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Emergy analysis of urban domestic water metabolism: A case study in Beijing (China)

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A B S T R A C T

This work elaborated an analysis of urban water metabolic system. The system's flows and processes were modeled and accounted on the basis of the ecosystem cumulative energy availability, also known as emergy. In detail, both the urban domestic water supplying process metabolism model and accounting framework were defined. Then, the whole process of the supplying of domestic water was analyzed, considering Beijing (China) as a case study. In particular, the existing water sources were included: surface water, underground water, water of the South-to-North Water Transfer Project; potential desalinated water from Tianjin. The results showed that, for the supply of 1 m^3 of tap water, the total emergy input from the above-mentioned four sources are 3.22E+12, 3.34E+12, 4.55E+12, and 12.55E+12 sej. These values reflect the different energy costs of the existing supply systems, that are related to water transportation, treatment and distribution, Moreover, the emergy cost of desalinated water is about 4 times higher than the one of surface water. Conversely, the value of South-to-North Water Transfer Project is not much higher than that of surface water. Finally, the higher costs are related to the water treatment phase. Consequently, some policy recommendations and future research directions are identified for improving the sustainability for Beijing domestic water supply.

1. Introduction

Finite water resources, increasing demands and aging water infrastructures are some of the greatest challenges for China and many other regions of the world. The rapid increase in water demand and the reduction of the fresh water supply, resulting in water shortages, are now a serious problem in many countries (Wang et al., 2016). The United Nations Educational, Scientific, and Cultural Organization (UNESCO) predicts that global water demand will increase by 44% in 2050, with residential water growing nearly 1.5-fold (UNESCO, 2014). Without a constant supply of water, human society cannot smoothly and continuously develop (Chen et al., 2016).

Urban areas are especially vulnerable to these problems, due to their higher population density. This is why, nowadays, an accurate planning for a sustainable use of water resources is of paramount importance. With this respect, complex water issues cannot be solved applying a chambered water management approach, especially at the urban scale. For example, Hu et al. (2013) showed that the majority of the present water consumption in Beijing was due to family use, i.e., domestic water. Before the operation of the South-North Water Transfer Project (SNWTP) in 2014, Beijing's water mainly came from the local surface water and groundwater. However, this limited supply couldn't meet the growing demands. As an "alternative source" of traditional surface water and groundwater, SNWTP greatly alleviated the pressures on the Beijing water supply.

In a water-connected world, sustainable solutions would require a system-based approach. In particular, water services (traditionally: wastewater, stormwater, and drinking water) should be integrated with the effort of maximizing the recovery of resources (*i.e.*: energy, nutrients, materials, and, obviously, water). The United States Environmental Protection Agency (US EPA) Safe and Sustainable Water Resources (SSWR) research program represented an example of a holistic approach to water resources management. In particular, SSWR research tried to avoid planning scenarios, which

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might transfer the existing problems from one area to another. Instead, an adaptive approach was chosen to address also changing societal aspirations, demographics, and climate.

Other researches involved an analysis at different process or spatial scales. Among them, supply facilities scale (e.g., such as water supply plants and sewage treatment plants), the entire process scale (e.g., such as water supply, water division, and sewage treatment), the regional scale (e.g., city, province, and country) (Lin, 2015).

Life cycle approach was used in different studies. Raluy et al. (2005) compared the expected energy consumption of the Transfer Project on the Obo River (Spain) in three different situations within the Spanish national hydrological planning. Nalanie and Robert (2006) explored energy consumption and CO_2 emissions associated to the water supply network system of Auckland, New Zealand. Lundie et al. (2004) predicted the water supply's influence on the environment in Sydney, Australia in 2021. Stokes and Horvath (2011) and Lyons et al. (2009), respectively, used the life cycle analysis method and hybrid life cycle analysis to study water energy consumption and its influencing factors in different water supply plants with different water sources. Venkatesh et al. (2014) performed a case analysis of Oslo, Nantes, Toronto, and Turin to investigate energy demand factors per unit of water, water treatment, water distribution, and sewage treatment. They also calculated the proportion of the water unit of energy demand and carbon emissions in the entire water system.

Other scholars attempted to find a way to minimize both biophysical and economic inputs, as well as greenhouse gas emissions. Different methods were applied, such as a genetic algorithm (Gupta et al., 1999; Prasad, 2010), nonlinear programming (Gomes and Silva, 2006), integer linear programming (Samani and Mottaghi, 2006), quadratic programming (Bai et al., 2007), multi-objective genetic algorithm (Wu et al., 2012; Vamvakeridou-Lyroudia et al., 2007), multi-objective hybrid algorithm (di Pierro et al., 2009), random transmission algorithm (Bolognesi et al., 2010), and multi-objective particle swarm optimization algorithm (Montalvo et al., 2010).

One of the key research questions, that still remains open, is the separation between economic and biophysical quantifications, which are too often unrelated. Thus, more holistic approaches would a valid alternative with respect to the purely economic ones. Among them, emergy synthesis represents a valid choice (Odum, 1996, 1998). Emergy, as defined by Odnm (1996), is the cumulative available energy, directly and indirectly involved in the generation and/or operation of a product or service. Emergy synthesis method is commonly used for various systems at multiple scales to incorporate environmental, social, and economic aspects into a common non-monetary unit of measure (solar energy equivalents, sej). Being capable of capturing the features and dynamics of different systems at multiple scales, emergy accounting can be used to assess the sustainability of the systems, as well as to provide indications about alternative scenarios in managing complex processes (Brown and McClannahan, 1996; Brown and Ulgiati, 2004, 2015). Not only emergy quantitatively assesses the direct and indirect available energy required to produce goods and services, but it also provides managers a decision criterion to evaluate the efficacy of alternatives. For example, emergy accounting is able to quantify the natural capital supporting any economic system, such as the "free" contribution of rain to drinking water supply (Brown et al., 2010). Emergy can be used to evaluate the impacts of water quality, nutrient and energy recovery, natural green infrastructure, aquifer storage recovery, and regional water allocation with respect to the overall system efficiency. Emergy accounting has the potential to integrate sustainability principles to water system management at different scales and levels. This method is often complementary to and integrated with other system metrics, such as life cycle assessment (LCA) (Raugei et al., 2014; Reza et al., 2014).

Beijing, the capital city of China, located in the northern portion of the North China Plain, can represent a very interesting open laboratory to study water metabolism through a holistic approach. Its water sources mainly come from surface runoff and groundwater water produced by precipitation (Ni et al., 2001). Beijing already experienced serious problems of water-deficiency, due to its rapid population growth, the economic development and the expansion of the third industry (i.e.: the service industry). The sharp divide between water resource supply and demand must be addressed promptly. In early 2014, the President of China, Xi Jinping, stated that the "City should adhere to the principle of determining water supply according to the city, place, population and production". A clear political will emerged from his indications. In fact, this would imply a transition from "supplying according to demand" to "consuming according to supply". For such a reason, an appropriate planning, based on a comprehensive approach, considering input, efficiency, and sustainability, is mandatory.

It is obvious that a large number of engineering and construction investments would inevitably increase the water supply cost, regardless of the economic costs or energy inputs. However, a quantification of costs is still missing. The application of emergy accounting to this problem can fill the existing gaps, providing suggestions for a rational planning and configuration. Consequently, the purpose of this work is to elaborate a complete analysis of an urban domestic water metabolic system. Domestic waters include the water used by residents and by the municipal public construction (Yuan, 2004). In detail, in the method chapter, an emergy based model of urban domestic water metabolism, as well as accounting framework, is proposed. In the results chapter, the whole supplying process is analyzed considering four sources for Beijing: (1) surface water; (2) underground water; (3) water of the South-to-North Water Transfer Project (SNWDP); and (4) potential desalinated water from Tianjin. The emergy inputs of the domestic water distribution system is also accounted. In the discussion chapter, new energy management tactics and solutions of the water supply system are discussed.

2. Methods

2.1. System description and boundaries

Beijing urban water supply system is made up of an engineered and natural solution, which supports the supply of water as required by each user (Ren and Fei, 2006). This engineered system includes the following phases: water withdrawal; water potabilization; water transportation; and water distribution (He, 2009). This study only considers the subject until water arrives to the terminal user. It does not include water and drainage from subsequent users or treatment by the sewage treatment plant. Currently, urban water can be obtained from surface water or groundwater through water pumps, processed in a water treatment plant or potabilization plant, and then distributed to each user through the urban water supply pipe network. Tap water supply processing requires material, energy, labor input, and corresponding facilities.

According to the traditional emergy analysis procedure, the boundaries of this part of the system were fixed from the source water entering into the potabilization plant to the source water being processed into the supply network. A system emergy diagram was drawn in Fig. 1, based on the emergy circuit language

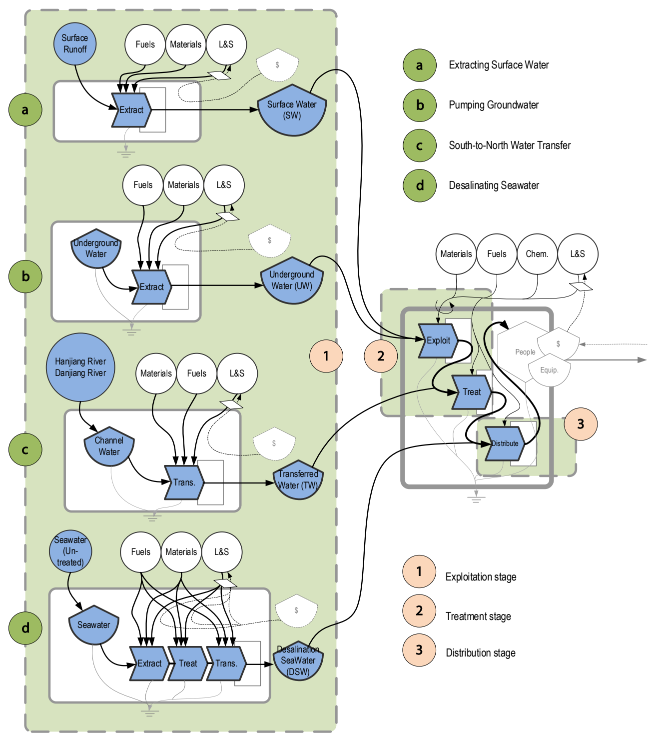

Fig. 1. Four potential water supply sources in Beijing.

created by H.T. Odum (Odnm, 1996; Brown et al., 2010).

Since the SNWTP in 2014, Beijing's water supply mainly comes from three sources: Miyun Reservoir (surface water); groundwater; the center-line water of the SNWTP, from 2016 (Qi, 2012). In fact, due to its frequent water shortages, Beijing received part of the water from four reservoirs in Hebei Province before 2014. However, water was diverted at the expense of the agricultural water in Hebei Province. Previously, it served as a part of the emergency water diversion that secured the 2008 Beijing Olympic Games, then replaced by the water diversion from the Danjiangkou Reservoir in Hubei Province and by SNWTP. The Danjiangkou Reservoir provides the center-line water for the South-North water Transfer Project for Beijing domestic water, also known as the Hanjiang River source of the Yangtze River. The emergy input caused by this project is accounted here accordingly. Besides, in the 13th Five Year Plan, Tianjin's desalination water is considered as one of the potential alternative sources of supply water in the future. Thus, it will be compared with Beijing's local surface water, groundwater, and water from the SNWTP using LCA-based emergy analysis method (Qi, 2012).

2.2. Exploitation process

2.2.1. Surface water exploitation

Energy is required to transfer surface water obtained from rivers, lakes, or reservoirs to potabilization plants for further processing. According to the data from Energy-Water Nexus in Beijing published by Hu et al. (2013), the average energy intensity factor for surface water in the process of obtaining water in Beijing is 0.19 kWh/m^3. Based on the Unit Emergy Value (UEV) of electricity is 7.95E+11 sej/kWh (after Odnm, 1996), the emergy input in surface water exploitation stage is 0.19 × 7.95E+11 = 1.51E+11 sej/m^3.

2.2.2. Groundwater exploitation

A staggering proportion of the supply water in Beijing comes from groundwater. The major groundwater source areas are the alluvial-proluvial fan of the middle and upper reach of the Yongding River and Chaobai River, where the two biggest underground reservoirs lie (Ni et al., 2012).

According to field investigation and calculations, the Beijing groundwater level is 19.14 m, and the average electricity intensity of pumping the underground water is 0.44 kWh/m^3 (Hu et al., 2013). The energy investment can be obtained by 0.44 × 3.6E+06 = 1.58 J/m^3. The emergy input in surface water exploitation stage is 0.44 × 7.95E+11 = 3.50E+11 sej/m^3.

2.2.3. Transferred water from the central route of the SNWTP

China is a Country relatively rich in total water resources. However, a serious imbalance in the spatial distribution of water resources exists, namely an abundance of water in the south and a water shortage in the north, and numerous northern cities encounter severe water shortages. The South-to-North Water Transfer Project (SNWTP) has very important significance in reasonably re-allocating domestic water resources, alleviating the serious shortages of water resources in northern China, and ensuring the sustained and stable development of the social economy. The SNWTP is China's most significant inter-basin water resource allocation project, covering a long distance and accounting for a large amount of water diversion. It has the advantages of good water quality, larger coverage, and artesian water. The strategy can effectively alleviate the water shortage in North China areas, especially Beijing and Tianjin, improve the regional ecological environment, and support sustainable social and economic development (The Beijing Office of the SNWTP Construction Committee, 2008). It is a major infrastructure project to solve the shortage of water resources in northern China. The centerline of the project has a total length of 1277 km, supplying water to Beijing since 2010. The length of the centerline in Beijing is 80.4 km. According to the water quantity allocation scheme in 2010, the domestic water accounts for 510 million m^3 and industrial water for 400 million m^3. The majority of the sum of the two parts (837 million m^3) is transferred to potabilization plants. In other words, potabilization plants are the main channel of realizing the water supply, as declared in the SNWTP overall planning of year 2008. In addition to the water supply to Beijing, the centerline provides domestic and industrial water to more than 20 cities in Henan Province and Hebei Province along the way (Liang, 2013). According to the achievements of the Proposal for SNWTP First Phase, the average water transferred for several years is 9.5 billion m^3, and the average distribution of water for several years in Beijing is 1.238 billion m^3, with 1.052 billion m^3 diverted in. Moreover, according to The SNWTP Overall Planning, after considering loss, the scale of the centerline water Transfer Project reaches 120–130 billion m^3, among which Beijing accounts for 1.4 billion m^3 (The Beijing Office of the SNWTP Construction Committee, 2008).

Based on the volume share per unit, the centerline project's water diversion cost and Beijing supporting engineering cost is calculated, based on the total input of the early project and yearly operation maintenance. The water Transfer Project's total cost should be reasonably allocated to each water-receiving area. The main factors influencing the cost allocation are water volume and distance. Thus, the cost allocation is calculated according to the water distance using the following formula:

$$C_{oi} = f_i \times C_{ot} \quad (1)$$

$$f_i = \frac{w_i}{\sum_{i=1}^{n} w_i \times l_i} \times l_i \quad (2)$$

where: f_i is the allocation coefficient area I; C_{oi} is total cost of water diversion; w_i is the designed water input; l_i is the distance from the branch water outlet in area i to the water diversion source (Xu, 2013). Based on the data and the formula, Beijing's water diversion cost is 27.1 billion yuan. The reason why it is calculated by investment is that the engineering investment data is intact, while the data of a variety of materials investment required in traditional emergy calculations is difficult to obtain. In addition, a significant portion of the total investment covers the compensating investment of demolition and relocation, which must be included in the calculation.

The yearly operation maintenance cost is calculated according to 1.5% of fixed assets investment of the water transfer project (Zhang et al., 2005). In parallel, the annual cost is 1.54 billion yuan. Salary is calculated on the basis of 18,000 yuan per person on average. Considering 4933 permanent staff members, the annually cost is 0.89 million yuan. With 14% of the welfare, 10% of the housing accumulation fund, and 17% of labor insurance included, the total is 125 million yuan (Xu, 2013). Similarly, Beijing's cost after the allocation is 440 million yuan.

The total investment of Beijing's supporting engineering for the South-North Water Transfer Project is 12.992 billion yuan. According to the 2016 financial budget report published on the official website of the Beijing Office of the SNWTP Construction Committee, the yearly operation maintenance investment (209.03 million yuan in 2016) was selected.

As mentioned, suppose that the net water input in Beijing is 1.052 billion m^3 every year from 2010 to 2019 and 1.4 billion m^3 every year from 2020 to 2049, and the investment per unit volume is 1.38 yuan. The emergy/$ ratio (9.84 E+12 sej/$) (Pang et al., 2015) is transferred to obtain the emergy/$ ratio in this study (7.46 E+12 sej/$ in 2016). With the known dollar/yuan rate of 6.47 (April 2016), the diversion emergy cost per unit volume reflected in the south-north water Transfer Project is 1.59 E+12 sej.

2.2.4. Water resources from seawater desalination project

This paper modifies the formula used by Zhou et al. (2013) and applies it to the energy consumption of the water extracted from the sea. The formula is:

$$E = \theta \times \gamma \times H \times Q \times T / 1000\eta \tag{3}$$

In the equation, E is the energy consumption of the water in the process of extraction/uplift (Mtce), γ is the unit weight of water (998 kg/m^3), H is the total dynamic head (9 m), Q is the daily water supply/mining (10 million m^3) (Zheng et al., 2014), η is the working efficiency of the pump (80% on average), T is the daily running time of the pump (16 h), and θ is the conversion coefficient from electricity to kgce/kWh (0.404). Since Zheng et al. (2014) calculated the coal equivalent consumption per m^3 water, the amount of time in the process of water extraction/uplift should also be taken into consideration. With E's value, the coal emergy conversion rate is 6.90 E+04 sej/J (Brown and Ulgiati, 2010), the fuel calorific value of coal conversion is 2.09 E+04 kJ/kg, and the conversion coefficient is 3.60E+06 kWh/J. Therefore, the input emergy per volume of the seawater is 2.71E+11 sej in the exploitation process.

2.3. Treatment and distribution stages

Water supply source is not always of sufficient quality. This is why it must be treated to alleviate peculiar smell, enhance purity and eliminate pathogenic bacteria. The worse the quality of the source water is, the higher standards would the water treatment require, which implies a higher cost (Buenfil, 2001). In this study, the Tian Cun Shan Water Treatment Plant (water source relies on inflow water to Beijing) is used as the case to analyze.

Supply water distribution processes shows the water resource that is being processed through a water treatment plant to meet quality standards is delivered to the end users. In such a process, high-pressure water pumps are applied to transport the water resource to users through a pipe system (Lin, 2015). The urban water supply pipe system provides an amount of water for daily consumption that is higher than actual consumption because waste exists in the distribution (Zhou et al., 2013).

2.4. Emergy indicators

Emergy indicators are accounted according to the following formulas (Arbault et al., 2013):

$$EYR = 1 + R/(F + G + L\&S) \tag{4}$$

$$ELR = (F + G + L\&S)/R \tag{5}$$

$$EmSI = EYR/ELR \tag{6}$$

Local nonrenewable resources are not considered. Thus, the formulas of EYR and ELR have been simplified.

3. Results

3.1. Emergy analysis of four kinds of water supply systems

Water system emergy analysis for Beijing is detailed for year 2016. In this study, we used the global emergy baseline (GEB), fixed as 12.0 E+24 seJ/yr (Brown and Ulgiati, 2010).

3.1.1. Surface water

F.1: The average energy intensity factor for surface water in the process of obtaining water in Beijing is 0.19 kWh/m^3 (Hu et al., 2013). Based on the UEV of electricity is 7.95E+11 sej/kWh (after Odnm, 1996), the emergy input in surface water exploitation stage is 0.19 × 7.95E+11 = 1.51 E+11 sej/m^3.

(a)-(c), (e)-(i) from Arbault et al. (2013); (d), (j) from Wang et al. (2012); (k), (l), (n), (o) from the website of Beijing Waterworks Group[1];

(m) is calculated from (a) and electricity price in Beijing 2016;

(p) is calculated based on loss ratio from Arbault et al. (2013).

In Table 1, the emergy inputs in exploitation process is 1.51E+11 sej/m^3. The emergy inputs in treatment process is 1.57E+12 sej/m^3, among which the energy consumption for the largest share at 25.8%. The UEV of surface water delivered to supply network increases about 19 times larger than the original one.

3.1.2. Underground water

F1: According to field investigation and calculations, the Beijing groundwater level is 19.14 m, and the electricity intensity of pumping the underground water is 0.44 kWh/m^3 (Hu et al., 2013). Based on the UEV of electricity is 7.95E+11 sej/kWh (after Odnm, 1996), the emergy input in surface water exploitation stage is 0.44 × 7.95E+11 = 3.50 E+11 sej/m^3.

(a)-(f) from Buenfil (2001); (g), (h), (j), (k) from the website of Beijing Waterworks Group;

(i) Is calculated from (a) and electricity price in Beijing 2013;

(l) Is calculated based on loss ratio from Buenfil (2001).

In Table 2, the emergy inputs in exploitation process is 3.50E+11 sej/m^3. The emergy inputs in treatment process is

[1] http://www.bjwatergroup.com.cn/352/2014_3_18/352_6961_1395135922284.html.

Table 1
Emergy analysis of surface water supply process (per m^3).

Item	Raw Data	UEV (sej/Unit)	Emergy (sej)	UEV reference
A. Renewable (R)				
R: Surface Water	1.00 m^3	1.00E+11	1.00E+11	This study
B. Inputs in exploitation process (F_1)				
F_1: Electricity	0.19 kWh	7.95E+11	1.51 E+11	After Odnm (1996)
C. Inputs in treatment process (F_2, G, L&S)				
F_2: Electricity	0.51 kWh [(a)]	7.95E+11	4.05E+11	After Odnm (1996)
G_1: Activated carbon	4.10 g [(b)]	1.98E+10	8.11E+10	After Arbault et al. (2013)
G_2: Regeneration of activated carbon (AC)	2.64 g [(c)]	1.09E+10	2.88E+10	After Arbault et al. (2013)
G_3: Ozone	0.10 g [(d)]	4.72E+10	4.72E+08	After Campbell and Tilley (2014)
G_4: Acyclic acid	0.16 g [(e)]	4.51E+09	7.22E+08	After Arbault et al. (2013)
G_5: Aluminum sulfide	23.69 g [(f)]	1.50E+09	3.55E+10	After Arbault et al. (2013)
G_6: Chlorine	1.32 g [(g)]	1.91E+09	8.48E+09	After Arbault et al. (2013)
G_7: NaOH	11.02 g [(h)]	1.86E+09	2.05E+10	After Arbault et al. (2013)
G_8: Sulfuric Acid	6.55 g [(i)]	5.28E+08	3.46E+09	After Arbault et al. (2013)
G_9: $FeCl_3$	17.00 g [(j)]	3.83E+09	6.51E+10	After Arbault et al. (2013)
$L\&S_1$: Employee Salary	0.033$[(k)]	7.46E+12	2.54E+11	This study
$L\&S_2$: Materials Expenses	0.0075$[(l)]	7.46E+12	5.77E+10	This study
$L\&S_3$: Electric Charge	0.039$[(m)]	7.46E+12	3.00E+11	This study
$L\&S_4$: Repair Charge	0.0084$[(n)]	7.46E+12	6.46E+10	This study
$L\&S_5$: Assets Depreciation	0.031$[(o)]	7.46E+12	2.42E+11	This study
D. Output (Y)				
Y: Surface water delivered to supply network	0.95 m^3[(p)]	**1.92E + 12**	1.82E+12	This study

Notes:R: UEV of surface water (world average) = Emergy of terrestrial precipitation/(Volume/Turnover time) = (Land precipitation*Gibbs energy* Transformity of chemical potential of Land precipitation)/(Volume/Turnover time) = 1.13E+20 g/yr (Adler et al., 2003) * 4.72 J/g * 7.01E+03 sej/J (Brown and Ulgiati, 2010)/(2.14E+03 km^3 (Shiklomanov and Rodda, 2003) *1000*1000000000*1000000)/0.057 yr (Shiklomanov and Rodda, 2003) = 1.00E+05 sej/g = 1.00E+11 sej/m^3.

Table 2
Emergy analysis of underground water supply process (per m^3).

Item	Raw Data	UEV (sej/Unit)	Emergy (sej)	UEV reference
A. Local Non-renewable (N)				
R: Underground Water	1.00 m^3	1.04E+12	1.04E+12	After Buenfil (2001)
B. Inputs in exploitation process (F_1)				
F_1: Electricity	0.44 kWh	7.95E+11	3.50E+11	After Odnm (1996)
C. Inputs in treatment process (F_2, G, L&S)				
F_2: Electricity	0.60 kWh [(a)]	7.95E+11	4.77E+11	After Odnm (1996)
G_1: Chlorine	2.67 g [(b)]	1.91E+09	5.10E+09	Calculated based on UEV of Chlorine from Pulselli et al. (2011)
G_2: Potassium Permanganate	2.74 g [(c)]	1.05E+10	2.88E+10	After Arbault et al. (2013)
G_3: Sulfuric Acid	9.05 g [(d)]	5.275E+08	4.77E+09	After Arbault et al. (2013)
G_4: Polymer	0.15 g [(e)]	6.70E+09	1.00E+09	Calculated based on UEV of polyethylene (PE) from Pulselli et al. (2011)
G_5: NaOH	3.52 g [(f)]	1.856E+09	6.53E+09	After Arbault et al. (2013)
$L\&S_1$: Employee Salary	0.033$[(g)]	7.46E+12	2.54E+11	This study
$L\&S_2$: Materials Expenses	0.0075$[(h)]	7.46E+12	5.77E+10	This study
$L\&S_3$: Electric Charge	0.039$[(i)]	7.46E+12	3.46E+11	This study
$L\&S_4$: Repair Charge	0.0084$[(j)]	7.46E+12	6.46E+10	This study
$L\&S_5$: Assets Depreciation	0.031$[(k)]	7.46E+12	2.42E+11	This study
D. Output (Y)				
Y: Underground water delivered to supply network	0.85 m^3 [(l)]	**3.39E + 12**	2.88E+12	This study

Notes:R: Underground water bodies (deep aquifers) are considered as non-renewable water resources since they have a slow rate of recharge on the human time-scale.

1.49E+12 sej/m^3, which is slight lower than the surface water treatment. The likely cause is that the underground water has lower pollution levels than surface water. What's similar is that the energy consumption for the largest share at 31.1%. The UEV of underground water delivered to supply network increases only 3.26 times larger than the original one due to the high UEV contributed by geographical process.

3.1.3. Transferred water from the south-north water transfer project

In Table 3, the emergy inputs in transferring process sharply increase the UEV of supply water from 1.00E+11 sej/m^3 to 1.59E+12 sej/m^3 (15.9 times larger). The emergy inputs in treatment process are 1.56E+12 sej/m^3, being equivalent to the surface water treatment and sharing a similar energy consumption proportion. The UEV of transferred water delivered to supply network is 33.2 times larger than the UEV of surface water.

3.1.4. Seawater

According to the research of Zheng et al. (2014), Table 4 is constructed by applying the seawater desalination data from Tianjin.

Note:R: UEV of seawater = GEB_{2016}/(Volumn of seawater/Tuneover time) = 12.0E+24 seJ/yr (Brown and Ulgiati, 2010)/(1.338E9 km^3 (Shiklomanov and Rodda, 2003)*1000000000000*1000000/2500yr (Shiklomanov and Rodda, 2003)) = 2.24E+04 sej/g = 2.30E+10 sej/m^3. (Average density of seawater = 1.025 g/cm^3)

N: With *E*'s value, the coal emergy conversion rate is 6.90 E+4 sej/J (Brown and Ulgiati, 2010), the fuel calorific value of coal conversion is 2.09 E+04 kJ/kg, and the conversion coefficient is 3.60E+06 kWh/J. Therefore, the input emergy per volume of the seawater is 2.71E+11 sej in the exploitation process.

(a), (h)-(m) from Zheng et al. (2014); (b)-(g) based on the same seawater desalination technology from Tarnacki et al. (2012).

(n) Is calculated based on loss ratio from Tarnacki et al. (2012).

Table 3
Emergy analysis of SNWDP water supply process (per m^3).

Item	Raw Data	UEV (sej/Unit)	Emergy (sej)	UEV reference
A. Renewable (R)				
R: Transferred Water	1.00 m^3	**1.59E + 12**	1.59E+12	This study
B. Inputs in treatment process (F, G, L&S)				
F: Electricity	0.53 kWh [(b)]	7.95E+11	4.21E+11	After Odnm (1996)
G_1: Activated carbon	3.54 g [(c)]	1.98E+10	7.01E+10	After Arbault et al. (2013)
G_2: Ozone	2.00 g [(d)]	4.72E+10	9.44E+10	Calculated based on Campbell and Tilley (2014)
G_3: Chlorine	1.00 g [(e)]	1.91E+09	1.91E+09	Calculated based on UEV of Chlorine from Pulselli et al. (2011)
G_4: Ammonia	0.50 g [(f)]	9.65E+08	4.83E+08	Calculated based on Campbell and Tilley (2014)
G_5: $FeCl_3$	12.00 g [(g)]	3.83E+09	4.60E+10	After Arbault et al. (2013)
L&G_1: Employee Salary	0.033$[(g)]	7.46E+12	2.54E+11	This study
L&G_2: Materials Expenses	0.0075$[(h)]	7.46E+12	5.77E+10	This study
L&G_3: Electric Charge	0.039$[(i)]	7.46E+12	3.11E+11	This study
L&G_4: Repair Charge	0.0084$[(j)]	7.46E+12	6.46E+10	This study
L&G_5: Assets Depreciation	0.031$[(k)]	7.46E+12	2.42E+11	This study
C. Output (Y)				
Y: Transferred water delivered to supply network	0.95 m^3 [(l)]	**3.32E + 12**	3.15E+12	This study

Note: (a), (h)-(k) from the website of Beijing Waterworks Group; (b) is calculated from (a) and electricity price in Beijing 2013; (c) from Arbault et al. (2013); (d)-(g) from Tiancunshan Water Treatment Plant[2]; (l) is calculated based on loss ratio from Arbault et al. (2013).

Table 4
Emergy analysis of seawater treatment (per m^3).

Item	Raw data	UEV (sej/Unit)	Emergy (sej)	UEV reference
A. Renewable (R)				
R: Seawater	1.00 m^3	2.30E+10	2.30E+10	This study.
B. Inputs in exploitation process (F_1)				
F_1: Energy (coal equivalent)	–	–	2.71E+11	This study.
C. Inputs in treatment process (F2, G, L&S)				
F_2: Electricity	4.16 kWh [(a)]	7.95E+11	3.31E+12	After Odum (1996)
G_1: filter membrane (Polyamide, PA)	0.03 g [(b)]	6.70E+09	2.01E+08	Calculated based on UEV of polyethylene (PE) from Pulselli et al. (2011)
G_2: Polypropylene	0.07 g [(c)]	6.70E+09	4.69E+08	Calculated based on UEV of polyethylene (PE) from Pulselli et al. (2011)
G_3: Chlorine	2.94 g [(d)]	1.91E+09	5.62E+09	Calculated based on UEV of Chlorine from Pulselli et al. (2011)
G_4: Ferric Chloride	2.94 g [(e)]	3.83E+09	1.13E+10	After Arbault et al. (2013)
G_5: Sulfuric Acid	24.50 g [(f)]	5.275E+08	1.29E+10	After Arbault et al. (2013)
G_6: Sodium Hypochlorite	2.45 g [(g)]	3.29E+09	8.06E+09	After Arbault et al. (2013)
L&S_1: Electric Charge	0.31$ [(h)]	7.46E+12	2.40E+12	This study
L&S_2: Capital investment	0.22$ [(i)]	7.46E+12	1.68E+12	This study
L&S_3: Charge of Filter Membrane	0.13$ [(j)]	7.46E+12	1.03E+12	This study
L&S_4: Employee Salary	0.036$ [(k)]	7.46E+12	2.77E+11	This study
L&S_5: Maintenance Charges	0.05$ [(l)]	7.46E+12	3.92E+11	This study
L&S_6: Charges of Chemicals	0.067$ [(m)]	7.46E+12	5.19E+11	This study
D. Inputs in water transmission process (F_3)				
F_3: Energy	–	–	–	See session 4.2
E. Output (Y)				
Y: Drinking Water	0.42 m^3 [(n)]	**2.37E + 13**	9.94E+12	This study

In Table 4, the emergy inputs in seawater exploitation process is 2.71E+11 sej/m^3. The emergy inputs in the desalination process is 9.65E+12 sej/m^3, which is over 6 times larger than the treatment inputs and the transferring process separately. Because the desalination project has not been carried out, emergy inputs in water transmission process from Tianjin to Beijing are not accounted. The UEV of surface water delivered to supply network increases about 19 times larger than the original one. Without the transmission input, the UEV of desalination water is lower than the transferred water, due to the low UEV of seawater.

3.1.5. Summary

Fig. 2 and Table 5 details the emergy indicators of the four water treatment processes.

In Table 5, if water treatment process is considered on its own, the EYR value of processing underground water is the highest, whereas that of processing seawater is the lowest. This is because the UEV value of ground-water is comparatively higher, while that of seawater is the lowest. The ELR value of seawater is the highest (much higher than the ELR value of the other water sources). Comparing EmSI values, which are characterized sustainable indicators of the treatment process, the EmSI of surface water is the highest, and that of seawater is the lowest, with the difference between the former and the latter reaching two magnitudes. Considering E_{input} (Total emergy input/output water), the value for seawater (the highest) is ~6.5 times than that of surface water (the lowest). From a holistic perspective, all the four indicators in Table 5 for surface and inflow waters to Beijing are not much different, because the SNTWP water to Beijing is also surface water and the water quality conditions of SNTWP water to Beijing and the local surface water are similar. However, if add the input from the water exploitation/transferring process, ELR and E_{input} of SNTWP water will be doubled. That means long-distance transmission greatly reduces the sustainability of water metabolic systems.

3.2. Emergy analysis of Beijing's domestic water distribution system

Based on calculations, the emergy input needed for the water transportation and distribution from the Beijing tap-water pipe

[2] http://www.chinabaike.com/t/11091/2015/0928/3376649.html.

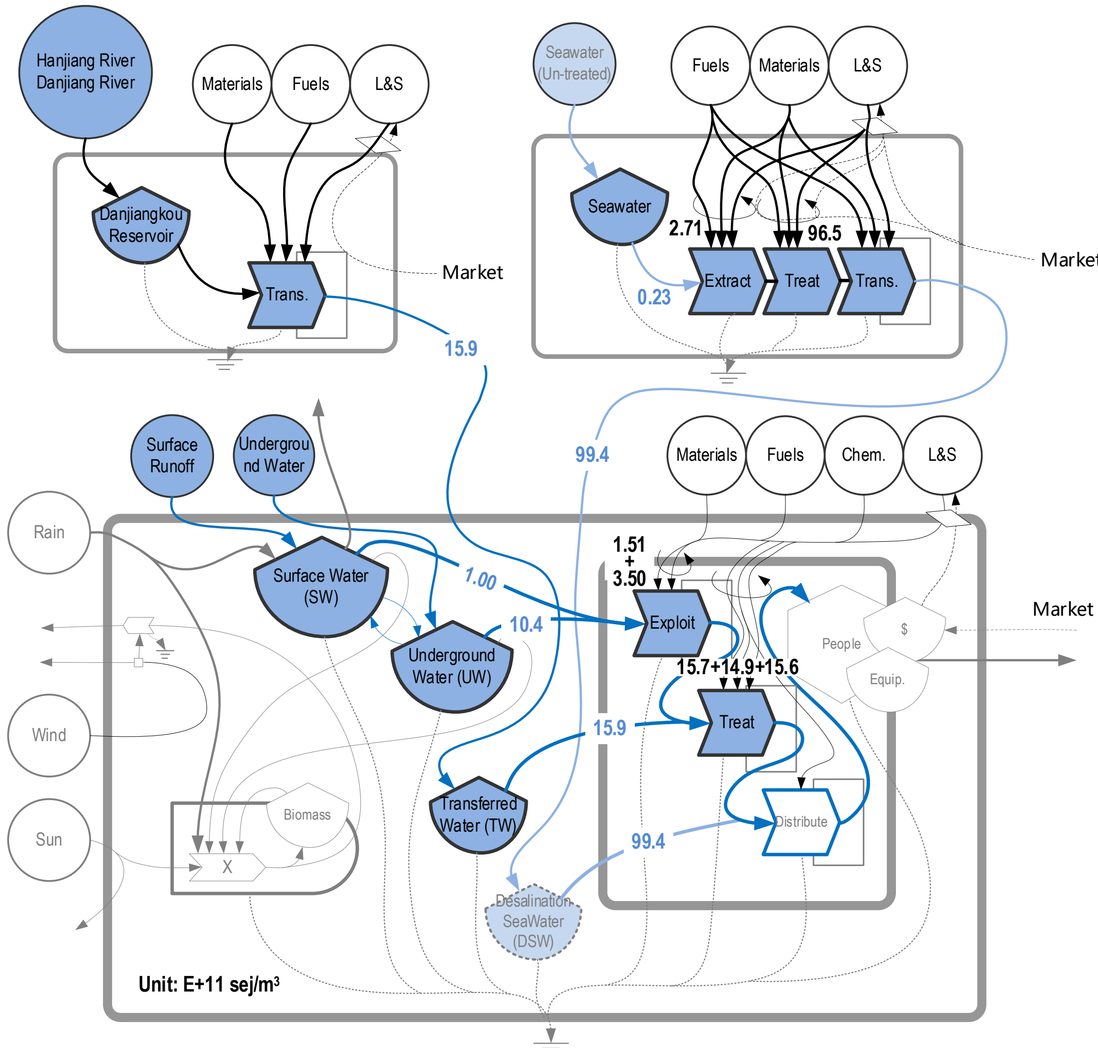

Fig. 2. Emergy diagram of urban water metabolic system in Beijing.

Table 5
Emergy indicators of the four water treatment processes.

	Surface Water		Underground Water		South-to-North Transferred Water		Desalination Seawater	
	Only treatment process	*Exploitation and treatment process*	*Only treatment process*	*Exploitation and treatment process*	*Only treatment process*	*Exploitation and treatment process*	*Only treatment process*	*Exploitation and treatment process*
EYR	1.06	1.06	1.70	1.57	1.06	1.03	1.00	1.00
ELR	15.67	17.18	–	–	15.63	30.53	419.42	431.20
EmSI	0.07	0.06	–	–	0.07	0.03	0.00	0.00
E_{input} (E+12 sej/m^3)	1.57	1.72	1.49	1.84	1.56	3.05	9.65	9.92

network is 1.50E+12 sej/m^3 (total *purchased emergy* (F), from Table 6). Adding the consideration of the waste in the course of distribution, the UEV of water for the end-user of Beijing is 4.58E+12 sej, a figure resulting from 4.58E+12 sej/m^3 being divided by 0.83 m^3.

If we consider the desalinated seawater supply in the future, transport from Tianjin to Beijing is required. Thus, we conducted an energy input assessment according to the energy intensity factor within the water intake process at 0.19 kWh/m^3 (Hu et al., 2013). Given that the distance between Beijing and Tianjin is 1.75-fold greater than that between the Miyun water reservoir and Beijing, we concluded the emergy value should be 2.63E+12 sej/m^3. Taking the waste rate applied in the Table above as the wastage rate in this assessment, and adding in the transportation and distribution of the energy input within Beijing's pipe system, we suggest that the overall transportation and distribution energy value needed after desalination per unit volume, which is obtained by the end users of Beijing, is 1.26E+13 sej/m^3.

4. Discussion

First, loss rates, during each stage of the water supply system, are considered from the above four water sources (Table 7).

Considering these loss rates, the emergy costs per unit volume

Table 6
Emergy analysis of domestic water distribution system of Beijing in 2016.

Item	Raw Data	UEV (sej/Unit)	Emergy (sej)	UEV reference
A. Water entering the supply network (N)				
N: Water	1 m^3	mixed	3.08E+12	This study
B. Fuels & materials (F, G)				
F: Electricity	0.29 kWh [(a)]	7.95E+11	2.31E+11	After Odnm (1996)
G_1: Steel	4.23 g [(b)]	8.56E+10	3.62E+11	Renzulli et al. (2016)
G_2: Concrete	1.50 g [(c)]	3.84E+10	5.76E+10	Renzulli et al. (2016)
G_3: Polyvinyl Chloride (PVC)	1.16 g [(d)]	7.51E+09	8.71E+09	After Pulselli et al. (2011)
G_4: Polyethylene	0.93 g [(e)]	9.70E+09	9.02E+09	After Pulselli et al. (2011)
C. Labor & Services (L&S)				
$L\&S_1$: Electric Charge	0.022$ [(h)]	7.46E+12	1.73E+11	This study
$L\&S_2$: Employee Salary	0.004$ [(i)]	7.46E+12	3.57E+10	This study
$L\&S_3$: Assets Depreciation	0.07$ [(j)]	7.46E+12	5.53E+11	This study
$L\&S_4$: Repair Charge	0.009$ [(k)]	7.46E+12	6.92E+10	This study
D. Output (Y)				
Y: Water for the end-user	0.83 m^3 [(i)]	**5.52E + 12**	4.58E+12	This study

Note:N: According to the existing water supply ratio in Beijing (the exploitation of underground water accounts for 62%, surface water accounts for 20%, and SNWDP water accounts for 18%. Desalination seawater is not considered here). The total emergy of 1 m^3 = 1 m^3*20%*1.92E+12 sej/m^3 + 1 m^3*62%*3.39E+12 sej/m^3 + 1 m^3*18%*3.32E+12 sej/m^3 = 3.08E+12 sej.
(a), (b) from Arbault et al. (2013); (c), (d) from Buenfil (2001).
(e) from Pulselli et al. (2011); (h)-(k) from the website of Beijing Waterworks Group.
(i) is calculated based on loss ratio from Arbault et al. (2013).

Table 7
The loss rates of the whole supplying process of the four kinds of water (Unit: E+11 sej/m^3).

	Exploitation	Purification & treatment	Distribution
Surface Water	1.00	0.95	0.83
Underground Water	1.00	0.85	0.83
SNTWP Water	0.82	0.95	0.83
Desalination Seawater	1.00	0.42	0.83 × 0.83[a]

[a] Desalination of water pipe network is distributed from Tianjin to Beijing (~137 km).

were accounted for each stage, as well as the ratio between their overall emergy input and the emergy value of each stage. These values are detailed in Table 8, Fig. 3 and Fig. 4.

According to the images above, it is discernible that the energy input of inflow water to Beijing from the south-north water transfer project is the highest during the stage of extraction/allocation, based on the water supply per unit volume obtained by users. In the stage of treatment and distribution, the energy input needed for seawater is the highest. For all four water sources, the energy input during the stage of water treatment accounts for the highest percentage within the entire water supply process.

Considering the four different water supply sources for Beijing, the overall energy inputs per unit volume obtained by the end users are 3.22E+12, 3.34E+12, 4.55E+12, and 12.55E+12 sej/m^3. These values refer to the surface water, ground-water, inflow water to Beijing from the south-north water transfer project and desalinated seawater supply system. Surface water has the lower emergy cost, while seawater has the highest one. The energy input of inflow water to Beijing from the SNWTP is not significantly greater than that of surface water. The reason for this is that, considering a low

Table 8
The emergy costs of different phases related to supplying a unit volume water from four sources (Unit: E+11 sej/m^3).

	Exploitation	Purification & treatment	Distribution
Surface Water	1.51	15.7	15.0
Underground Water	3.50	14.9	15.0
SNTWP Water	14.9	15.6	15.0
Desalination Seawater	2.71	96.5	**26.3**

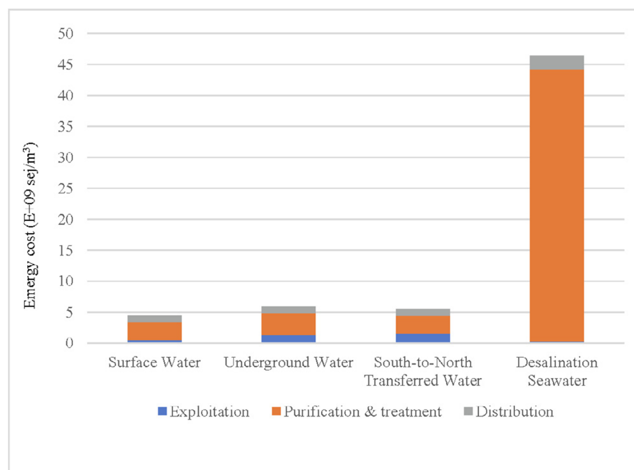

Fig. 3. The emergy costs of the phrases and the whole process of supplying from four sources.

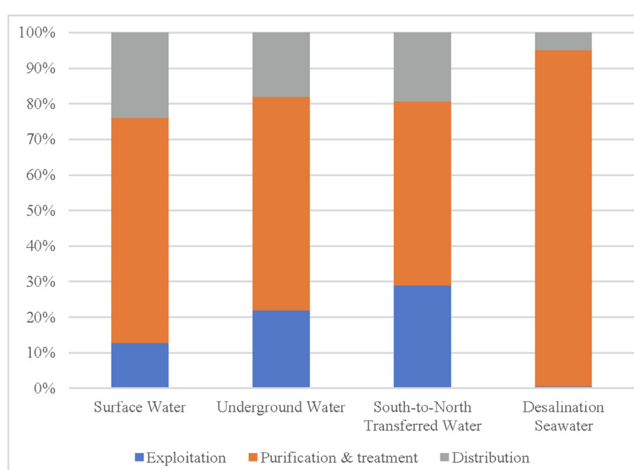

Fig. 4. The proportions of emergy costs of the phrases supplying from four sources.

variability of the emergy input, we calculated the amount of inflow water over the course of the past 40 years, which "diluted" the ratio of the main parts of the south-north water transfer project in Beijing and the preliminary input of Beijing's auxiliary projects.

The principle of Beijing's water supply regulation is "safety comes first and energy-saving is the key; find water sources in a scientific manner and ensure water supply." It is important to enable scientific water transfer, water processing, water distribution, and water supply and ensure the safety of the urban water supply by following the laws of science and finding ways to save energy.

A priority challenge to address is the losses of water resources caused by leakage, which must not be ignored in the management of the urban water system (Zhou et al., 2013). Thus, the technological strategic development in detecting, predicting, controlling and restoring water pipe leakage is vital to water suppliers and the masses (Alliance do Save Energy, 2007; Global Water Research Coalitino, 2010; Kishawy and Gabbar, 2010; Li et al., 2011). To address this challenge, the research on pipe material for water supplies and anti-leaking water meters should be improved. Moreover, the promptness rate for the pipe network repairs should grow, eliminating stealing water to reduce unnecessary losses and pipe network leakage.

The water supply system needs new energy management tactics and solutions to improve the energy of the water supply system and the efficiency of utilizing water, and such tactics and solutions should be innovative, cost-effective and environmentally friendly (Ramos et al., 2011). Water transfer powered by solar energy could represent an alternative for traditional water supply systems that are based on electricity or fuel. In fact, compared to the traditional energy supply, water transfer powered by solar energy is economically feasible for an urban water supply (Chandel et al., 2015). In addition, other renewable energy soureces are also available for water transfer, such as wind power (Vilanova and Balestieri, 2015). By applying renewable energy, the index of sustainability in the energy value of the system can be enhanced.

An optimized water supply system can reduce the energy demand from the municipal water sector (Mass, 2009; Debra et al., 2011; Martin et al., 2011). In this study, UEV values for surface water increased 19 times from 1.00E+11 sej/m^3 to 1.92E+12 sej/m^3 before water delivered to supply network. At the end-user stage, the UEV of water will be 42 times larger (4.21E+12 sej/m^3), reflecting huge resource investments.

From the perspective of demand, water-saving efforts by the end users would also result in energy-saving efficiency (Alliance to Save Energy, 2002). The reduction of the water demand from the end users can reduce both the water in demand and the sewage treatment required, as a result of which water and energy are both saved (Zhou et al., 2013). In addition, helping the end users utilize water more efficiently and enhancing the public awareness and the acceptance of water-reuse from the masses are also good approaches (Po et al., 2003; Ahmad and Prashar, 2010; The Energy Sector Management Assistance Program, 2012). Although the central and local governments have emphasized household water-saving devices and their technology, the use of such devices and technology should still be promoted (Zhou et al., 2013). It is suggested that the saving water scheme be expanded in all levels of locality, region, and state (Buenfil, 2001).

Approximately 1% of household water consumption is for drinking, 6% for cooking, 10% for washing kitchen appliances and 20% for other cleaning purposes (Martire and Tiberi, 2007; Gambassi and Iozzi, 2008). Consequently, only 37% of daily water consumption requires comparatively high-quality water. The use of circulating water can be done by avoiding unnecessary water treatment to reach drinking water's purity so as to save energy. It is suggested that this circulating water that is processed to a certain degree be applied to fire-distinguishing, toilet flushing, and some other outdoor occasions (Zhou et al., 2013). Governments should support rainwater harvesting technology and its apparatuses by administrative and finance means (Muthukumarana et al., 2011), such as requiring new buildings install with the rainwater harvesting and utilizing systems and providing incentives for those who install such systems.

To maximize the "utility" of the energy value appearing in drinking water, it is beneficial to promote a "double water pipe": 1) pipe one is for daily drinking water to flow; and 2) pipe two is for daily cleansing water to circulate. Cleansing water can be the untreated water (such as surface water or underground water) subjected to chlorine bleaching. The former pipe is to transfer drinking water into locations like bathrooms and kitchens; the latter is to bring "cleansing water" into turf irrigation systems and bathrooms (Buenfil, 2001).

5. Conclusion

In this study, we constructed an emergy-based urban domestic water supplying process metabolism model to analysis four sources for Beijing (surface water, underground water, water of the South-to-North Water Transfer Project; potential desalinated water from Tianjin). Results show that the emergy costs related to the water, supplied from the south-north water transfer project, are the highest. This cost depends on the potential desalinated seawater from Tianjin in terms of the alternative water source for Beijing's domestic water consumption.

Saving water is more important than transferring water. Thus, the optimization of reservoirs' operational capacities should be planned, while pipe passageways and water networks design should be improved. Planning should consider that high-quality water should be used in important places, working on a dual water supply system and versatile utilities of water (Vilanova and Balestieri, 2015). The water supply from the south-north water transfer project shifted the emergy cost to support the transition from groundwater to surface water supply, in order to prevent the impoverishment of groundwater resources and to improve the urban environment.

Beijing has announced several major national water policies in recent years – the 'three red lines' and the Water Pollution Prevention and Control Action Plan, for example, established instruments and targets for water quantity and quality control – and it is still unclear precisely how policies will interact with the whole water metabolism functioning. What is clear is that existing institutions of water governance will continue to be challenged by the multiple water supply patterns. Thus, further institutional change is required, to guarantee an equitable distribution of benefits derived from the preservation and sustainable distribution of domestic water resources in highly-urbanized areas, such as the one of Beijing.

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