relatively small and few, it is not difficult to obtain

Y. Han (✉) · S.-g. Xu · X.-z. Xu
School of Civil & Hydraulic Engineering, Dalian University of Technology, Dalian 116024, China
e-mail: hanyan78@163.com

water even in the arid areas. However, the urban water consumption has been remarkably increasing with the city and population expansion, so the limited water resource can not meet the demand of city development. Water resources in China are scarce. The total amount of water resources in China is 2.413×10^{13} m^3 in 2004, which is equal to 1,856 m^3 per capita (Zhang et al. 2007). More than half of the 667 cities in China are facing water shortage (He et al. 2001), and 27% of surface water quality in China is much lower than the lowest class of national water standard (FAO 1999). In China, the cities short of water are mainly located in the north or nearby the littoral, and the urban water shortage amounts to 4×10^{10} m^3 in 2000 (Ruan 2004). The shortage of water resources greatly influences the development of city and the basic lives of residents, and has become the main factor to obstruct the sustainable development of economy and society (Han and Xu 2005). To tackle the water crisis, the government of China has published a lot of regulations, but the water resource becomes increasingly deficient and the environmental quality becomes worse in most regions with the development of economics (Zhang et al. 2007). Especially in the northern arid area, the watercourse's basic flow is little or almost dry in the non-flood season. There is perennial sewage water in the watercourse, which has a bad effect on the environment of city and neighborhoods (Ran 2001).

Fortunately, treated wastewater reuse, including rainwater collection and utilization, and seawater desalination, etc., has been put in practice in some cities. Papaiacovou (2001) studied the wastewater reuse in Limassol as an alternative water source. Chu et al. (2004) analyzed the potential capacity of wastewater reuse in China. Zhang and Xu (2003) discussed the rainwater utilization in Dalian City of China. Tsiourtis (2001) introduced the experience of seawater desalination projects in Cyprus. Yen and Chen (2001) established an optimization linear programming model, in which the surface water and groundwater are integrated. Yamout and El-fadel (2005) presented a water resources allocation model and served it as a multi-sector decision support system for water resources management in the Greater Beirut Area. However, the socio-environmental impacts were only incorporated into the costs of water supply in this model, and the benefit of socio-environment had not been embodied well by a single objective function.

The objective of this paper is to present a systematic framework of multisource multiuser water resources allocation combining unconventional water resources with conventional water, and establish a multi-objective linear programming model to allocate multisource water among multiuser.

2 Urban Water Resources

Urban water resources refer to that hold enough water quantity and water quality, and can be utilized by urban residents, industry and agricultural (Liu 2003). They are the most precious resource and play an important role in course of urban development.

2.1 The Sort of Urban Water Resources

The types of urban water resources are different if the taxonomy is different. According to the regional characteristics of water, the urban water resources can be classified as local water resources and the diverting water from external region. According to the water's origin, urban water resources can also be classified as rainwater, surface water, groundwater, diverting water, seawater and reclaimed water. In this paper, the latter is adopted.

2.2 The Characteristics of Urban Water Resources

The characteristics of various water resources are as follows:

(a) Groundwater: Due to imbedding in underground, the groundwater is not easier to be polluted than surface water. The groundwater is relatively stable, and the water quality is preferable. The groundwater is mainly used in domestic and agriculture, also can be used by industry in abundance region.
(b) Surface water: As supplied by rainwater and groundwater, the amount of surface water is relatively abundant. Its impurity is higher than groundwater, but its salinity and rigidity is lower than seawater. Water quantity, level and quality can be greatly influenced by season and rainfall, and it is easily polluted. The range of utilization of surface water is extensive, such as domestic, industry, agriculture.
(c) Reclaimed water: As the second water source of city, the reclaimed water is more significant than diverting water, seawater desalting, rainwater gather. The merit of reclaimed water is that the water quantity is stable, and the water quality usually stabilizes within a certain extension. The reclaimed water might be used as water source to partially replace the groundwater and surface water. The reclaimed water can be used in landscape irrigation, industry cooling, toilet-flushing, and so on.
(d) Rainwater: Urban rainwater is a kind of resource, meanwhile can also be a possible disaster. Rainwater utilization will be an important measure to alleviate the urban water shortage and improve the urban water environment in course of urbanization. However, the rainwater utilization is usually affected by the natural condition, such as climate, distribution of rainfall in different season and rainwater quality.
(e) Diverting water from the external region: In arid region, as the local water resources are difficult to meet the demand of industry and agriculture, hydraulic structures are needed for diverting water from the external region. The diverting water is mainly used in domestic, agriculture and industry. The cost of diverting water is more expensive than local water, so the diverting water is usually used as supplement water source.
(f) Seawater: The utilization of seawater is usually restricted in littoral area. The seawater can be used for industry cooling and toilet-flushing, and it can also be desalted for high pressure boiler water. The cost of desalinization is about \$0.67~2.5 per cubic meters (Zheng and He 2003). In China, the cost of desalinization is about \$0.58~0.91 (4.5~7.0 Yuan) per cubic meters (Zheng and He 2003).

2.3 The Characteristics of Urban Water Consumption

The urban water consumption can be classified as water consumption of domestic, industry, agriculture and ecology. Their respective characteristics are as follows:

(a) Domestic water consumption: The domestic water consumption includes corporation, government, school, hotel, restaurant, bathroom, household, and so on. Domestic water consumption of city increases rapidly. The demand for the quality of domestic water is higher, which is mainly from tap water or well (groundwater). The guaranteed efficiency of water supply is higher (usually more than 95%), too.
(b) Industrial water consumption: Usually, the industry is one of the main water consumption sectors in a city. There is a high demand for the water consumption in industry, and the drainage amount of wastewater is also large, which is the main

pollution source to urban water environment. The demand for the quality of the industrial water consumption depends on the production type, facility and technology.

(c) Agricultural water consumption: The proportion of agricultural water consumption accounting for total urban water consumption is related to urban industry scale and structure. Although the amount of water consumption is large, the efficiency is lower, and the seasonal peculiarity is evident. The demand for quality of agricultural water consumption is lower than domestic water.

(d) Ecological water consumption: The ecological water consumption is usually used for improving the urban ecological environment or maintaining the ecological environment not to decline. It includes irrigating greenbelt, supplying water for river and lake, offering water for environment and sanitation. The demand for quality of ecological water consumption is usually lower, and the treated water can meet the requirement.

3 Methodology

3.1 Reasonable Allocation of Water Resources in City

On one hand, facing to the water resources shortage, the conflict of water supply and demand stands out, and the water environment is worsening in city; on the other hand, the disasters of flood and waterlog occur frequently; the volume of sewage (waste) water has been increasing year after year, and the treated sewage is let out without being used. In order to satisfy the urban water demand, the transporting water project need to be built to alleviate the urban water scarce, but a large amount of manpower, material resources and money have to be needed. It is well known that if there is no recycling of treated water, the more water is consumed, the more sewage (waste) water will be produced.

The definition of reasonable allocation of water resources is presented by Xu et al. (1997). Through using the structure measures and non-structure measures, the temporal-spatial characteristics of water resources is changed. He emphasized the water resources should be protected while it is exploited and utilized; the benefit from water exploitation and utilization is not for a while, but a long-time; the local surface water, groundwater, reclaimed water, diverting water and brackish water are allocated uniformly through using the optimization method. Thus, reasonable allocation of water resources changes the traditional water supply pattern, which only the groundwater and surface water are viewed as water resources. The groundwater, surface water, rainwater, reclaimed water, diverting water and seawater are regarded as the classification water source, then the multisource water are reasonably allocated based on users' demand for water quality and quantity.

3.2 The Systematic Framework of Reasonable Allocation

Urban water resources are taken from nature. It is transported to various users through series disposal and collocation. Eventually it is returned to nature as the wastewater (sewage). In this process, the original state of water resources has been disturbed and destroyed. The urban water resources system is a complicated system of multisource water for multiuser. The system might be simply divided into two sections: the water supply and the water demand. According to the systems analysis method, based on the sufficient considering of characteristics of multisource water and users, the water supply and the water demand will be unified through the reasonable allocation. In this way, the multisource water are uniform planned and rational allocated, so the whole utilization efficiency of urban water resources can be enhanced and the urban water environment can be restored. The system framework of multisource water for multiuser is shown in Fig. 1.

3.3 The General Model of Reasonable Allocation

The goal of reasonable allocation of multisource water is to realize the sustainable utilization of urban water resources, and to promote the harmony developments of economy, society and environment. So it is a multi-objective decision-making problem. However, one of the major difficulties in formulating a water resource planning model is the integration of those non-commensurable objectives. In this analysis, taking the sustainable development as the guidance, the maximal synthesis benefit of economy, society and environment is regarded as the overall objective.

$$\text{Objective function}: \quad \max f\,[\mathrm{EC}(\mathbf{Q}), \mathrm{SO}(\mathbf{Q}), \mathrm{EN}(\mathbf{Q})] \tag{1}$$

$$\text{Subject to} \begin{cases} G(\mathbf{Q}) \leq 0 \\ \mathbf{Q} \geq 0 \end{cases} \tag{2}$$

where, **Q** is the decision-making vector. EC(**Q**), SO(**Q**), EN(**Q**) is objective function of the economy, society and environment respectively. G(**Q**) is the restriction condition set.

4 Case study

4.1 Area Description

Dalian locates on the southern tip of Liaodong Peninsula with Yellow Sea on the east and Bo Sea on the west, and enjoys a marine climate. The annual average rainfall is from 600 to 800 mm. Dalian is one of cities, which are badly water scarcity. The fresh water resource is

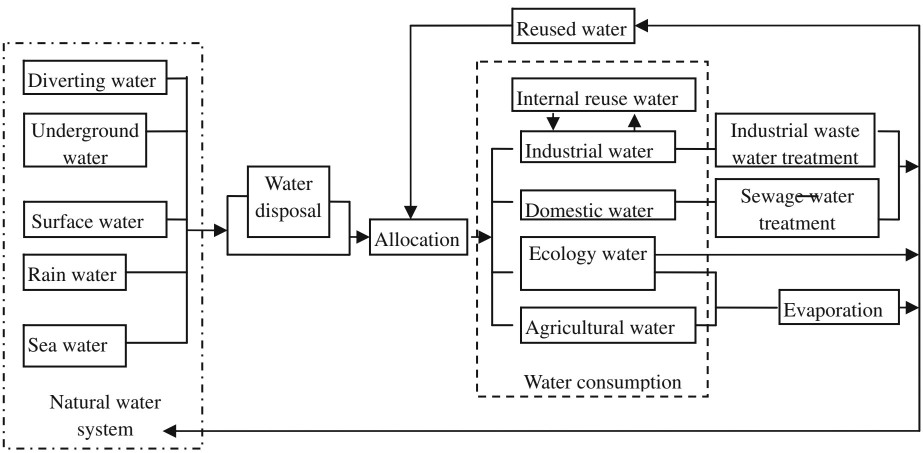


Fig. 1 The multisource water for multiuser system structure

innate shortage in Dalian. The per capita per year water resource in Dalian is about 640 m^3, which is no more than a quarter of per capita all over the country. Not only the water scarcity is severe, but also the water resources distribution is uneven in Dalian, descending from the northeast to southwest. The per capita per year water resource is only 164 m^3 in downtown (the southern of Jinzhou). The problem of urban water supply is always the main factor to obstruct the economy development in Dalian (Xu 1998).

To tackle the problem of urban water scarcity, the Transporting Water Project from Biliu River Reservoir had been maintained for 16 years since 1981, and the investment was almost 3.5 billion Yuan. This makes the water supply capacity reach to 1.2×10^6 m^3 per day, and basically satisfies the demand of urban development before early twenty-first century (Cong and Zhang 2003). To meet the water demand of the increasing population and rapid economic development, the aim has been turned to the more complex, farther and more investment Yingna River and Dayang River. On one hand, with the enlarging of urban scale, expediting of urbanization and growth of urban population, the demand for water is constantly increasing; on the other hand, the distance of diverting water is farther and farther, and the cost is higher and higher. Because the water resources are limited, the method through diverting water from other far places to meet the urban water using is not an eventual strategy, and it can not be carried out ultimately. The multisource water reasonable allocation in city is an available solution to enhance the utilization efficiency and achieve the urban water resources sustainable development.

4.2 The Forecast of Water Demand

According to the Tenth Five-Year Plan about water resources in Dalian (Planning Committee of Dalian 2001), the water demand of Dalian City has been predicted. The result of forecast is shown in Table 1.

According to the Tenth Five-Year Plan about water resources in Dalian (Planning Committee of Dalian 2001), the amount of water supply is 6.146×10^8 m^3 in Dalian City. The limited water supply can not satisfy the constantly increasing water demand, and it will gradually influence the development of Dalian City. The utilization of reclaimed wastewater and seawater is imperative. The forecast amounts of seawater and reclaimed wastewater in 2010, 2015 and 2020 respectively is 4.928×10^7 m^3, 5.476×10^7 m^3, 6.024×10^7 m^3 and 9.125×10^7 m^3, 1.278×10^8 m^3, 1.643×10^8 m^3. Only through the reasonable allocation of multisource water, can the crisis of water supply be alleviated.

4.3 Multi-Objective Model of Multisource Water Allocation Formulation

Based on the forecasts of water demand in Dalian City in 2010, 2015 and 2020, the different water resources are allocated reasonably. Combining the practical condition and

Table 1 The forecast of water demand in Dalian city in 2010, 2015 and 2020 units (10^4 m^3)

Year	Industrial Water	Agricultural water	Domestic water	Ecology water	Livestock water	Unpredictable water	Total water demand
2010	27255	9125	30672	1919	980	6495	76446
2015	29364	8954	34198	2039	990	7264	82809
2020	32421	8704	37734	2156	1000	8033	90048

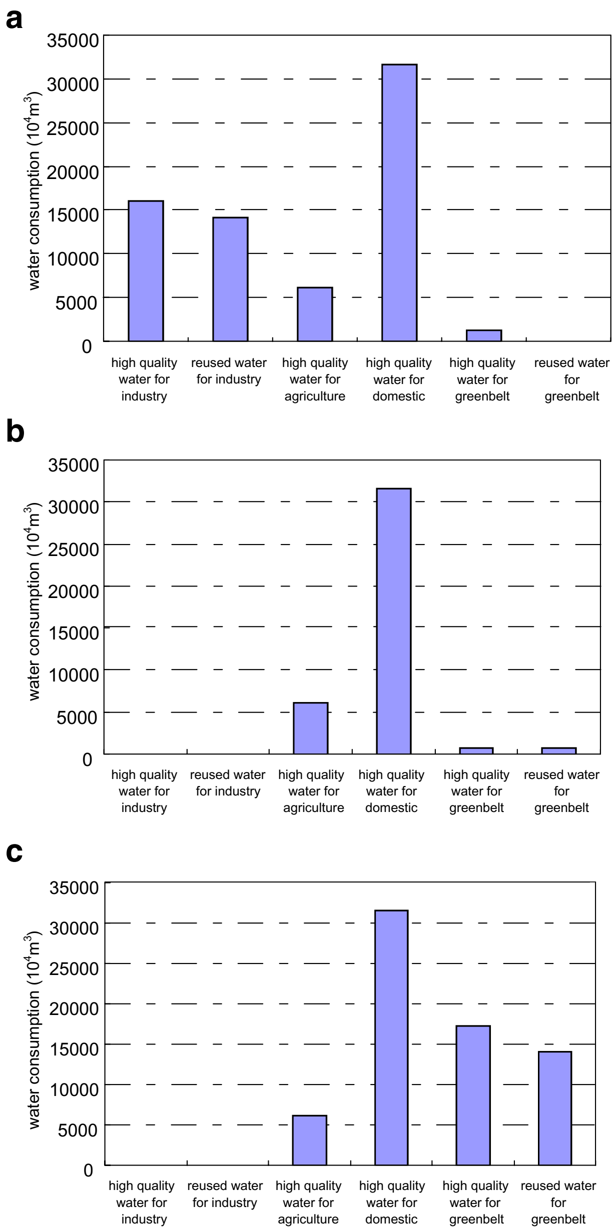


Fig. 2 The allocation results of multisource water under different objective. **a** Economy benefit maximization; **b** Sewage drainage minimization; **c** Greenbelt area maximization

model simplicity, the reclaimed wastewater and seawater have been unified as the reused water. The definitions of objective functions are expressed by Eqs. 3, 4 and 5.

4.3.1 Objective Function

a. Net benefit maximization: The economy net benefit maximization objective is commonly aspired to every decision maker involved the planning process. It can be

Table 2 The results of reasonable allocation in Dalian City in 2010, 2015 and 2020 units (10^4 m^3)

Year	High quality water for industry	Reused water for industry	High quality water for agriculture	High quality water for domestic	High quality water for greenbelt	Reused water for greenbelt	Total water supply
2010	12,318	13,048	10,806	31,562	275	1,005	69,014
2015	10,162	16,892	8,842	35,188	0	1,359	72,443
2020	7,732	21,012	7,857	37,834	0	1,437	75,872

expressed by Eq. 3 which considers the maximization of benefits of supplying water to industrial, agricultural and domestic sector from different water source.

$$\max f_1 = b^i\left(Q^{i1} + Q^{i2}\right) + b^a Q^a + b^d Q^d \tag{3}$$

b. Sewage drainage minimization: Besides water quantity scarcity, water crises also results from the degradation of the quality of water. Water pollution is one of the most serious global problems. Thus, the water environment problem should be considered as one of objectives of reasonable allocation of multisource water. The sewage is from the inadequate treatment of domestic sewage and the insufficient controls on the discharge of industrial wastewaters. It can be expressed by Eq. 4.

$$\min f_2 = p^i\left(Q^{i1} + Q^{i2}\right) + p^d Q^d \tag{4}$$

c. Greenbelt area maximization: Beautiful sceneries of large gardens everywhere in the city are the desired target of urban residents. The greenbelt may offer recreation space for the dwellers, where people's tire is dispelled through amusement activity. Therefore, the greenbelt area maximization has been regarded as one of goals of urban construction. The Eq. 5 is the objective function.

$$\max f_3 = \left(Q^{e1} + Q^{e2}\right)/m \tag{5}$$

4.3.2 Constraints

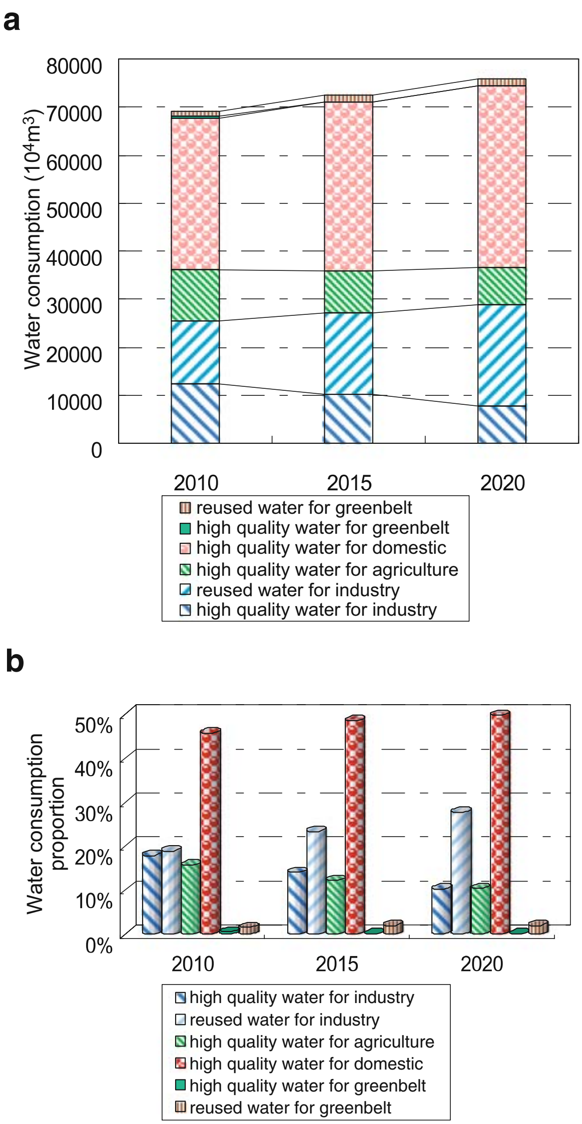
The objective functions are subject to six constraints, namely total high quality water availability, total reused water availability, lowest limitation amount of greenbelt irrigation, lowest limitation amount of agricultural irrigation, lowest limitation amount of domestic water consumption, and non-negativity which are expressed by Eqs. 6, 7, 8, 9, 10 and 11.

a. High quality water availability constraint: The amount of conventional water from surface and ground supplied to industry, agriculture, domestic and landscape should be no more than high quality water forecast availability. It will suffer from the hydrology structures.

$$Q^{i1} + Q^a + Q^d + Q^{e1} \le Q_1 \tag{6}$$

b. Reused water availability constraints: The amount of reused water supplied to industry and ecology should be no more than the reused water availability. The reused water

Fig. 3 **a** Distribution of various water quantities among multiuser in different plan year; **b** Proportion of various water in different plan year. Computed future allocation of multi-water resources for Dalian City



mainly suffers from the capability of wastewater treatment plant and seawater desalination technology.

$$Q^{i2} + Q^{e2} \leq Q_2 \tag{7}$$

c. Greenbelt irrigation constraints: In order to maintain the normal survival of greenbelt, the irrigating water should be no less than the minimum ecology water demand of urban greenbelt.

$$Q^{e1} + Q^{e2} \geq Q^1 \tag{8}$$

d. Agricultural irrigation constraints: According to the urban development plan, the agriculture must maintain a certain area. Therefore, the amount water supplied to agriculture should be no less than the minimum agricultural water demand. For ensuring the foodstuff security, no reused water supply to agriculture.

$$Q^a \geq Q^2 \tag{9}$$

e. Domestic water constraints: Domestic water supply would influence the social stability. The amount of high quality water supplied to domestic should be no less than domestic water demand, which mainly determined by population and standard of living.

$$Q^d \geq Q^3 \tag{10}$$

f. Non-negativity constraint:

$$Q_i \geq 0 \tag{11}$$

where

Q_1	is the maximal amount of high quality water availability. The high quality water is the groundwater, surface water and diverting water, which utilized by domestic, industry, agriculture, etc.
Q_2	is the maximal amount of reused water availability. The reused water mainly is treated sewage water and seawater, which is utilized by lower water quality users, such as industry and environment.
Q^1	is the lowest limitation amount of greenbelt water irrigation. For maintaining the normal survival of gardens and greenbelt in arid period, the greenbelt water irrigation should not be less than the lowest limitation.
Q^2	is the lowest limitation amount of agricultural water irrigation. For guaranteeing the normal survival of crop in arid period, the agricultural water consumption should not be less than the lowest limitation.
Q^3	is the lowest limitation amount of domestic water consumption. For guaranteeing the resident's survival and social stability, the domestic water consumption should not be less than the lowest limitation.
Q^{i1}	is the amount of high water supplied to the industry sector.
Q^{i2}	is the amount of reused water supplied to industry sector.
Q^a	is the amount of agricultural water consumption. (For ensuring the foodstuff security, no reused water supply to agriculture).
Q^d	is the amount of high quality water supplied to domestic.
Q^{e1}	is the amount of high quality water supplied to greenbelt.
Q^{e2}	is the amount of reused water supply to greenbelt.
b^i, b^a, b^d	are the net benefit coefficient of industry, agriculture and domestic water consumption, respectively. $b^i = 588\,\text{Yuan}/m^3$, $b^a = 0.5\,\text{Yuan}/m^3$, $b^d = 2.5\,\text{Yuan}/m^3$.
p^i, p^d	are the sewage water drainage coefficient of industry and domestic, respectively. The p^i and p^d is 0.8 and 0.43, respectively.
m	is the irrigation water consumption per acre, $m = 400\,\text{m}^3/acre$.

4.3.3 Solution Techniques

Step method (STEM), proposed by Benayoun et al. (1971), is one of the well-known multi-objective optimization techniques. The basic idea of STEM is to solve a Multi-objective optimization problem through an interactive procedure between the decision maker and a model (Qian 1990).The objectives is represented as

$$\forall - \max_{x \in \Omega} Cx \tag{12}$$

The model of this method first generates a local solution according to the given optimization goal. The ideal objective function value $f_i^*(i = 1, 2, \cdots, n)$is obtained by optimizing each individual objective function over the initial feasible region Ω

$$f_i^* = \max_{x \in \Omega}\{f_i(x) = c_i x\} \tag{13}$$

Solve the optimization model

$$\min_{\{x,\lambda\}} \lambda$$
$$\text{Subject to} \begin{cases} \lambda \geq \pi_i\{f_i^* - f_i(x)\}, & i = 1, 2, \cdots, n \\ \lambda \geq 0 \\ x \in \Omega \end{cases} \tag{14}$$

where π_i is the relative weight of the distance between $f_i^*$and $f_i(x)$. λ is the maximal value among the weighted distances.

$$\pi_i = \frac{\alpha_i}{\sum\limits_{i=1}^{n} \alpha_i}, \text{ and, } \alpha_i = \begin{cases} \frac{f_i^{\max} - f_i^*}{f_i^{\max}} \frac{1}{\sqrt{\sum\limits_{j=1}^{m} \left(c_i^j\right)^2}} & f_i^{\max} \succ 0 \\ \frac{f_i^* - f_i^{\max}}{f_i^{\max}} \frac{1}{\sqrt{\sum\limits_{j=1}^{m} \left(c_i^j\right)^2}} & f_i^{\max} \leq 0 \end{cases} i = 1, 2, \cdots n$$

The decision maker compares the k th iteration f_i $(x^{(k+1)})$ with f_i^* and then judges whether f_i $(x^{(k+1)})$ is satisfactory or not. If all f_i $(x^{(k+1)})$s are considered satisfactory, the algorithm successfully ends. Otherwise, the decision maker specifies the relaxation amount Δ_i. The feasible region is revised as:

$$\Omega^{(k+1)} = \begin{cases} \Omega^{(k)} \\ f_i(x) \geq f_i\left(x^{(k)}\right) - \Delta_i, i \in j \\ f_i(x) \geq f_i\left(x^{(k)}\right), & i \notin j \end{cases} \tag{15}$$

where $\Omega^{(k)}$ is the feasible region in the k th iteration, Δ_i is the amount by which f_i $(x^{(k)})$ is to be relaxed, for $i \in j$.

Under $x \in \Omega^{(k+1)}$, go to Eq. 14. The model solves the revised problem. This process is repeated from Eq. 14 to Eq. 15 until a satisfactory compromise is found or iteration time is finished.

5 Results and Discussion

Taking the economy benefit maximization as the objective function, the optimal net benefit f_1 is 1.7722×10^5 million Yuan in 2010. The allocation results of multisource water are shown in Fig. 2a. In the same way, taking sewage drainage minimization or greenbelt area maximization as the objective function, the optimal sewage drainage f_2 is 136.10 million Ton and the optimal greenbelt area f_3 is 781,975 acre in 2010. Their results are shown in Fig. 2b, c respectively.

Although one of the objectives is optimal, the multisource water can not been effectively and reasonably allocated under single objective optimization. The reasonable allocation should be overall optimization under taking economic and socio-environmental factors into consideration. In this study, based on single objective, the multi-objective linear programming model is solved by using the above-mentioned Step Method. After examining the solution, the decision maker's ideal objectives are: f_1 is 1.5×10^5 million Yuan, f_2 is 338.65 million ton and f_3 is 31,982.5 acre in 2010. The solution is (12,318, 13,048, 10,806, 31,562, 275, 1,005). Similarly, under the decision maker's participation, the results in 2015 and 2020 can also be obtained. The results of reasonable allocation in 2010, 2015 and 2020 are shown in Table 2 and Fig. 3.

The Fig. 3 shows the distribution of multisource water among multiuser in different plan year. According to the Fig. 3a, the total water consumption will increase from 690.14 million cubic meters in 2010 to 758.72 million cubic meters in the 2020, which almost by 10% increase. The domestic is the main water consumption user in Dalian City. In this period, the domestic water consumption increase is maximal, which by 62.72 million cubic meters. For the reused water, owing to adjusting of industry structure and improving of technology, the industry reused water consumption increase is maximal, which by 79.64 million cubic meters increase. However, the high quality water used by industry is decreased, which by 45.86 million cubic meters decrease. According to the Fig. 3b, the proportion of reused water consumption to total water consumption is gradually rising, which from 20% in 2010 to 25% in 2015, and to 29.5% in 2020. As the lower benefit of agricultural water consumption, for optimization of whole benefit of water resources, the agricultural water consumption has been cut down gradually.

6 Conclusion

Although reasonable allocation of urban multisource water for multiuser doesn't reach the maximal economic benefit or minimal sewage drainage, it makes the overall objective optimized by compromising among multi-objectives. It changes the traditional water supply pattern, which only the groundwater and surface water are viewed as water resources. In this paper, based on taking multisource water, multiuser and multi-objective into consideration, a linear programming model of multisource water reasonable allocation for multiuser was developed. This model had been applied to the reasonable allocation of water supply and demand in Dalian in 2010, 2015 and 2020. The step method was adopted to solve this multi-objective linear programming model. The results indicate that the proportion of reused water to total water consumption is gradually increasing, but that of the high quality water is gradually decreasing. The various water resources were allocated scientifically and reasonably according to users' demand for water quality and quantity. Thus, on one hand, the high quality water has been saved, and the utilization efficiency of water resources will be enhanced; on the other hand, the sewage water from the city will be reduced, and the urban water environment will be improved. The results also embody the idea of high quality water for superior users, low quality water for inferior users, and supplying water based on based on users' demand for water quality.

Acknowledgements The authors wish to acknowledge the financial support of The National Basic Research Program of China (973 Program) (No. 2006CB403405) and the "Eleventh Five-Year" National Key Technologies. R&D Program of China (No. 2006BAB14B05). The authors are also very grateful to the referees for their meticulous and helpful comments. The first author wishes to acknowledge M.Sc. Ying-fei LIU for her kind advices.

References

Benayoun R, Montgolfie J, Tergn J et al (1971) Linear programming with multiple objective function: Step Method (STEM). Math Program 1(1):366–375

Chu JY, Chen JN, Wang C et al (2004) Wastewater reuse potential analysis: implications for China's water resources management. Water Res 38:2746–2756

Cong GC, Zhang HW (2003) Discussions on reclaimed water recycle in Dalian. Water Resources & Hydropower of Northeast China 6:28–29 (in Chinese)

FAO (1999) Water quality management and control of water pollution. Proceedings of A Regional Workshop. Bangkok, Thailand, pp 26–30 (October)

Han Y, Xu SG (2005) Reasonable allocation and management of multi-water resources in Dalian City. Proceeding of XXXI IAHR Congress. Seoul, Korea pp 1025–1033 (September)

He PJ, Phan L, Gu GW et al (2001) Reclaimed municipal wastewater—a potential water resources in China. Water Sci Technol 43(10):51–58

Liu JL (2003) Theory and technology of urban water saving and planning. Chemical Industry Press, Beijing (in Chinese)

Papaiacovou I (2001) Case study—wastewater reuse in Limassol as an alternative water source. Desalination 138:55–59

Planning Committee of Dalian (2001) Tenth five-year programming about water resources guarantee in Dalian. (in Chinese)

Qian SD (1990) Operation research. Tsinghua University Press, Beijing (in Chinese)

Ran XY (2001) Discussion on urban water environment rehabilitation. Beijing Water Resources 4:12–14 (in Chinese)

Ruan GL (2004) Seawater desalts to alleviate the shortage of water resources. Construction Science and Technology Z1:74–75 (in Chinese)

Tsiourtis NX (2001) Seawater desalination projects. The Cyprus experience. Desalination 139:139–147

Xu BC (1998) Discussions on Water Supply Problem in Dalian City. Water Resources and Hydropower Technology 29(11):4–7(in Chinese)

Xu XY, Wang H, Gan H (1997) Management and method of macro-economy water resources in north China. Yellow River Water Conservancy Press, Zhengzhou (in Chinese)

Yamout G, El-fadel M (2005) An optimization approach for multi-sector water supply management in the greater Beirut area. Water Resour Manag 19:791–812

Yen JH, Chen CY (2001) Allocation strategy analysis of water resources in south Taiwan. Water Resour Manag 15:283–297

Zhang J, Xu SG (2003) Discuss of rainwater resources utilization in littoral in China. Water Resour Hydropower Eng 34(11):4–7 (in Chinese)

Zhang J, Cao XS, Meng XZ (2007) Sustainable urban sewerage system and its application in China. Resour Conserv Recycl DOI:10.1016/j.resconrec.2006.10.001

Zheng ZZ, He CD (2003) Urban water business management. China Water Power Press, Beijing (in Chinese)