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Drops of Energy: Conserving Urban Water to Reduce Greenhouse Gas Emissions

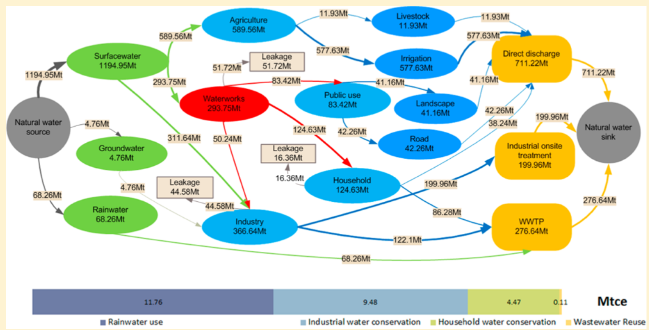
Yuanchun Zhou,[†] Bing Zhang,[*,†,‡] Haikun Wang,[†] and Jun Bi[*,†]

[†]State Key Laboratory of Pollution Control & Resource Reuse, School of Environment, Nanjing University, Nanjing, 210046, P. R. China

[‡]Key Laboratory of Environmental Planning and Policy Simulation, Chinese Academy for Environmental Planning, Beijing 100012, P. R. China

Supporting Information

ABSTRACT: Water and energy are two essential resources of modern civilization and are inherently linked. Indeed, the optimization of the water supply system would reduce energy demands and greenhouse gas emissions in the municipal water sector. This research measured the climatic cobenefit of water conservation based on a water flow analysis. The results showed that the estimated energy consumption of the total water system in Changzhou, China, reached approximately 10% of the city's total energy consumption, whereas the industrial sector was found to be more energy intensive than other sectors within the entire water system, accounting for nearly 70% of the total energy use of the water system. In addition, four sustainable water management scenarios would bring the cobenefit of reducing the total energy use of the water system by 13.9%, and 77% of the energy savings through water conservation was indirect. To promote sustainable water management and reduce greenhouse gas emissions, China would require its water price system, both for freshwater and recycled water, to be reformed.



1. INTRODUCTION

Energy and water are two essential resources that are important to national security and to economic health,[1] and both water and energy scarcity are major and growing challenges. Furthermore, these two vital resources are inextricably linked with each other. Water is used to cool steam electric power plants and is utilized in great quantities during fuel extraction, refining, and production, and energy is used to extract, move, and treat water for drinking and irrigation.[2−4] Arguably, meeting the future energy needs depends on water availability, and energy is, in turn, indispensable for meeting water needs.[5] There is currently an overwhelming scientific consensus that global warming and climate change are occurring,[6] and the escalating energy usage with increased water consumption and wastewater discharge also has brought much attention to climate change mitigation.[7]

Urban water systems, including supply,[8] distribution,[9] end-use,[10] and wastewater treatment,[8] have significant impacts on energy consumption and greenhouse gas emissions.[4,11] Approximately 2−3% of the world's energy consumption is estimated to be used to pump and treat water for urban residents and industry.[12] CO_2 embodied in nation's water represents 5% of all U.S. carbon emissions.[13] The state of California, the city of Toronto, the region of Peel, and the city of Guelph have each identified water and wastewater facilities as significant energy consumers, reportedly accounting for 25−60% of their respective municipal electricity bill.[1,14,15] Additional studies have also determined that optimization of water supply systems would reduce energy demand of the municipal water sector through water demand/supply management.[1,16,17] Research in Tucson has shown that a 20% decrease in water demand across all sources directly equals a 20% decrease in energy consumed for water,[16] and municipal energy savings associated with a 20% increase in water efficiency today could achieve an impressive 34% of reported energy reduction potential for municipalities in Ontario.[18] Thus, although the cobenefits of municipal water conservation offer an untapped opportunity to realize energy savings for climate change mitigation, such conservation has not yet received the attention that it merits.[5]

The interconnection between water and energy provides opportunities for sustainable water and energy management and for reducing greenhouse gas emissions. Therefore, assessing energy use in an entire water sector is important.

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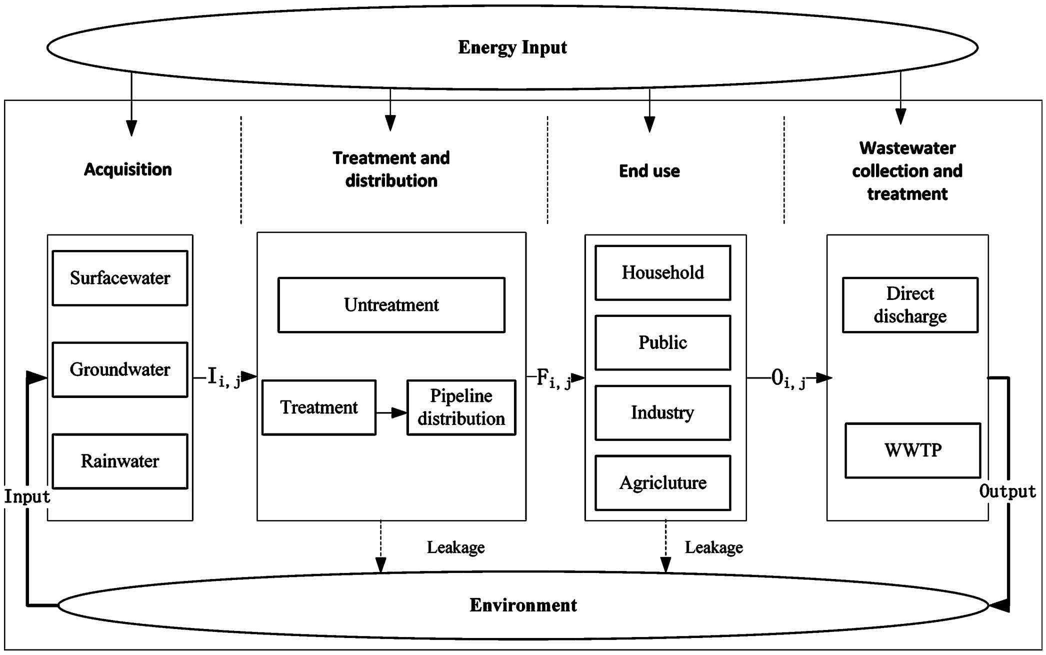

Figure 1. Water system and energy use by stage.

Additionally, the systematic analysis of water delivery and use is fundamental for modeling energy use of water system.[16] Life cycle analysis (LCA) is often used to determine the energy use and environmental burden of water sectors.[19,20] Despite being a comprehensive approach, the elements and processes included in LCA studies may vary and tend to focus on the differences between water supply systems and wastewater treatment technologies rather than on the total energy consumption of the entire water sector.[7,21] In addition, although national input−output (I−O) analysis can be extended to quantify the environmental impacts, average national data are not suitable for application to a particular city.[4,16]

Material flow analysis (MFA) provides an analytical method for quantifying the flows and stocks of materials or substances in a well-defined system, which can help planners to develop strategies for improving material flow systems in form of material flow management.[22,23] Furthermore, such systematic calculations for the urban metabolism of cities can be used to examine embodied energy use, both direct and indirect, of a specific water-use approach.[16] Therefore, water flow-based energy-use analysis can provide both sustainable water and energy management opportunities for the urban water system.[24]

This research attempted to establish a water flow analysis framework to determine water flow of cities and related energy consumption, which can then be used to optimize water system and reduce energy consumption. The water flow by quantity was determined based onwater I−O analysis of different stages of an urban system. Subsequently, energy use of different stages of a water system was calculated according to various factors, including water technologies, transportation distance, and end-use methods. In addition, this framework was applied to a city in China to examine water and energy usage. A sensitivity analysis to evaluate sustainable water flow management scenarios is suggested to provide insight into the cobenefit of water conservation and energy savings. The current study also conducted an uncertainty analysis on water flow and the related energy consumption.

2. MATERIALS AND METHODS

2.1. System Boundary. The material analyzed for study included water, and all possible important interactions involved in the system analysis were considered. System boundary of water is the geographic boundary of city, and the total input, inventory, and output of water flow in urban metabolism and related energy consumption were examined stage by stage of the water flow. Figure 1 shows the system for the overall water system that we considered in this study and includes the water network and main activities relevant to water flow in the city. Water inputs include groundwater, surface water, and rainfall. Water outputs include wastewater treated by wastewater treatment plants (WWTPs) or factories and untreated that directly discharged. Intercity flows include the entire water cycle, which was summarized as extraction, transportation, end use, wastewater collection, and treatment.[25] End users include agriculture, household, industry, and public use. Agricultural water consumption includes plants, irrigation, and livestock breeding. Household water consumption includes residential and public welfare facility consumption (such as the service sector). Industrial water consumption includes consumption during the production process. Public use refers to landscape irrigation and road sprinkling. Evapotranspiration and soil moisture are excluded from the system. The water flows into, within, and out of system are represented by arrows; for each of these flows, our model quantifies corresponding average annual flow for the city (in million tons/year).

Water flow is fueled by energy to maintain normal operation. For a traditional life cycle analysis, energy consumption of operation phase and energy consumption embodied in construction and demolition phases should all be considered.[20,21] However, results of existing studies have shown that operational phase generally consumes much more energy from water system than other phases.[26] Hence, energy consumption in installation and demolition phases was not taken into consideration in this study. Energy inputs to water cycle can be further divided into following: indirect energy consumed by water agencies (municipal energy to pump, transport and treat water and wastewater), direct energy used to consume water (energy used at end use, such as heating water) and embedded energy required to manufacture chemicals used to treat water and wastewater.[1] Due to its small amount compared to direct and indirect energy, the embedded energy was also beyond the scope of this paper.[1] The direct and indirect energy consumption of operation phase of water flow was calculated stage by stage. As the actual energy consumption can vary significantly for each process due to a host of geographical, physical, and technological factors,[27] all of the subsystems were greatly simplified, showing only main energy consumption of various activities. To express energy in uniform units, the authors chose equivalent coal units of Mtce.

2.2. Modeling Approach. *Water Flow.* A complete set of equations was used to describe all variables of water flow on the basis of acquired system; equations in this system describe either demands (such as water demand for plants) or input–output relationships (such as water distribution). In mathematical terms, the set of linear and nonlinear equations is a parametrization of relevant flows and energy inputs of the system. These parameters represent production parameters (such as number of livestock), operating parameters (such as transfer coefficients), and specific physiological parameters (such as local elevation). All mathematical equations were set according to three rules. First, the flow has a fixed value; in general, these precise values can be acquired from field surveys and statistical analyses. Second, the flow is dependent on other flows; these flows are usually calculated by quantifying other flows and applying the mass balance principle. Third, the model consists of equilibrium flow to balance the flows into and out of a subsystem within the context of law of mass conservation and thermodynamics.[28]

There are three types of flows described in the defined system: input flows, internal flows, and output flows. Input flows: $I_{1,1}$ = surface water extracted by waterworks, $I_{1,2}$ = surface water extracted by agriculture, $I_{1,3}$ = surface water extracted by industry; I_2 = rainwater collected by WWTPs; I_3 = groundwater extracted by industry. F_i denotes the internal flows, $F_{1,1}$ = industrial consumption of tap water, $F_{1,2}$ = household consumption of tap water, $F_{1,3}$ = public use of tap water. $F_{2,1}$ = $I_{1,2}$ = surface water extracted by agriculture, $F_{2,2}$ = $I_{1,3}$ + I_3 = groundwater and surface water extracted by industry. Output flow of wastewater: $O_{1,1}$ = industrial discharge to WWTPs, $\mathrm{O}_{1,2}$ = household discharge to WWTPs, $\mathrm{O}_{1,3}$ = public discharge to WWTPs, $O_{1,4}$ = rainwater discharge to WWTPs; $O_{2,1}$ = industrial discharge to the environment, $O_{2,2}$ = household discharge to the environment, $O_{2,3}$ = agricultural discharge to the environment, $O_{2,4}$ = public discharge to the environment; $O_{2,5}$ = leakage of different stages to the environment.

Energy for Water. Both the energy use by different sectors and the water distribution are involved in calculating the energy for a water system. Based on the water flow, the energy use of the urban water system can be calculated by summing the energy use of all the water delivery or use flows:

$$E = \sum_{j}^{n} \sum_{i}^{n} Q_{ij} \times ED_{ij} \tag{1}$$

where E is the total energy use of water system, Q_{ij} is quantity of water flow from sector i to j, and ED_{ij} is energy intensity of the water flow from sector i to j. When $i = j$, Q_{ij} and ED_{ij} represent water use and energy intensity of sector i, respectively.

In concrete terms, energy consumption of water extraction and distribution are estimated through an operational situation of pumps. Energy consumed by wastewater collection and treatment is estimated through an operational situation of pumps, blowers, and dewatering machines in WWTPs. Energy consumption of water use is mainly considered for water heating for industrial uses and circulating cooling water systems during industrial process; water heating for bathing and drinking are considered household water uses. The agricultural sector was considered to have no energy input during water-use process, and energy consumption of public water use is not calculated. The detailed approach of water flow analysis and energy for water accounting can be found in Supporting Information (SI) SI-A and SI-B.

2.3. Research Site and Data Collection. This research area chose Changzhou as a case study (SI Figure S1). Changzhou covers a total area of 4385 km^2 and has a population of approximately 3.6 million. Changzhou also has a high level of municipal services: its water penetration rate reaches 100%, and its household wastewater treatment rate was 88.9% in 2009.[29]

On-site visits, values reported in the literature, and estimations/plausible reasoning were used to gather water and energy data. Local and international research reports and the scientific literature were adapted to Changzhou conditions and combined with order of magnitude estimations and plausible reasoning, such as circulating cooling water systems and groundwater treatment. Face-to-face interviews with government officials, entrepreneurs, experts, and farmers were used to obtain on-site data, such as ratio of wastewater discharge to WWTPs, energy consumption of water and wastewater treatment, and average energy consumption of water distribution. These interviews can help us obtain the best estimates for the parameters used and to improve our understanding of the statistics. The roof and street runoff coefficients are assumed to be the same, and we only consider rainwater collected in WWTPs. The details of data sources can be found in SI Table S1. In addition, because accounting methods and relevant parameter assumptions are not consistent with each other, the statistical data of water flow supplied by a statistical yearbook[29] and water resource bulletin[30] show large differences. For example, quantity of wastewater discharge from the industrial sector according to a water resource bulletin is 129 Mt, but it is 377 Mt according to a statistical yearbook. Therefore, to ensure consistency, we do not use these data directly in our study, and we perform calculations based on population, number of livestock, irrigation area of plants, area of road and landscape, and their water consumption quota. For industrial water use, we calculated it based on industrial enterprises' monthly report of water consumption plan.

2.4. Water Conversation Scenarios. Scenario analysis allows us to determine those scenarios with the highest potential to reduce energy consumption of water system. This research developed four scenarios to show the cobenefit of water conservation and energy savings: demand reduction and supply alternatives. For supply side, recycled water and rainwater collection are more operational in urban areas.[17] For demand side, conservation by consumers, both industry and household, can also provide energy-saving benefits.[12]

Wastewater Reuse. From an energy perspective, recycled water can save energy under most circumstances by avoiding energy used to treat water unnecessarily to reach drinking water quality standards. The use of recycled water is advisable for

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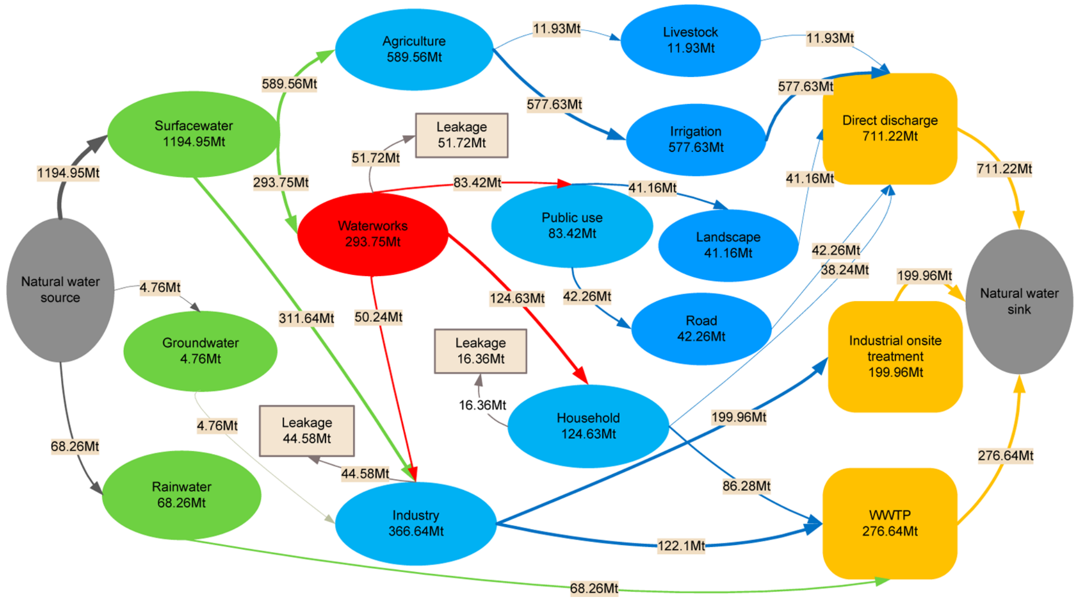

Figure 2. Estimated urban water flow of Changzhou (2009).

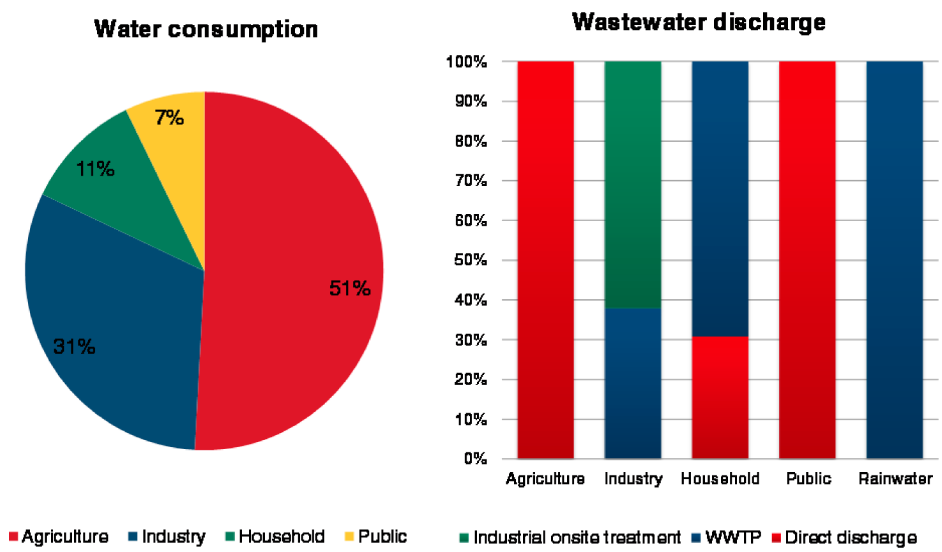

Figure 3. Water consumption and wastewater discharge in Changzhou (2009).

many purposes, including fire protection, toilet flushing, and so on, and requires different levels of water quality and treatment.[15] In this study, we set a target of 10% wastewater reuse for road sprinkling and landscape irrigation.[31] In general, wastewater for these purposes needs additional energy input for tertiary treatment and distribution from WWTPs to end users.[32] For purposes of proxy, we assumed that energy consumed for distribution of recycled water was similar to the distribution of tap water. Road sprinkling and landscape irrigation was assumed to have no energy input requirement. So this scenario can bring indirect energy savings through tap water treatment.

Rainwater Use. Rainwater reuse schemes are commonly used in water-sensitive design strategies for new urban development,[33] and the Chinese government has also proposed requirements for rainwater use.[31] From an energy perspective, harvesting rainwater for safe reuse can help reduce energy consumed for wastewater treatment and avoid energy used to treat water unnecessarily to drinking water quality and distribute it to end users. Rainwater can supply water for toilet flushing, laundry, and outdoor uses. We assume toilet flushing is a main purpose, requiring no additional energy input. Therefore, this scenario can provide indirect energy savings through tap water production and distribution, wastewater collection, and treatment.

Water Conservation in the Household. Water conservation has long been recognized as an important institutional and social adaptation to address climate change.[34] In this scenario, we established a target of a 10% reduction in domestic water consumption in Changzhou compared to the national average (excluding water used for public service). Water conservation in households will result in a substantial decrease in energy use, including less energy needed for the production and distribution of drinking water, less energy used by consumer (i.e., heating), and less energy needed for collection and treatment of wastewater.[35] People prefer to save water through efforts related to personal hygiene, such as toilet flushing and taking short showers;[36] thus, we assume that half of the water

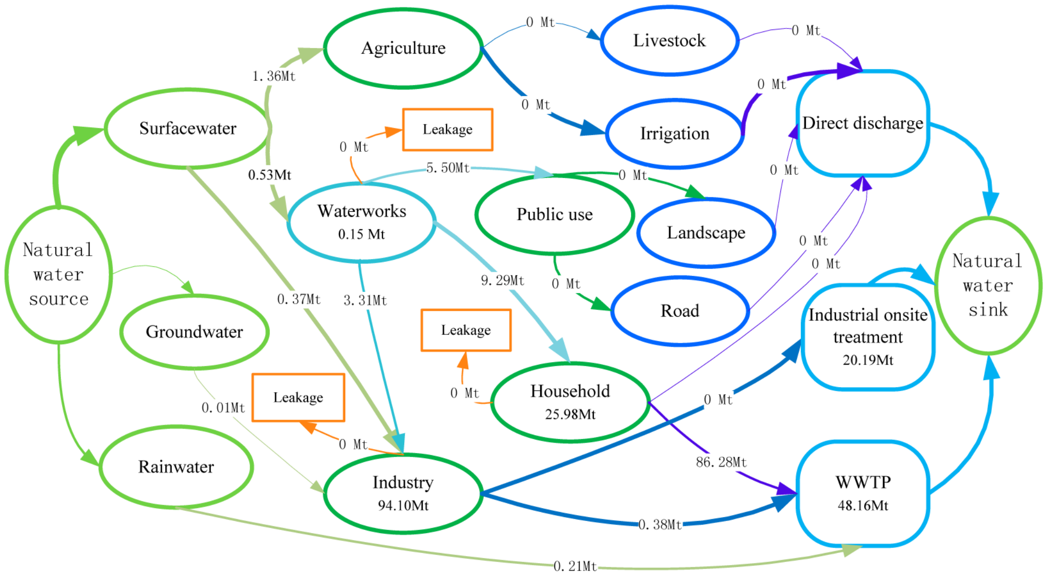

Figure 4. Estimated energy consumption of the urban water flow of Changzhou (2009).

savings are derived from showering and the remainder from other ways that require no additional energy input. This scenario can afford indirect energy savings through tap water production and distribution, wastewater collection and treatment, and direct energy savings from water heating for showering.

Water Conservation by the Industrial Sector. The energy savings involved in water conservation by the industrial sector are similar to those by the household sector. In this scenario, we established a target of a 15% reduction in water consumption in the industrial sector compared to the national average and the government's requirement. For industrial water use, technical improvements that include increased water efficiency benefits, reduced water loss, and alternatives to conventional water resources are very crucial.[37] In this study, we assume that technologies for improving existing production processes are mainly water-saving methods, with 30% of the saved water derived from water heating. This scenario can result in indirect energy savings through tap water production and distribution, wastewater collection and treatment, and direct energy savings from water heating for industrial use. The detailed approach of energy saving estimation can be found in SI SI-C.

3. RESULTS

3.1. Water Flow of Changzhou City. The water flow of Changzhou City is illustrated in Figures 2 and 3. The total water acquisition in Changzhou was 1199.7 million tons in 2009. Changzhou's public water supply system is a surface water-based supply system, with groundwater only accounting for 0.4%. Specifically, of total water extraction, agriculture accounts for 49%, industry accounts for 26.5%, and waterworks account for 24.5%. The agricultural sector satisfied all of its water demands using surface water without treatment. Nearly half of surface water (48%) was consumed for irrigation, whereas aquaculture without fisheries only consumes 1%. The industrial sector satisfies 85% of its demand with self-extraction of surface water, 14% with tap water supplied by waterworks and remainder with groundwater. Water was mainly consumed by water-intensive industries, such as textiles, raw chemical materials, and the power sector. The household sector consumed 10% of the surface water supplied by waterworks for heating, and public sectors only consumed approximately 7%. The tap water supplied by waterworks was mainly consumed by the household sector, accounting for 44.7%, whereas industrial and public sectors consumed 34.5% and 20.8%, respectively. Overall, 15.2 Mt of surface water extracted by waterworks was lost during treatment, and 36.5 Mt of tap water was lost during distribution to end users.

Approximately 90% of urban household wastewater and 40% of rural household wastewater was collected to WWTPs for further treatment; the remainder was directly discharged into environment without treatment. There was no wastewater collectedin to WWTPs from the agricultural sector: all the water was absorbed, evaporated, or seeped and was discharged into nearby rivers during the process of end use. Because a rain and sewage diversion system functions in Changzhou, 68.26 Mt rainwater was collected into WWTPs. Additionally, 62% of wastewater from the industrial sector was treated by the firms themselves, whereas the remainder was collected by WWTPs. All of the wastewater from the public sector evaporated into the environment or seeped into groundwater without treatment. The excess landscape irrigation flow was minimal and was not calculated.

3.2. Energy Consumption of the Water System in Changzhou. The estimated energy consumption of the total water system reached a notable level, approximately 10% (189.95 Mtce) of the city's total energy used by the water system (see Figure 4). Based on conversion factor of energy and GHGs, the energy consumption of water system may lead to emissions of 466.7 Mt CO_2. A breakdown of total energy consumption showed that end-use and wastewater treatment stages were the main contributors, accounting for 63.2% and 25.4%, respectively. Distribution of tap water consumed 9.7% of total energy, whereas water acquisition stage and wastewater collection stage only consumed 1.7%. Direct energy consumption accounted for 63.2%, and indirect energy consumption accounted for 36.8% of the entire water system in Changzhou.

The energy consumption of different end users varies drastically, with some use requiring no additional energy

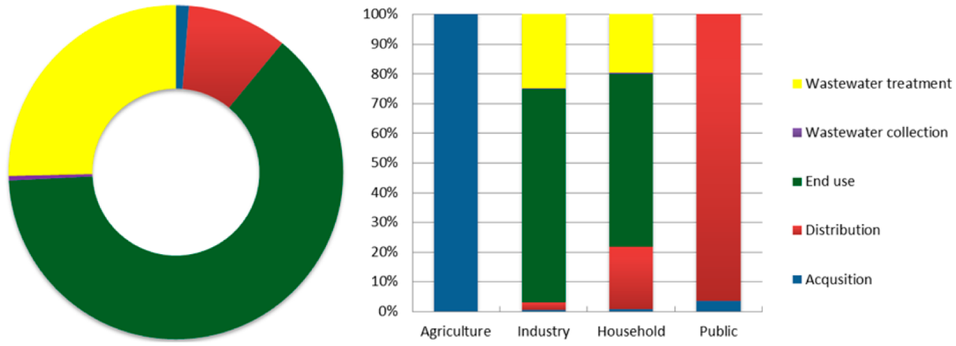

Figure 5. Estimation of the annual energy consumption of the urban water system (2009).

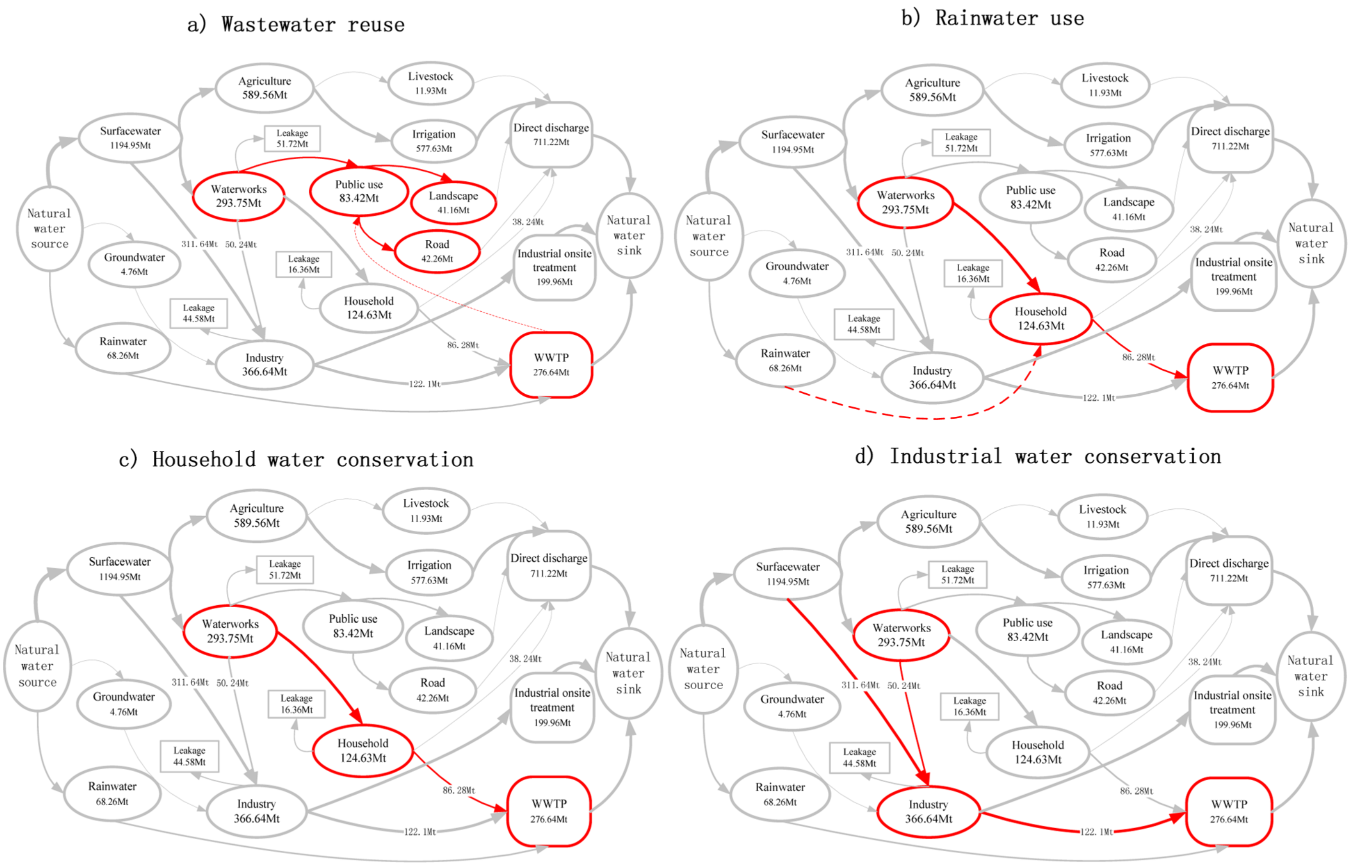

Figure 6. Scenario analysis of the energy savings through water conservation.

(e.g., irrigation and toilet flushing). The agriculture sector consumed the least energy (0.7%) in our study because only energy consumed for the extraction of surface water was considered, and there was no energy consumed for end-use, wastewater collection, and treatment stages. Industrial and household sectors consumed much more energy than other sectors, particularly the end-use stage. The industrial sector consumed 71.7% of the total amount, whereas the household sector consumed 24.4%. For end use of water, the industrial sector consumed 49.5% of the total energy of the water system, whereas the household sector consumed 13.7%. Urban public water use only accounts for 5% of the total energy use because there is no energy consumed for end-use and wastewater collection and treatment stages, See Figure 5.

3.3. Energy Savings by Conserving Water. Based on the water flow and energy use estimation, four water conservation scenarios are proposed in this study (Figure 6). This research established a goal of 20% wastewater reuse, which was required by regional water conservation management approach. Because wastewater still needs to be distributed to end users after treatment, we did not consider the energy savings of tap water distribution. Rainwater is assumed to be mainly used in daily life, such as in toilet flushing. In addition, a target of a 10% reduction in domestic water consumption was established compared to the national average (excluding water used for public service). Lastly, this research established a target of a 15% reduction in water consumption by the industrial sector compared with the national average. The related changes in energy consumption of different stages were all calculated.

The results of four scenarios presented above showed a considerable benefit in energy savings by conserving water usage (Figure 7). A 10% decrease in water demand (11 Mt) by

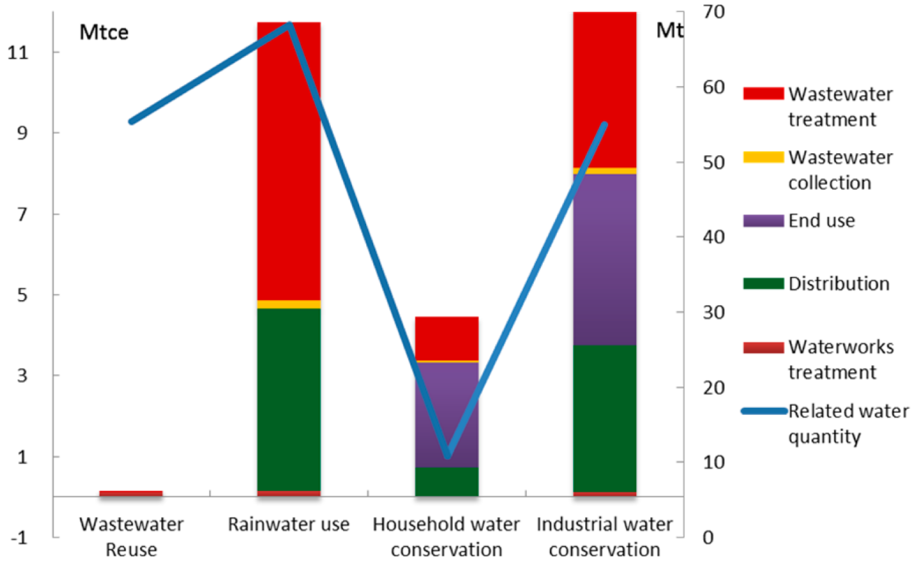

Figure 7. Comparison of the energy-saving potential among different scenarios (Mtce).

the household sector would lead to a 4.47 Mtce energy saving, accounting for 2.35% of total energy used by the water system; water savings by the industrial sector (55 Mt) would lead to a 13.7 Mtce reduction in energy consumption. Reuse of 20% wastewater (55 Mt) would introduce 0.06% energy savings, and rainwater use (68 Mt) would result in a 6.19% reduction in the total energy used for water. Additionally, water conservation by the household sector shows the largest degree of energy saving (energy savings per ton water, tce/m^3). The benefit of wastewater reuse is the lowest among all the solutions due to the offsetting effect of wastewater treatment and reclaimed water distribution. Furthermore, 77.3% of the energy savings from water conservation is indirect, with only 22.7% of the energy savings directly originating from end-use stage. The energy reduction for tap water distribution and wastewater treatment largely contributes to indirect energy savings, and industrial water conservation resulted in more direct energy savings when compared to household energy conservation.

3.4. Uncertainty Analysis of Energy Consumption. Parameter uncertainties could vary the degree of water and energy consumption. In present study, most of operational parameters were obtained from our surveys and interviews in Changzhou. Hence, it is critical to evaluate the uncertainty in our results to increase accuracy and robustness, though this is a challenging process due to a wide range of reliability with regard to information. In this section, five parameters are assumed to be uncertain during the modeling of the water system, including coefficient of rainwater collected to WWTPs, runoff coefficient of impervious areas, leakage ratio of tap water, leakage ratio of industrial water use, and leakage ratio of household water use. At the same time, five parameters are assumed to be uncertain during modeling of the energy consumption of water system: operational efficiency of pumps, service time of the pumps per year, energy consumption of unit wastewater treatment, total dynamic head, and wastewater quantity to be treated, which was influenced by the water flow analysis, as shown in SI Table S2. Other data, such as those extracted from the statistical yearbook, are not tested for uncertainty. A Monte Carlo simulation with 10 000 iterations was performed to estimate the range of water resource extraction, wastewater treatment and energy consumption produced by Decision Tools Suite@Risk5.5. The probability distribution for input parameter represents a reasonable operating definition of the uncertain parameter. A triangular distribution was used because the sample data of an uncertain parameter were limited.

The results are presented over a 90% confidence interval (CI), as shown in SI Figures S3, S4, and S5. Water resources of surface water, groundwater and rainwater flowing into water system ranged from 1253.6 to 1302 Mt. Wastewater treated in WWTPs and by industrial companies ranged from 397.6 to 652.9 Mt. The regression coefficient (RC) in uncertainty analysis reflects how parameter uncertainties affect the water system. The coefficient of rainwater collected to WWTPs ranked first, indicating that this parameter most influences water quantity, whereas tap water leakage presented the least influence on water quantity. The leakage of industrial and household water has a large influence on the wastewater quantity, whereas runoff coefficient of impervious areas has a small influence. With respect to parameter uncertainties, total energy consumption of the water system ranged from 176.3 to 229.4 Mtce (9.3−12.1% of the total energy consumption) in Changzhou. Regarding energy consumption, quantity of wastewater treated most influenced increase in energy consumption, whereas minimum RC by the energy consumption of unit wastewater treated indicated minimal positive effects. The fact that pump efficiency RC is negative demonstrates its negative role in energy consumption.

4. DISCUSSION AND POLICY IMPLICATION

This research measured the climate cobenefit of water conservation based on a water flow analysis. The results showed that estimated energy consumption of a water system reached approximately 10% of a city's total energy consumption. Differences in site conditions lead to wide-ranging results between studies, which makes comparisons between our results and those of others difficult, resulting in relatively crude energy use estimates.[26] For example, most of water used in Changzhou is surface water, which needs less energy input compared with groundwater or seawater, though these sources may be the main water sources in other areas.[8] However, the end-use[13,38] and distribution stages are commonly energy intensive,[19,27] and the water consumption of other stages varies due to different conditions and estimation methods.

This study conducted a complete assessment of energy consumption of a water system at different stages, as illustrated by the main sources, sinks, and flows. A significant amount of information is available regarding direct water and energy savings through end uses of water, though much less is known about the indirect benefits, such as embedded energy values in saved water at different stages.[15] Therefore, this type of analysis framework allows us to track the direct and indirect energy-saving benefits in different stages of entire water systems with different water conservation scenarios. Based on the water flow analysis, this research found that approximately 77% of the energy savings through water conservation was indirect. Such a systematic analysis would deepen the understanding of climate cobenefit of sustainable water management. Indeed, decision makers should pursue sustainable water management and take climate impact of the water system into consideration.

Reducing the water demand of consumers can decrease amount of water required and wastewater treatment, saving both energy and water. Helping consumers to use water more efficiently and increasing the public perception of water conservation are popular options.[39,40] Although water-efficient household appliances, industrial water reuse, and water-saving technologies have been emphasized by the Chinese central and local governments, Changzhou still needs to make great efforts to promote the implementation of these solutions. Low water prices is one of the main obstacles to water conservation in China.[41] Water pricing has been found to be economically feasible, publicly affordable, and acceptable with reasonable policy design [42] to curb the water demand,[43,44] promote the application of water-saving technologies [45] to fulfill the goal of water savings. Thus, water price reform, such as stepped and increasing water prices, are critical to stimulate water conservation in China.[46]

Increasing the water supply through wastewater reuse and rainwater use would not only alleviate the scarcity of water resources but also would have a climate cobenefit.[47,48] The Chinese government has also emphasized this issue in several documents,[31,49] but most of the measures are recommended instead of required. Price is also very critical, as the public will not use recycled water if the price is not competitive.[48,50,51] Therefore, the government needs to establish suitable prices for wastewater reuse.[46,48] In addition, supporting wastewater treatment and reuse by infrastructure construction to reduce the cost of wastewater reuse[48,51] and raising the public acceptance of water reuse[52] are very important. Rainwater harvesting technology and infrastructure should also be supported by the government through administrative and financial measures,[53] such as requiring rainwater collection and utilization systems for new buildings [54] and providing rewards for installing them.[55]

To some extent, the water lost through leakage cannot be ignored in the urban water system management. Our uncertainty analysis also shows that leakage is very important for water resource estimation, and reducing water loss can increase the water supply. The Chinese government has emphasized water leakage; for example, "12th Five-Year Plan of Construction of Water-saving Society" has requirements for controlling water leakage. The development of technologies and strategies for detecting, providing, advance warning, and controlling water pipeline leakage is of crucial importance for both water supply companies and the public.[56−58]

ASSOCIATED CONTENT

Supporting Information

Additional information includes details on the water system modeling approach (SI-A) and supplementary tables and figures. This material is available free via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

*Phone/fax: 86-25-89680536; e-mail: zhangb@nju.edu.cn; jbi@nju.edu.cn.

Notes

The authors declare no competing financial interest.

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