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Cost-benefit analysis of reclaimed wastewater reuses in Beijing

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ABSTRACT

Costs and benefits of reclaiming and reusing Beijing's municipal wastewater were analyzed based on the 2010 figures. The evaluation took into account the tangible categories of capital investment, operation and maintenance, chemical reagents, and revenues and the intangible categories of environmental improvements, public health impacts, and groundwater recharge and pollution. The outcomes showed the water reuse program would generate a net benefit of 712 million RMB, and the total benefits were 1.7 times of the costs. The inclusion of intangible benefits in the analysis provided extra incentives to go forward with the water reuse project.

Keywords: Cost-benefit analysis; Wastewater reclamation and reuse project; Reclaimed water irrigation; Intangible environmental benefits; Opportunity cost

1. Introduction

Water resources are serious environmental issues worldwide. According to the Global Environment Outlook of the United Nations Environmental Program [1], one-third of the world's current population lives in countries experiencing moderate-to-high levels of water shortage stress. Many countries in Africa and Asia have very low or catastrophically low water availability. Metropolitan centers around the world are seeking means to use the limited water supplies more efficiently. Even water from nonconventional sources, such as seawater desalination, interbasin water transfers, wastewater reclamation and reuse are widely accepted [2,3].

Wastewater reclamation and reuse has distinctive advantages. It requires less investment in infrastructure, takes less time to bring the supply on line as the source water is readily available and technologies for water quality improvements are proven, and users of the reclaimed water exist [4,5]. To be sustainable, a water reuse project must fulfill environmental, socio-cultural and economic needs [6,7]. The feasibility of reusing municipal wastewater requires rigorous assessment.

Cost-benefit analysis is an objective and systematic approach for decision-making and is used by public agencies and businesses to evaluate whether benefits of an action outweigh the costs in monetary terms [8,9]. The costs and benefits considerations are relevant as there are multiple options of producing and utilizing the reclaimed water. Water reclamation and reuse decision-making requires multifaceted assessments of costs, benefits, and environmental risks. Prihandrijanti et al. [10] analyzed the costs and benefits of centralized vs. decentralized wastewater

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reclamation systems for Surabaya, Indonesia. They, however, did not include environmental, public health, and social aspects in the assessments. In fact, few cost-benefit analyses considered and accounted for environmental benefits and damages that were intricate to assign tangible monetary values.

In economic terms, the nontangible values were defined as positive externalities. The contingent valuation method was often used to quantify such externalities in water resources issues [11–14]. Godfrey et al. [15] analyzed the costs and benefits of a grey water reuse system in India. Seguí et al. [16] used travel costs to determine the environmental benefits arising from wastewater reuse for a wetland restoration project. Molinos-Senante et al. [17] used the shadow price to quantify environmental benefits derived from wastewater treatment when they assessed the costs and benefits of wastewater treatment plants along the Mediterranean coast of Valencia region in Spain.

Beijing leads municipalities in China in reclaiming and reusing municipal wastewater. Annual water demand of Beijing amounts to 3.5 billion m^3 yet available water supply estimate is 2.4 billion m^3 [18]. To meet the 1.1 billion m^3 per year water deficit, Beijing is actively reclaiming the municipal wastewater and promoting water reuses. Reclaimed wastewater has become a significant water resource in Beijing. Beijing started to promote large-scale uses of reclaimed water in 2002. About $1.5 billion RMB was invested from 2002 to 2007 to build infrastructures of wastewater reclamation including water reclamation plants at Jiuxianqiao (60,000 m^3/day), Wujiacun (40,000 m^3/day), Qinghe (80,000 m^3/day), and Fangzhuang (10,000 m^3/day), pumping station at Xiaohongmen (300,000 m^3/day), and 400 km of pipeline facilities. Annual reclaimed wastewater reuse reached 495 million m^3 in 2007. The city is now investing additional $10 billion RMB to upgrade eight existing sewage treatment plants to improve the effluent qualities from simply meeting discharge standards to meeting water reuse requirements. The utilization amount of reclaimed water continues to increase. In 2010, 680 million m^3 reclaimed water was reused, among of which, about 47% was used for agricultural irrigation, 30 and 20% of it was used for environmental reuse and industrial reuse, respectively, and 3% was used for urban miscellaneous reuses [19].

Municipal wastewater once reclaimed is a dependable, locally controlled water supply that may provide a great deal of environmental benefits. The water reuse projects are often undervalued and less favored in comparison with other water resources development options due to failures to properly account for the environmental benefits. In this research, all costs and benefits, including the non-environmental and environmental benefits related to reclaimed water reuses, were identified and quantified, and the approach was then applied to assess the feasibility of municipal wastewater reuses in Beijing. The cost-benefit analysis presented herewith is based on data of 2010.

2. Methodology

2.1. Cost analysis

The costs of reclaimed water reuses include the following: (1) reclaimed water treatment plant construction costs (C_1); (2) annual operating costs, including power (C_2), chemical reagents (C_3), maintenance (C_4), and manpower (C_5); and (3) distribution network construction costs (C_6).

According to Shanghai Municipal Engineering Design and Research Institute [20], reclaimed water treatment plant construction costs (C_1) is represented by the annual amortization charge of project investment, which can be calculated as the product of the total project investment (T) and depreciation rate (d):

$$C_1 = T \times d \quad (1)$$

The electrical power is used in pumping, sludge sedimentation tank, filter backwashes, and water conveys throughout the distribution network. As majority of the power is spent on transporting water, the electricity consumptions of pumping stations are the bases of calculating power cost, C_2. The power demands for sludge sedimentation tank, filter backwash, and others are proportional to volume of water transported and their costs are estimated as fractions of the power consumption at pump stations. According to the laws of energy conservation and conversion, the electrical energy is transformed into mechanical work lifting water over elevation and overcoming fractions over distances. The annual power costs of reclaimed water reuse project may be calculated as follows:

$$C_2 = 365(1+\alpha)e \times \frac{\rho g Q H}{1000 \times 3600\eta} \quad (2)$$

where e represents the electricity rate; Q represents the flow of treated water; g represents gravitational acceleration which is 9.8 m/s^2; α is the electricity consumption ratio of other electrical equipment vs. that of the pump station; η is the efficiency of pumping stations; ρ is the density of water; H is the full head of the network, including all head of pumping stations and booster pumps throughout the network.

The annual reagent chemical costs, C_3, can be calculated as sum of all the chemical reagent costs including coagulant (a_1), flocculant (a_2), disinfectant (a_3), etc.:

$$C_3 = \frac{365Q}{10^3}\sum_{i=1}^{n}(a_i p_i) \tag{3}$$

where a_i represents average dosage of reagent i; p_i represents the unit price of reagent i.

According to SMEDRI [20], the maintenance costs, C_4, may be calculated as the product of total project investment, T, multiplies a comprehensive factor, b, which represents the ratio of major repair and maintenance costs accounting for total investment:

$$C_4 = T \times b \tag{4}$$

where b is the comprehensive factor. The value of b is obtained in accordance with the overall rates of depreciation and maintenance for the industry nationwide.

The manpower costs, C_5, including salaries and wages, employee benefits, and indirect costs in management and other fees may be calculated as:

$$C_5 = (C_1 + C_2 + C_3 + C_4) \times \beta \tag{5}$$

where β is a scale factor, usually 15% according to the Water Supply and Drainage Design Manual [20].

The cost of the distribution pipeline network, C_6, may be divided into two categories, namely, in built-up area (BU) and nonbuilt-up area (NBU). Considering the service life of the pipe network, the annual cost of the distribution pipeline network may be calculated as follows:

$$C_6 = (L_{\mathrm{BU}}C_{\mathrm{BU}} + L_{\mathrm{NBU}}C_{\mathrm{NBU}})/\mathrm{SL} \tag{6a}$$

where L_{BU} and L_{NBU} represent the length (km) of pipe network in the built-up area and nonbuilt-up area, respectively; SL represents the service life of the pipe network (years). According to SFIMC [21] and Liu and Huang [22], the pipe network construction cost per 100 m may be estimated according to the depth pipes are laid, ld, using one of the following formulae as:

$$C_{\mathrm{BU}} = \begin{cases} 0.00002x^2 + 0.0180x + 0.1682, & \text{for ld} = 1\text{m} \\ 0.00002x^2 + 0.0187x + 0.2020, & \text{for ld} = 2\text{m} \end{cases} \tag{6b}$$

$$C_{\mathrm{NBU}} = \begin{cases} 0.00002x^2 + 0.0165x + 0.0089, & \text{for ld} = 1\text{m} \\ 0.00002x^2 + 0.0173x + 0.0326, & \text{for ld} = 2\text{m} \end{cases} \tag{6c}$$

where x is the pipe diameter (mm). The cost is based on unit of \$10,000 RMB.

2.2. Benefit analysis

Reclaimed wastewater reuses generate many benefits including revenues of reclaimed water sale (B_1), resources saving in water and fertilizers (B_2), and environmental benefits (B_3). The revenue and resources saving may be evaluated by the market values of what reclaimed wastewater replace, while environmental benefits may be estimated by using the opportunity cost method based on statistics and market estimates [23].

Water sale revenue, B_1, may be obtained as the product of the sale price of reclaimed water and the volume of water sold:

$$B_1 = \sum_{i=1}^{n} Q_i p_i \tag{7}$$

where Q_i is the amount of reclaimed water sold for use i, and p_i is the corresponding market price of reclaimed water.

The resources saving due to reclaimed water reuses, B_2, may be calculated based on the market value of resources reclaimed wastewater replaces. As the reclaimed water is used for toilet flushing, landscaping and crop irrigation, and others, it will correspondingly reduce the need (therefore costs) of developing additional water resources. For irrigation, it potentially saves fertilizer applications as the reclaimed wastewater contains plant nutrients. The benefits in water savings (B_{21}) and fertilizer savings (B_{22}) may be expressed in monetary terms using the following formula:

$$B_{21} = \sum_{i=1}^{n}(T_{p,i} - W_{p,i})Q_i \tag{8a}$$

$$B_{22} = \sum_{f=1}^{m} Q_{irr}C_f P_f \tag{8b}$$

$$B_2 = B_{21} + B_{22} \tag{8c}$$

where $T_{p,i}$ is tap water price for use i, $W_{p,i}$ is the corresponding market price of reclaimed water, Q_{irr} is the amount of reclaimed water for irrigation, C_f is the concentration of fertilizer f, P_f is the price of fertilizer f.

The environmental benefits brought about by reclaimed water reuses include reducing the discharge of treated effluents, B_{31}, improving the local environment, B_{32}, and mitigating harmful effects on human health, B_{33}, and groundwater pollution, B_{34}, and recharging groundwater aquifer, B_{35}.

Implementation of water reuse project will reduce the amount of water discharged to the urban water bodies, thus reduce negative environmental impacts on the receiving water bodies. Therefore, benefits of treated discharge reduction may be quantified as the savings in sewage charge. The State Environmental Protection Department has developed standards for sewage fee collection and calculation method [24] that:

$$B_{31} = \sum_{i=1}^{x} \varphi_i \frac{\rho_i}{1000 n_i} Q \tag{9}$$

where φ_i is collection standard of per pollution equivalent, ρ_i is the concentration of pollutant i from sewage treatment plant effluent, n_i is pollution equivalent value of pollutant i, and x is number of types of pollutants.

The environment improvements come in reduced effluent discharges, preventing the environmental pollution caused by sewage discharge and enhancing the local environmental aesthetics by creating greeneries, wetlands, and water bodies. It is difficult to separate the intangible benefits. We sum up them to equal the cost of recovery for local environment [25]. Based on the opportunity cost method [23], the environment improvement benefit, B_{32}, can be calculated as follows:

$$B_{32} = \sum_{i=1}^{x} h_i(\rho_i - S_i)Q \tag{10}$$

where h_i is removal cost of per unit mass of pollutant i, ρ_i is the concentration of pollutant i in the sewage treatment plant effluent, s_i is the permissible concentration of pollutant i in the ambient environment as regulated by the Chinese national standards.

For potential public health impacts due to reclaimed wastewater reuses, we consider the spread of contaminants especially pathogenic micro-organisms due to the reclaimed water uses in domestic settings, landscape irrigation, and food productions, which will spread as an aerosol form and indirect contact with the human body thus increasing the risk of human exposure to pathogens, thereby increasing risks of sickness. This part of the benefit is negative. According to Hu [26], the public health impact can be calculated as follows:

$$B_{33} = -\frac{\sum_{t=1}^{m} L_t}{m} = \frac{P_0(1+\lambda)^{t-1}\left(\frac{TB}{35} + y\right)f_t + AB}{m} \tag{11}$$

where L_t is the loss of health due to a particular disease during year t, P_0 is the base year population, m is the calculation period, λ is the local natural population growth rate, T is the ratio of sick vs. working days, B is the local average per capita lifespan worth that is expressed in terms of local average per capita GDP worth of the entire working life, y is the annual per capita cost of medical treatment, f_t is the number of medical cases due to water pollution in year t, A is the number of deaths due to water pollution.

Impacts on groundwater include two opposite aspects, namely the contamination and replenishment of groundwater aquifer. Groundwater contamination due to long-term repeated uses of reclaimed wastewater in irrigation may be estimated based on the principle of replacement costs by the costs of pollution control and water recovery [23]. Benefits of groundwater recharge may be calculated alternatively by measuring increase of the aquifer yields. The impact on groundwater contamination can be calculated as follows:

$$B_{34} = -\frac{17}{14} Q_d C k l \gamma P \tag{12}$$

where Q_d is the amount of reclaimed wastewater that can infiltrate into groundwater, C is the concentration of N in reclaimed wastewater, k is the proportion of reclaimed wastewater-borne N leaching into groundwater, l is the proportion of groundwater exploitation, γ is removal ratio of ammonia nitrogen in groundwater, P is the unit removal cost of NH_3-N.

The benefits to groundwater recharge can be calculated as follows:

$$B_{35} = Q_r V \tag{13}$$

where Q_r is the amount of reclaimed water using for recharging groundwater, V is average unit cost of utilizing the groundwater.

2.3. Cost-benefit analysis

The outcome of cost-benefit analysis shows the difference between benefits and costs:

$$\text{NBV} = \sum B_i - \sum C_j \tag{14}$$

where NBV is the net benefit value, B_i is the value of ith beneficial item, C_j is the value of jth cost item in the cost benefit analysis. NBV > 0 indicates economically the overall benefits outweigh the overall costs. For the reclaimed water reuses, Eq. (14) may be written as follows:

$$\text{NBV} = (B_1 + B_2 + B_{31} + B_{32} + B_{33} + B_{34} + B_{35}) - (C_1 + C_2 + C_3 + C_4 + C_5 + C_6) \quad (15)$$

2.4. Data collection

Data were obtained from official government statistics and published literature for the calculation of itemized costs and benefits. As there is not a universally agreed methodology to evaluate treatment costs of water, the parameters employed in this study were synthesized through cost information of existing reclaimed water projects, and the information and guidelines in National Public Works Investment Estimation Indicators [21]. The material costs were estimated according to the 2010 market price in Beijing. The operating costs were evaluated in accordance with the relevant indicators of the Water Supply and Drainage Design Manual [20]. Quality of effluents at existing water reclamation plants in Beijing was also obtained.

3. Results and discussion

3.1. Annual costs of reclaimed water reuse

Equation parameters for the cost calculations were assessed, and the typical and most representative value for each parameter was selected as the default for the calculations (Table 1). Based on the optimal parameter values, the annual costs for producing the reclaimed wastewater for reuses in Beijing, namely the sum of C_1–C_5, are 384.9 million RMB (Table 2). Depending on the size and technology of the treatment plants and other conditions, it may range from 278.8 to 484.2 million RMB (Table 2). Power requirements, C_2, and chemical agent, C_3, combine to account for two thirds of the annual production expenditures. The debt service (amortization charge), C_1, and maintenance, C_4, together accounts are 20% of the total annual production costs, while the labor, C_5, accounts for 13% of the total annual production costs. The cost distributions are reasonable and in line with the actual situations of reclaimed water productions according to national public works investment estimation indicators and experiences of wastewater treatment system construction in the study area [21].

The average amortized unit cost of reclaimed wastewater production in Beijing is approximately 0.70 RMB per m^3 and the City produced 680 million m^3 reclaimed wastewater in 2010. The total costs of

Table 1
Parameterization of cost factors for reclaiming and reusing municipal wastewater in Beijing, 2010

Cost category	Parameter value		Data source
	Range	Default	
Capital investment, T	0.9×10^9 RMB	0.9×10^9 RMB	[27]
Depreciation rate, d	4–7%	6%	[20]
Power consumption ratio vs. pumping station, α	5%	5%	[20]
Electricity rate, e	0.5575 RMB/KW-h	0.5575 RMB/KW-h	Local data
Reclaimed wastewater flow, Q	6.8×10^8 m^3	6.8×10^8 m^3	Local statistical data
Pumping efficiency, η	0.55–0.85	0.65	[18,28]
Hydraulic lift of the water distribution network, H	70–110 m	100 m	[18,28]
Dosage of chemical (coagulant), a_1	$3\text{–}4 \times 10^{-4}$ g/g	3.5×10^{-4} g/g	*
Dosage of chemical (flocculent), a_2	10–15 mg/l	12.5 mg/l	*
Dosage of chemical (disinfectant), a_3	$3.45\text{–}4.60 \times 10^{-7}$ g/g	4.025×10^{-7} g/g	*
Unit price of chemical (coagulant), p_1	4.0×10^3 RMB/ton	4.0×10^3 RMB/ton	#
Unit price of chemical (flocculent), p_2	1.2×10^3 RMB/ton	1.2×10^3 RMB/ton	#
Unit price of chemical (disinfectant), p_3	1.2×10^3 RMB/ton	1.2×10^3 RMB/ton	#
Comprehensive maintenance factor, b	2–4%	2.5%	National average
Manpower scaling factor, β	13–18%	15%	[20]
Pipe diameter, x	$1\text{–}1.8 \times 10^3$ mm	1.8×10^3 mm	[18,28]

*Provided by wastewater treatment authority in Beijing;
#Based on current market prices in northern China.

Table 2
Estimated annual costs of reclaimed wastewater production in Beijing (in million RMB per year)

Cost factor		Mean	Maximum	Minimum
Treatment plants operation	Amortized capital investment, C_1	54.0	63.0	36.0
	Power requirements, C_2	167.0	217.0	89.0
	Reagent chemicals, C_3	90.3	106.0	78.0
	Maintenance, C_4	23.4	24.3	22.5
	Manpower C_5	50.2	60.2	43.5
	Subtotal	384.9	484.2	278.8
Distribution pipeline	C_6, based on Eq. (6)	171	172	170
	C_6, base on situation specific of Beijing	611	873	349

reclaimed water reuse in Beijing would amount to 476 million RMB that is in agreement with the calculated cost range given in Table 2. The method employed for calculating the costs of reclaimed water production is reasonable and the outcomes of cost estimations are realistic. The mean amortized annual reclaimed wastewater production cost of 385 million RMB was adopted as the basis of discussions hereafter.

The pipeline construction, according to Eq. (6), would cost 170 million RMB. However, the formula is a national average. In a twenty million plus densely populated metropolis such as Beijing, the construction costs are considerably higher than the national average because of high costs in land acquisition, resident relocation, demolition and traffic diversion. Liu and Zhao [29] showed that the unit cost of pipeline construction in Beijing varied from 20,000 to 50,000 RMB per meter depending on the construction methods. For the 524 km of pipeline that had been constructed, the total investment on reclaimed wastewater distribution in Beijing would amount from 1.0470 to 2.6190 billion RMB. Based on a service life of 30 years, the amortized annual cost for pipeline construction is from 349 to 873 million RMB, with a mean of 611 million RMB per year. The discrepancy is due to the added costs of land acquisition and associated issues unique to Beijing.

The latter figures were adopted. In this manner, the amortized annual cost of water reuses in Beijing is 996 million RMB per year with a range from 628 to 1,357 million RMB per year.

3.2. Annual benefits of reclaimed water reuse

3.2.1. Benefit of water sales

Reclaimed water pricing are customarily based on contemporary rates of community water supply, operating expenditures, taxes and a reasonable return. In Beijing, however, the reclaimed water price has been kept at 1 RMB per m^3 since the advent of water reuse programs. For 680 million m^3 of reclaimed wastewater produced and used in 2010, the revenue, B_1, is 680 million RMB.

3.2.2. Benefit of water and fertilizer saving

In 2010, 140, 300, 30, and 210 million m^3 of reclaimed water were used for industrial, agricultural, municipal, and environmental enhancement, respectively [19]. Had the reclaimed wastewater not been available, users would have tapped into the public water supplies at much higher costs. The savings by the industries, the municipality and environmental enhancement use are thus derived (Table 3). Based on the water price and the amount of reuse, the water-saving benefits from the industries, the municipality and environmental enhancement use are 729.4, 144, and 67.2 million RMB per year, respectively. For agriculture utilization, water-saving benefit is calculated as the power saving in lifting water as farmers do not pay for the ground water they use for crop irrigation except for pumping. The annual power cost based on results of our field investigations is about 600 RMB per hectare when the groundwater is pumped for crop irrigation. There are about 36,700 hectares of reclaimed water irrigated fields in Beijing. Through field observations, the lift height for reclaimed wastewater used in agriculture is 2–3 m with average of 2.5 m and the average depth to the groundwater table is 22.9 m in Beijing [18]. For these fields, the power cost decreases by an average of 89% when the reclaimed wastewater instead of groundwater is employed. The annual water-saving benefit for agriculture amounts to 19.58

Table 3
Savings in using the reclaimed wastewater in Beijing, 2010

Reuse category	Water used (10^8 m^3)	Water rate (RMB/m^3)		Saving (million RMB)
		Public water	Reclaimed water	
Agriculture	3.0	–	–	19.58
Industries	1.4	6.21	1	729.4
Landscaping	2.1	1.32	1	67.2
Municipality	0.3	5.80	1	144

million RMB. Counting the four types of reuse together, the total water-saving benefits, B_{21}, is 960.18 million RMB per year.

The N and P inputs through reclaimed wastewater irrigation would reduce the fertilizer needs in crop productions. The fertilizer-saving benefit is derived from the volume of reclaimed wastewater applied, and the amount of fertilizer constituents the water provides. Ninety percent of the reclaimed wastewater used in agriculture in Beijing, namely 2.7×10^8 m^3, is used for crop irrigation. Using the advanced treatment in the Beijing's 6th water plant as a realistic depiction, the average N and P concentrations of effluents are 14.71 and 1.53 mg/L, respectively [30]. Annually, the reclaimed wastewater for crop irrigation would provide 3971.7 and 413.1 tons of nitrogen and phosphorus, respectively, that are the fertilizer equivalent to 8,634 tons of urea and 6,308 tons of superphosphate. At the market prices of 2,300 and 478 RMB per ton for urea and superphosphate, respectively, the benefits due to fertilizer saving, B_{22}, add up to be 22.87 million RMB per year.

3.2.3. Environmental benefits

(1) Benefit to wastewater discharge reduction

Benefit due to reduction in wastewater discharge may be evaluated through the sewage discharge fee. According to the official sewage fee collection standards [24], the fees for discharge of pollutants to water bodies are levied in accordance with the type of pollutants and quantity of pollutants discharged. The standard charge per unit pollution equivalent, φ_i in Eq. (9), is 0.7 RMB. The pollution equivalents for pollutants discharged are given by MEPC (Table 4). Feng et al. [31] launched a thorough investigation of the water reclamation facilities in Beijing and determined the effluent concentrations of MEPC regulated pollutants, ρ_i in Eq. (9). The pollution equivalents for each category of pollutants in the reclaimed wastewater of Beijing, n_i in Eq. (9), are obtained accordingly (Table 4). For each discharge outfall, the fees levied are determined by the pollution equivalents of the top three pollutant categories and for Beijing's reclaimed wastewater only the Chemical Oxygen Demand (COD), NH_3-N, and Suspended Solids (SS) need to be taken into account. The benefits derived from eliminating the wastewater discharge, B_{31}, are estimated at 39.9 million RMB per year.

(2) Benefit to improving environmental quality

The benefits due to improvements in environmental quality from reusing reclaimed wastewater are approached through two aspects, namely preventing pollution and restoring impaired environment and are estimated through the opportunity cost method illustrated by Eq. (10) to equal the costs of pollution control and environmental restoration (Table 5) in which the pollutant remove costs, h_i in Eq. (10), are based on outcomes in Li et al. [32]. The concentrations of ith pollutant in effluent, ρ_i, and the ambient water quality standards for pollutants, s_i, are derived from Feng et al. [31] and Yang et al. [33]. The benefit to improving environmental quality, B_{32}, is estimated at 205 million RMB per year.

(3) Adverse human health impacts

Adverse human health impacts represent the acute and chronic diseases that are caused by exposures to pathogenic microorganisms in reclaimed water during the course of water reuses. It includes estimations on costs of medical treatment, loses of time and wages due to illness, and financial losses due to deaths as outlined in Eq. (11). An estimated 2 million people in Beijing annually are exposed the reclaimed wastewater through ornamental water bodies and irrigated landscape in public parks [34]. For 2010, the average hospital stay in Beijing's medical institutions

Table 4
2010 pollution equivalent of reclaimed wastewater of Beijing

Pollutant category	Pollution equivalent/kg of pollutant discharged	Effluent concentration (mg/L)	Pollution equivalent of reclaimed wastewater
SS	4	20	3.4×10^6
COD	1	25	1.7×10^7
NH_3-N	0.8	4.5	3.825×10^6
TP	0.25	1.0	2.72×10^6

Table 5
Parameterization for pollutant removal costs evaluation

Parameter	COD	SS	NH_3-N	TP
Unit remove cost, h_i (RMB/kg)	3.64	5.34	6.16	292.45
Effluent concentration, ρ_i (mg/L)	25	20	4.5	1.0
Reclaimed water quality, s_i (mg/L)	17	10	2.3	0.3

was 13.7 days and, accounting for the recuperation, total sick days would reach 15 days. If annual working day is 250 days, the sick vs. working day ratio, T, is 0.06 (Table 6). Other parameters used include: the calculation period, m, of one year, the population growth rate, λ, of zero (since $m = 1$) and local average per capita lifetime earning, B, of 2.8 million RMB based on the local per capita GDP of 80,000 RMB in 2010 and a working life of 35 years. According to the statistical information of BMBPH [35] and BMBS [27], the annual cost of medical treatment, y, is 15,100 RMB/capita; the incidence of sickness in year t due to reclaimed water pollution, f_t, is 1%; and annual deaths due to reclaimed wastewater exposures, A is 10. In monetary terms, the adverse public health impacts due to reclaimed water reuse, B_{33}, was estimated to be −399 million RMB per year.

(4) Impacts on groundwater pollution

When reclaimed water reused for crop and landscape irrigations, potential pollutants such as nitrogen may leach into the groundwater aquifer and degrade the groundwater quality. The damages can be estimated by the costs of pollution control employing the recovery methods as shown by Eq. (12). Amounts of reclaimed wastewater used for crop and landscape irrigation, Q_d in Eq. (12) are 510 million m^3 in 2010. Given an average total N concentration of 14.71 mg/L, the reclaimed wastewater contains 7,502 tons of N. According to Yang and others [36], approximately 1% of the N, that is, 75.02 tons, may find their way into the groundwater. If 55% of the annual groundwater yield, l in Eq. (12), is extracted for the public water supply [37], 41.261 tons of N will be removed from the aquifer. Li et al. [38] reported that the rate of ammonia over standard is 24.1–62% of the total N in Beijing's groundwater. Accordingly, an average 43% of the extracted N, that is, 17.74 tons corresponding to γ in Eq. (12), need to be removed to meet the drinking water quality standards. In turn, 17.74 tons of N is equivalent to 22.81 tons of NH_3-N whose removal cost, P in Eq. (12), is 23.82 RMB/kg. The total pollution control cost of preventing groundwater N pollution, B_{34}, was estimated at −0.543 million RMB per year.

(5) Benefit to groundwater recharge

In crop and landscape irrigation, the reclaimed wastewater applied is primarily consumptively used and contributes little to recharge groundwater. Besides, the downward water movement is hampered in Beijing by a pervasive impermeable layer. The Yongding River, flowing along the north to west geological fault line, is an important source of water supply for Beijing. It is a protected area for water resources and is the primary groundwater recharge area in the Beijing Basin. Each year, the Yongding River receives 120 million m^3 of reclaimed water [28] of which the annual groundwater recharge is about 100 million m^3 [39]. The average charge for extracting groundwater, V, in Beijing is 2 RMB/m^3. Therefore, the benefits to recharge groundwater with reclaimed wastewater, B_{35}, were set at 200 million RMB.

Table 6
Parameters to evaluate public health impacts due to reclaimed wastewater exposures in Beijing

Parameter	Default values
Exposed population, P_0	2×10^6
Evaluation period, m	1 year
Ratio, sick vs. total working days/year, T	0.06
Lifetime per capita earning, B	2.8×10^6 RMB
Annual per capita medical cost, y	15.1×10^3 RMB
Sickness due to reclaimed wastewater exposure, f_t	1%
Annual death due to exposure to reclaimed wastewater, A	10

3.2.4. Net benefit

The cost-benefit analysis shows that the water reuse program in Beijing produces 712 million RMB of benefits per year (Table 7) and the total benefit is 1.7 times of the total cost. In Beijing, reusing reclaimed wastewater appears feasible and economically positive.

The total cost of reclaiming and reusing Beijing's municipal wastewater, based on the 2010 figures, is estimated at 996 million RMB per year. Between the two major cost categories, the capital investment on pipeline construction costs 1.58 times that of the wastewater reclamation plant operation. As water reuse is frequently an afterthought, the necessary infrastructures for water distribution and reclamation are not planned and built in as the city develops. Once the community has been established, adding technical capacities and laying the pipelines to distribute reclaimed wastewater become extraordinarily costly [40]. Lacking an effective water distribu-

Table 7
costs and benefits of water reuse (unit: million RMB)

Cost category		Benefit category	
Amortized investment C_1	54	Revenues from water reuse B_1	680
Power consumption C_2	167	Water resources saving, fertilizer B_{21}	960.18
Chemical reagents C_3	90.3	Water replacement savings B_{22}	22.87
Maintenance C_4	23.4	Wastewater discharge reduction B_{31}	33.9
Manpower C_5	50.2	Environmental improvement B_{32}	205
Pipeline construction C_6	611	Public health impacts B_{33}	−399
		Groundwater pollution B_{34}	−0.543
		Groundwater recharge B_{35}	200
Total cost	996	Total benefit	1,708

tion network has become the primary issue limiting the reclaimed wastewater reuse in China [5].

The benefits of reclaimed water reuse, based in the 2010 figures, was 1,708 million RMB per year that were derived primarily from savings from substituting the public water supply with reclaimed wastewater, revenues of selling the reclaimed water, and intangible benefits of environmental improvement when the wastewater no longer was directly discharged into natural water bodies. Yet the savings derived from the N and P fertilizer benefits in irrigating with reclaimed wastewater were minor and essentially negligible in the cost-benefit analysis.

The opportunity cost method was employed to evaluate the nonmarketable benefits of water reuses. In this manner, the intangible benefits of saving water resource and environmental enhancement were about two times that of the direct tangible benefits of selling reclaimed wastewater to customers. The nonmarketable intangible benefits provided extra incentives for going forward with the water reuse projects. On the other hand, the adverse impacts to public health, at −399 million RMB per year, should not be overlooked. It often becomes an obstacle to implementing the community water reuse programs.

4. Conclusions

The cost-benefit of the wastewater reclamation and reuse program was analyzed. The cost categories considered included: (1) the wastewater reclamation cost of amortized capital investment of treatment facilities, power requirements in facility operations, reagent chemicals, maintenance, and manpower; and (2) the water distribution cost in constructing a pipeline network. The benefit categories include: (1) tangible benefits of revenues in selling the reclaimed wastewater, savings from substituting the public water supplies with the reclaimed wastewater, savings of N and P fertilizers when reclaimed wastewater is used in crop and landscape irrigations; and (2) intangible benefits of environmental improvements, reduced wastewater discharges, public health impacts due to exposures to reclaimed wastewater, and groundwater recharge and pollution. The opportunity cost approach was employed to evaluate the intangible benefits. For Beijing, the wastewater reclamation and reuse program resulted in a net benefit of 712 million RMB per year. The total benefit is 1.7 times greater than the total cost. The inclusion of intangible benefits in the analysis had provided the extra incentive to go forward with the water reuse program.

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