Engineering 2 (2016) 460–469

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Environmental Protection—Article

Sustainable Application of a Novel Water Cycle Using Seawater for Toilet Flushing

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ARTICLE INFO

Article history:
Received 18 April 2016
Revised 17 June 2016
Accepted 4 November 2016
Available online 20 December 2016

Keywords:
Alternative water resources
Seawater toilet flushing
SANI
Urban water system
Life-cycle assessment

ABSTRACT

Global water security is a severe issue that threatens human health and well-being. Finding sustainable alternative water resources has become a matter of great urgency. For coastal urban areas, desalinated seawater could serve as a freshwater supply. However, since 20%–30% of the water supply is used for flushing waste from the city, seawater with simple treatment could also partly replace the use of freshwater. In this work, the freshwater saving potential and environmental impacts of the urban water system (water-wastewater closed loop) adopting seawater desalination, seawater for toilet flushing (SWTF), or reclaimed water for toilet flushing (RWTF) are compared with those of a conventional freshwater system, through a life-cycle assessment and sensitivity analysis. The potential applications of these processes are also assessed. The results support the environmental sustainability of the SWTF approach, but its potential application depends on the coastal distance and effective population density of a city. Developed coastal cities with an effective population density exceeding 3000 persons·km^{-2} and located less than 30 km from the seashore (for the main pipe supplying seawater to the city) would benefit from applying SWTF, regardless of other impact parameters. By further applying the sulfate reduction, autotrophic denitrification, and nitrification integrated (SANI) process for wastewater treatment, the maximum distance from the seashore can be extended to 60 km. Considering that most modern urbanized cities fulfill these criteria, the next generation of water supply systems could consist of a freshwater supply coupled with a seawater supply for sustainable urban development.

1. Introduction

Freshwater supports life and is the most essential natural resource. However, its quantity and quality are currently threatened by the anthropogenic activities of a fast-growing global population [1]. Approximately 80% of the global human population is affected by either water scarcity or water insecurity [2]. Even when the estimation of freshwater scarcity is made using a blue water footprint instead of blue water availability (i.e., by considering treated wastewater as newly available freshwater), the worldwide water shortage remains a critical issue [3]. In view of this issue, wastewater reuse/recycling, rain water harvesting, and seawater use have been extensively researched as viable solutions [4–6]. Considering that, on the one hand, over half of the world's population lives in coastal areas that cover only 10% of the earth's land surface [7] and, on the other hand, that seawater accounts for

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http://dx.doi.org/10.1016/J.ENG.2016.04.013

97.5% of all water resources on the planet [5], the use of seawater appears to be the best solution.

Seawater desalination—using reverse osmosis (RO)—for a potable water supply is a mature technology. Technologies for the optimization of seawater desalination have been the focus of much development in water research, but the wide application of this process is still hindered by its high costs and high energy consumption [5,6]. Meanwhile, seawater for toilet flushing (SWTF) has been developed as a unique approach to alleviate water shortage in places such as Hong Kong [8]. The SWTF system has been applied in Hong Kong since 1958, and today serves up to 80% of the city's inhabitants, enabling the city to cut its annual freshwater consumption by at least 22% [8,9]. The successful implementation—for more than 50 years—of the SWTF system to supply water for non-potable uses demonstrates that SWTF is an excellent way to increase water efficiency at a city level [4].

In addition, the presence of sulfate in seawater has been exploited in the sulfate reduction, autotrophic denitrification, and nitrification integrated (SANI) process that was invented for the treatment of saline wastewater [10,11]. By integrating the microbial sulfur cycle into conventional biological wastewater treatment, which is based on the carbon and nitrogen cycles, the SANI process applies low sludge-yielding microbes such as sulfate-reducing bacteria (SRB) and autotrophic denitrifiers to remove carbon and nitrates. Use of the SANI process reduces the space required for the process of wastewater treatment and sludge handling by 30%–40%, slashes biological sludge production by 60%–70%, lowers energy consumption by 10%, and reduces greenhouse gas emissions by 10%, compared with conventional activated sludge processes that are coupled with anaerobic sludge digestion and biogas energy recovery [10–16]. The SANI process has been thoroughly investigated—and its advantages and suitability solidly demonstrated—in a 500-day lab-scale trial [13,14], a 225-day 10 $m^3 \cdot d^{-1}$ onsite pilot-scale trial [10,15], and a 1000 $m^3 \cdot d^{-1}$ demonstration-scale trial at the Sha Tin Sewage Treatment Works in Hong Kong [16]. The results indicate that SWTF, coupled with the SANI process for wastewater treatment, may afford enhanced economic and environmental benefits over other urban water cycle systems.

To this day, the applicability of the SWTF-SANI coupled approach for coastal water-scarce urban areas has not been evaluated by life-cycle assessment (LCA) in the context of a full urban water system. Hence, an extensive environmental sustainability analysis of this novel hybrid water resource management system with respect to its impacts on climate change, energy consumption, and land occupation is deemed necessary.

This study is therefore aimed at assessing the environmental performance of a city-scale water system incorporating SWTF and SANI in comparison with a conventional system that applies seawater desalination for partial potable water supply and/or reclaimed water for toilet flushing (RWTF). To achieve this assessment, an LCA of these different systems is conducted to evaluate their respective environmental sustainability [17]. A whole-system perspective is taken in this study in evaluating the environmental impacts of an urban water system over its entire life-cycle, covering aspects such as water eutrophication, energy consumption, climate change, ozone depletion, and land occupation. Since water security is a serious issue in some of the eastern coastal cities of the Chinese mainland [2,3], four representative cities—Hong Kong and Shenzhen, which purchase water originating from Dongjiang River, and Beijing and Qingdao, which depend on the diversion of water through the South-to-North Water Diversion Project (SNWDP)—are selected for our case study. Six categories of environmental impacts are first evaluated in these four cities under five urban water scenarios. Next, a sensitivity analysis is carried out to identify the most important impact factors for a city, such as seaside distance, effective population density, and water scarcity condition, under the different water system scenarios. Finally, suitable conditions for applying the SWTF system are suggested. This study provides valuable information for the choice of water resources management systems to mitigate water scarcity in a sustainable manner.

2. Material and methods

2.1. Life-cycle assessment

According to the ISO standard, an LCA consists of four phases: ① goal and scope definition, ② inventory analysis, ③ impact assessment, and ④ results interpretation [18].

2.1.1. Goal and scope definition

When seawater is used for toilet flushing, the discharge of the resulting saline wastewater to the sewer affects the subsequent wastewater treatment process. In addition, the treated saline wastewater should be discharged back to the sea instead of to a freshwater ecosystem. Based on this concept, the evaluation and comparison of water resources management approaches should comprehensively consider the water pumped from a water resource all the way to the final discharge of the effluent from a wastewater treatment plant (WWTP) to the ecosystem. The particular aspects that should be considered include the water catchment, water treatment, water supply system, wastewater collection system, wastewater treatment processes, and discharge of the treated wastewater [19,20], as shown in Fig. 1(a). The goal of this study is to assess the environmental impacts of alternative water resources and wastewater treatment methods for water-scarce cities. The functional unit is set as 1 m^3 of supplied water.

Fig. 1(a) illustrates the chosen system boundary, which encompasses ① water abstraction from sources such as local freshwater, imported freshwater, or seawater; ② potable water treatment processes such as conventional freshwater treatment, RO desalination, or wastewater reclamation; ③ pipelines for freshwater distribution, seawater distribution or reclaimed wastewater distribution, and sewage collection systems; ④ wastewater treatment processes, namely conventional activated sludge processes or the SANI process; and ⑤ effluent discharge back to the sea (where applicable). Both the construction and operation phases are considered to be within the scope of this study, while the material transportation and demolition phases are excluded, given that their impacts are generally considered insignificant [21–23].

Five typical or potentially applicable scenarios are compared in this study, as shown in Fig. 1(b). The conventional freshwater system (FWA) scenario refers to a conventional freshwater supply, with a single pipe system coupled with the conventional activated sludge process for wastewater treatment. This scenario is set as the control for comparison. In the seawater desalination (FRA) scenario, seawater desalination with RO is applied to replace the importation of freshwater from other regions in the FWA scenario. In the SWTF (DSA) scenario, seawater is simply treated with grid and screen for large particle removal, followed by disinfection to produce a water supply for toilet flushing in a separate pipe system, in which used freshwater and seawater are collected together and treated using the conventional activated sludge process. In the SWTF-SANI (DSS) scenario, the wastewater treatment process in the DSA scenario is replaced with the SANI process for comparison. Finally, the freshwater and grey water system (DNA) scenario is an example of applying RWTF, in which centralized nanofiltration is used for treating grey water and the treated water is supplied to the user in an individual pipe system.

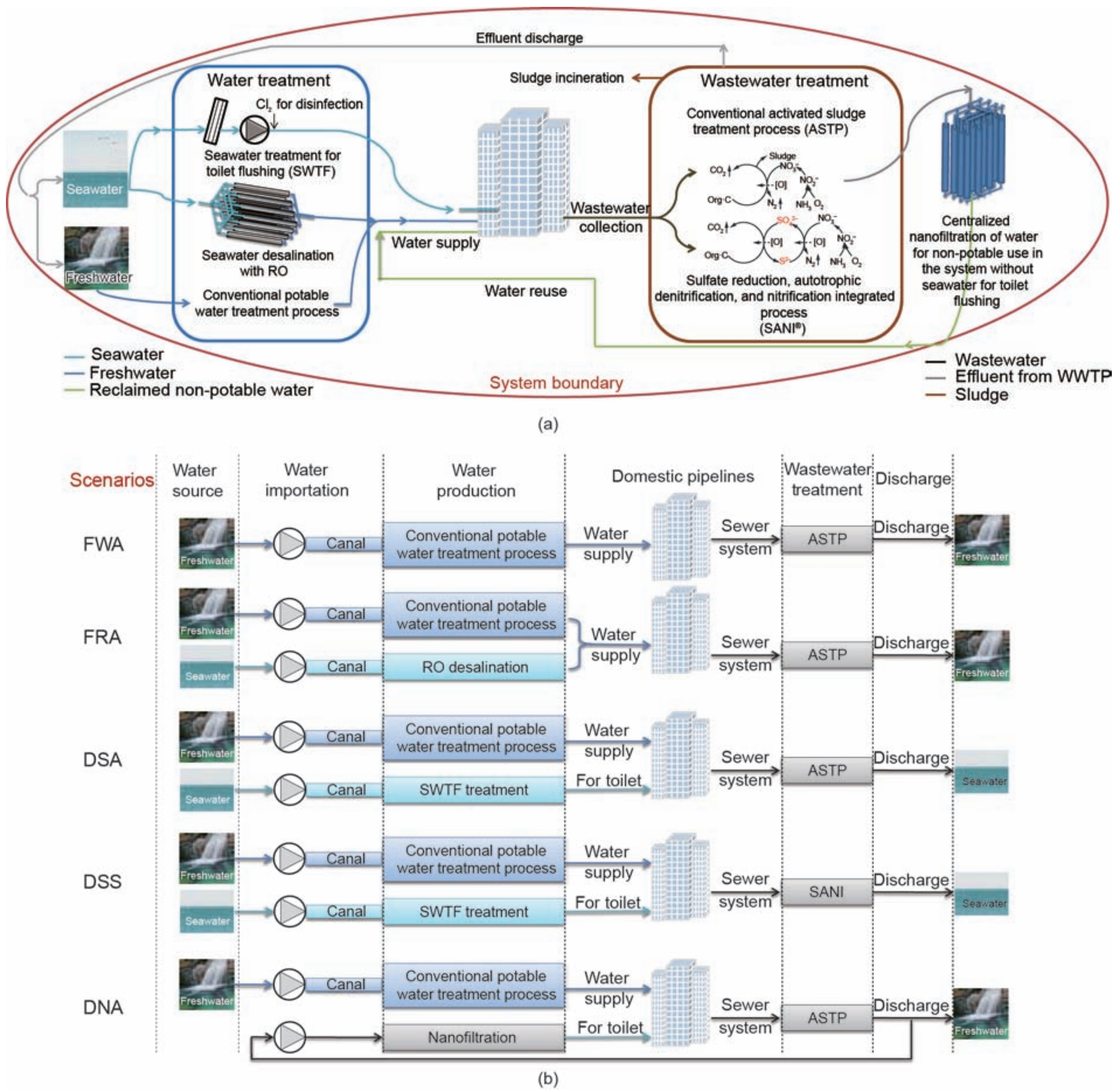

Fig. 1. (a) An urban water system is considered as a complete water cycle system, where the water-wastewater loop is closed. Seawater, freshwater, and centralized water reuse are considered as different types of water supplied to the cities in this study. Other considerations include different processes for water treatment, relevant systems for different water supplies, relevant pipe systems for wastewater collection, different processes for wastewater treatment, and discharges of treated effluent based on the requirements of the various water resources. (b) The five scenarios compared in this study are: the freshwater supply with conventional activated sludge (FWA), seawater desalination coupled with the freshwater system (FRA), SWTF coupled with the conventional activated sludge process for wastewater treatment (DSA), SWTF coupled with the SANI process for wastewater treatment (DSS), and the freshwater and grey water system (DNA).

2.1.2. Inventory

The life-cycle inventory consists of inputs of materials, chemicals, and energy, primarily based on data from the water utilities in Hong Kong or, if this is unavailable, on the most accurate data taken from the literature [11,14,23–26]. All the inputs are determined based on the functional unit. For simplicity, the inventories of similar facilities in different scenarios are considered to be the same. Detailed input inventories are provided in Table S1 to Table S5 in the Supplementary Information (SI).

2.1.3. Impact assessment

SimaPro 8.1 software is used to organize the inventory data according to the ISO 14044 standard procedure. The impacts are calculated using the ReCiPe Midpoint (H) method provided by SimaPro 8.1 for the proposed harmonized impacts in the cause-effect chain; the midpoint indicators quantify the relative impacts that occur during the life-cycle of systems in terms of climate change (CO_2 eq), human toxicity (1,4-DB eq), freshwater eutrophication (P eq), land occupation (m^2·a eq), and ozone depletion (CFC-11 eq). The climate change impact is calculated using the Intergovernmental Panel on Climate Change (IPCC) equivalent factors for direct effect. Energy consumption is determined by the Ecoinvent 2.0 method because it is not defined in the ReCiPe Midpoint (H) method.

2.2. Specific and general cases

Hong Kong, Shenzhen, Beijing, and Qingdao are chosen as the specific study areas, given that they all suffer from water shortage under different geographical and water conditions. For example, Hong Kong and Shenzhen import water from Dongjiang River, while Beijing and Qingdao heavily rely on the SNWDP. Table 1 provides a preliminary summary of the water and geographical conditions for these four cities. Detailed information and their sources are provided in Table S1 in the SI.

The major variations considered for these different cities are the importing distance of freshwater, distance from the coast (seaside distance), availability of freshwater, ratio of water used for toilet flushing to total water consumption, and effective population density. For the effective population density, only the density in the city core is considered. The city core contains more than 75% of the city population; that is, the low population densities of the surrounding residential suburbs are excluded. In the sensitivity analysis of four indicators, the critical conditions were initially considered (Table 2). These conditions represent the worst-case scenario for the application of an urban water system with SWTF. However, these initial values were found to be too specific, considering that cities vary in their endowments, such as in the availability of groundwater resources. Hence, the parameters were subsequently varied in relatively large but reasonable ranges, as listed in Table 2. Detailed computation methods and relevant equations are described in the SI.

In addition to the measures described above, 5% and 10% uncertainties are adopted from a real system and from the recent literature, respectively, and an extra uncertainty of 15% is further considered for the estimated lengths of domestic pipe networks and the importing distance of freshwater [27]. Uniform random distributions are assumed for the 10 000 iterations of Monte Carlo simulation in order to achieve high precision of the simulation results.

3. Results

Hong Kong, Shenzhen, Beijing, and Qingdao are four typical cities facing serious water scarcity because of quantitative deficiency in their water resources. Hong Kong and Shenzhen purchase non-local freshwater (from Dongjiang River) to meet their demands, while Beijing and Qingdao rely on water imported from southern China in 1432 km and 1467 km long canals, respectively [23]. These two solutions are neither environmentally friendly nor economically ideal. Therefore, seawater desalination (FRA), SWTF (DSA and DSS), and reclaimed water (DNA) are evaluated as alternatives for the water supply in the four cities in comparison with the conventional freshwater supply (FWA).

3.1. Freshwater savings

The use of seawater or reclaimed water is intended to reduce reliance on freshwater. The freshwater withdrawals in the different scenarios in the four cities are summarized in Fig. 2. Theoretically, seawater desalination in the FRA scenario can replace all non-local uses of freshwater, but it is unsustainable. Hence, the bulk of the freshwater demand in the FRA scenario for each city represents the amount of freshwater withdrawal locally, and the balance of the freshwater demand is considered to come from seawater. Given the differences in the amounts of freshwater used in the FWA and FRA scenarios for all four cities, Hong Kong and Shenzhen are found to be in a more precarious situation than Beijing and Qingdao. In the case of Hong Kong and Shenzhen, seawater and reclaimed water for toilet flushing in the DSA, DSS, and DNA scenarios can only replace the freshwater used for toilet flushing, which constitutes approximately 20%–30% of the total freshwater demand of a city. Therefore, neither SWTF nor RWTF can meet the water demand in Hong Kong or Shenzhen. This finding suggests that an additional amount of water must be imported from a distant water source, that is, Dongjiang River, to meet the current demands. However, in the case of Beijing and Qingdao, the amount of seawater or reclaimed water used for toilet flushing is sufficient to alleviate the freshwater shortages, indicating that the application of SWTF or RWTF in these cities can totally eliminate their reliance on the SNWDP.

3.2. Environmental impacts

The environmental impacts of the five urban water systems studied in this paper—that is, freshwater only (FWA), seawater desalination (FRA), SWTF coupled with the conventional activated sludge process (DSA), SWTF coupled with the SANI process (DSS), and reclaimed water (DNA)—were analyzed for each of Hong Kong, Shenzhen, Beijing, and Qingdao. Fig. 3 shows the results.

Overall, the FRA scenario with seawater desalination using RO yielded the worst environmental impacts in terms of all six aforementioned indicators, especially in Hong Kong and Shenzhen. Replacing 80% of the freshwater demand in the FRA scenario with seawater desalination (Fig. 2) triples the resulting negative environmental impacts, because of the significant share of freshwater (from water production) in comparison with other scenarios. Apart from the FRA scenario, the environmental impacts of

Table 1
Water and geographical conditions for Hong Kong, Shenzhen, Beijing, and Qingdao.

City	Annual water withdrawal (10^8 $m^3 \cdot a^{-1}$)	Toilet flushing amount ($m^3 \cdot (person \cdot a)^{-1}$)	Urban population (10^4 persons)	Living area (km^2)	Effective population density ($persons \cdot km^{-2}$)
Hong Kong	12.2	34	707	280	25 000
Shenzhen	18.0	34	1 050	1 200	8 700
Beijing	23.5	34	1 850	2 500	7 400
Qingdao	6.0	34	500	1 300	3 800

Table 2
The critical conditions used for sensitivity analysis.

Indicator	Initial value	Variation range as impact parameter
Effective population density	3 000 $persons \cdot km^{-2}$	3 000–30 000 $persons \cdot km^{-2}$
Distance from the coast	300 km	0–300 km
Importing distance of freshwater	70 km	30–300 km
Ratio of water used for toilet flushing to total water consumption	20%	20%–40%
Availability of freshwater	70%	0–100%

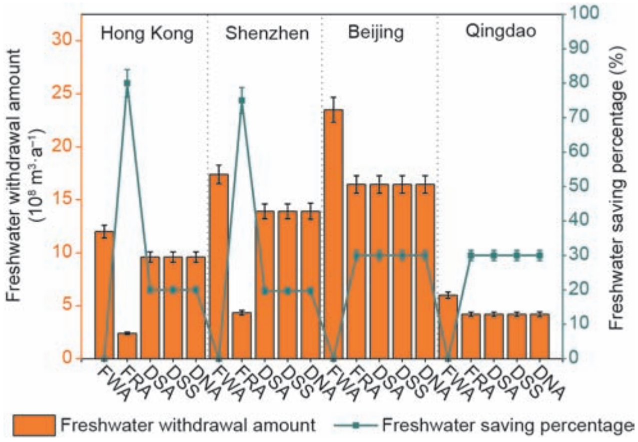

Fig. 2. Total freshwater demands (including demands for residential, industrial, and landscaping uses) and potential for freshwater savings in the four different cities considered under the five different scenarios.

the other four scenarios are relatively similar for all four cities considered, although the impacts are different for freshwater eutrophication in Beijing. However, the scenario of SWTF coupled with the SANI process for wastewater treatment (i.e., DSS) yielded lesser environmental impacts (in most cases) in Qingdao, Hong Kong, and Shenzhen, mainly because of the combined effects of a simple treatment of seawater for toilet flushing and the environmental friendliness of the SANI process. The comparisons of FWA, DSA, DSS, and DNA for Beijing show trends that are dissimilar to those for the other three coastal cities. The application of reclaimed water in Beijing is more environmentally friendly than the use of either the SNWDP for the total freshwater supply or the SWTF systems. The relatively poor environmental impacts of the DSA and DSS options in Beijing are attributed to the long-distance pipes (270 km) for seawater supply and the discharge of treated saline water into the sea, although these options result in a significant reduction of freshwater eutrophication compared with other options, as shown in Fig. 3(a). Therefore, the distance from

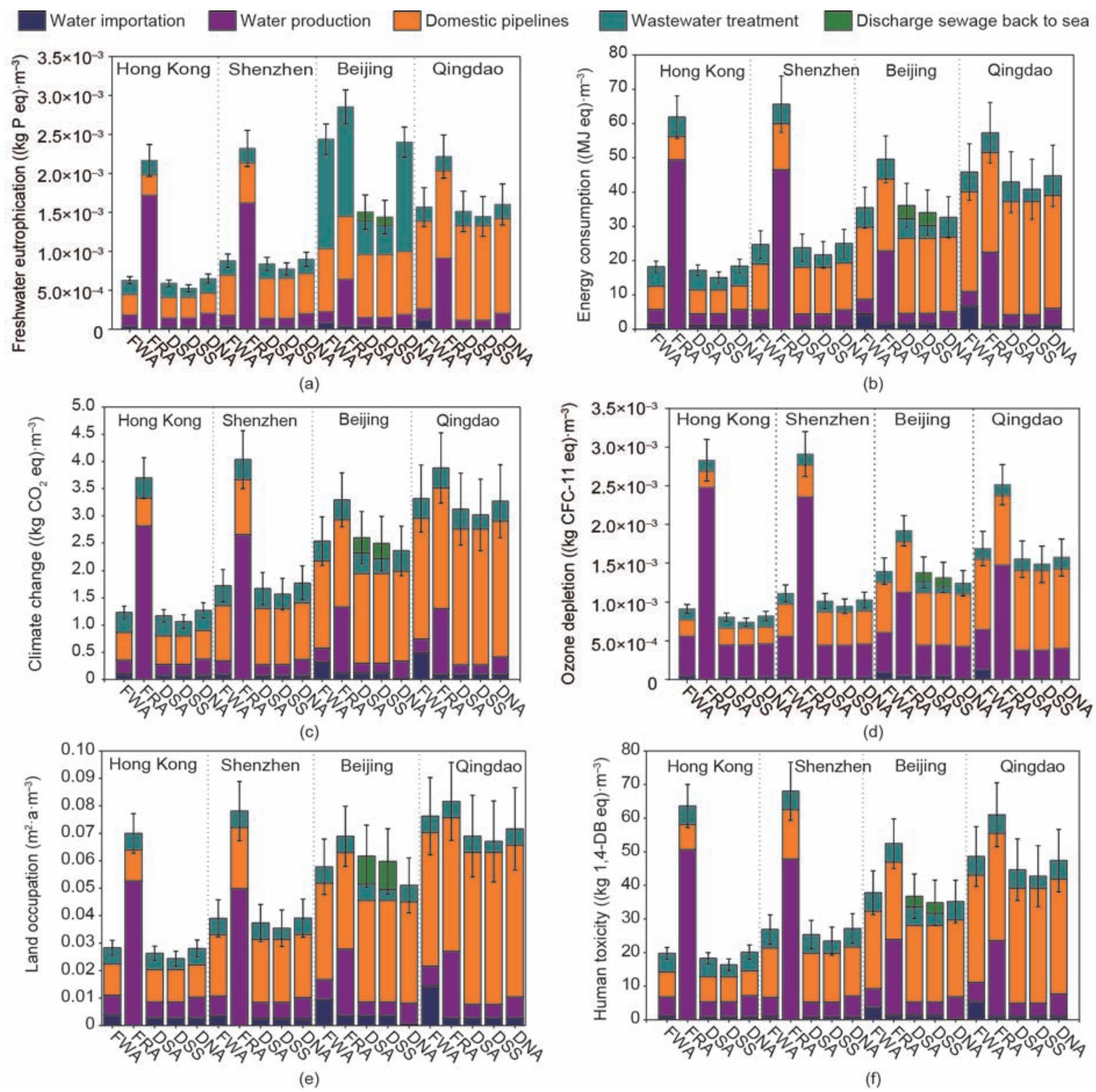

Fig. 3. Comparison of environmental impacts for the five selected scenarios in Hong Kong, Shenzhen, Beijing, and Qingdao. (a) Freshwater eutrophication; (b) energy consumption; (c) climate change; (d) ozone depletion; (e) land occupation; (f) human toxicity.

the coast is an essential parameter in the evaluation of SWTF-associated scenarios.

The negative environmental impacts in Beijing and Qingdao are substantially greater than those in Hong Kong and Shenzhen, owing to the former two cities' more extensive domestic pipeline networks (including both water supply networks and sewers). Most previous studies have also indicated that water transportation is responsible for more than 30% and up to 70% of the contribution of urban water systems to climate change and electricity consumption. In particular, in cities with a population density below 4000 persons·km^{-2}, relatively longer domestic pipelines for each unit volume of water transported are needed [21,24,28,29]. In addition, the lower water consumption per capita in northern China means that the pipeline systems in Beijing and Qingdao contribute substantially to the negative environmental impacts. In summary, the significant environmental impacts of domestic pipeline networks are caused by a low effective population density and a low water transportation efficiency per unit length of pipeline. With rapid urban development, it is expected that per capita water consumption will surge, thereby leading to a decrease in the environmental impacts of the pipe networks per cubic meter of water transported [30]. Clearly, effective population density—rather than per capita water consumption—is another important factor in the evaluation of the environmental impacts. Hence, distance from coast and effective population density are two of the most important parameters associated with the impact of an urban water system on the environment. The development of a simple model to predict environmental impacts as these two parameters are varied could aid decision makers in selecting an optimum water supply alternative, based on the specific conditions in a given city. A sensitivity analysis is, therefore, conducted to assess the effect of the aforementioned parameters for each city. In the next section, the parameters with the most significant effects are presented and the different scenarios are compared.

4. Discussion

4.1. Sensitivity analysis

The results of the LCA for the four scenarios of the urban water system showing the largest variations in energy consumption, climate change, land occupation, and human toxicity in the four cities are shown in Fig. 3(b), (c), (e), and (f), respectively. The results suggest that these indicators are likely to be strongly dependent on the geographical conditions and state of urban development of a city, such as the distance from the coast for seawater abstraction, distance from the importing source of freshwater, and effective population density. The sensitivity analysis was conducted with these city-specific parameters as the input variables for the different scenarios for all four cities. (The seawater desalination scenario, FRA, was excluded from the analyses, given that it yielded environmental impacts far greater than all the other scenarios.)

Fig. 4 shows the variations in energy consumption, climate change, land occupation, and human toxicity for the four scenarios as functions of the variations in the importing distance of freshwater, availability of freshwater, effective population density, distance from coast, and ratio of water used for toilet flushing to the total water consumption of a city. In general, the environmental impacts of the seawater-based scenarios (DSA and DSS) are more adverse than those of the freshwater-based scenarios (FWA and DNA). The worst environmental impact of the two scenarios involving SWTF arises from the choice of parameters for the sensitivity analysis, which represented the critical cases for the application of SWTF. These parameters include a short freshwater importing distance of 70 km, a low effective population density of 3000 persons·km^{-2}, and a long distance from the coast of 300 km. With these assumptions, the negative environmental impacts shown in this study are higher than those found in similar studies. Taking the impact category of most concern, that is, climate change, the values are higher than those in all recent relevant studies (0.6–1.6 kg CO_2·m^{-3}) [21,31,32]. Therefore, the results presented in Fig. 4 should only be used for analyzing the most important parameters. It appears that in the SWTF scenario, the environmental benefits increase as the distance from the coast decreases, which is not the case in the other scenarios.

Effective population density is the parameter with the highest impacts on the results of the LCA. There is a power law relationship between effective population density and environmental impacts for all scenarios. However, the impacts of the other parameters tested are much lower. For all scenarios, the environmental impacts increase sharply as the effective population density decreases. This variation is less remarkable at densities above 12 000 persons·km^{-2}—equivalent to just 40% of the maximum environmental impacts (Fig. 4)—which indicates that there is potential for large cities with population densities above 12 000 persons·km^{-2} to reduce the environmental impacts per cubic meter of water used in the closed loop of a water cycle system. Therefore, the development of water supply and wastewater treatment in megacities such as New York, Shanghai, Guangzhou, Tokyo, Seoul, and Singapore, all of which have high population densities, is more environmentally sustainable than in cities with lower densities.

The second most important parameter is distance from the coast, which shows significant effects on the LCA results only for the scenarios involving SWTF (DSA and DSS). (The results show a linear relationship between this parameter and the environmental impacts.) It is clear that the environmental impacts worsen as the distance from the coast increases because long-distance canals are needed for transporting seawater and discharging saline wastewater. An increase in distance from the coast from 0 to 300 km led to approximately 20% more energy consumed on average, resulting in 24% and 10% increases in climate change and human toxicity, respectively. Land occupation was the most affected indicator, increasing by approximately 45% as distance from coast rose from 0 to 300 km. Therefore, the potential for applying SWTF in inland cities should be carefully assessed by LCA, particularly for land occupation.

For other parameters, namely freshwater transport distance, freshwater availability, and ratio of water used for toilet flushing to total water consumption, the variations used in the sensitivity analysis were 30–300 km, 0–100%, and 20%–40%, respectively. Despite the large variations, these parameters had minimal effects on the environmental impacts. In addition, the results indicate that these three parameters with negligible effects are related to the water supply system, thus leading to the conclusion that the water supply system causes low environmental impacts compared with those of domestic pipelines. This finding is consistent with the results of the case study shown in Fig. 3, where domestic pipelines contributed 30%–80% of the total environmental impacts. Hence, reducing the environmental impacts of water and wastewater treatment systems largely depends on optimizing the domestic pipe network. The environmental impacts of the domestic pipe network mainly come from the construction of the pipe network itself and from the energy used for water lifting, which are closely related to the length of pipe and amount of water transported. A higher population density can reduce the total per capita pipe length and improve the energy efficiency of water transportation. This result explains the significant effects of population density on the environment.

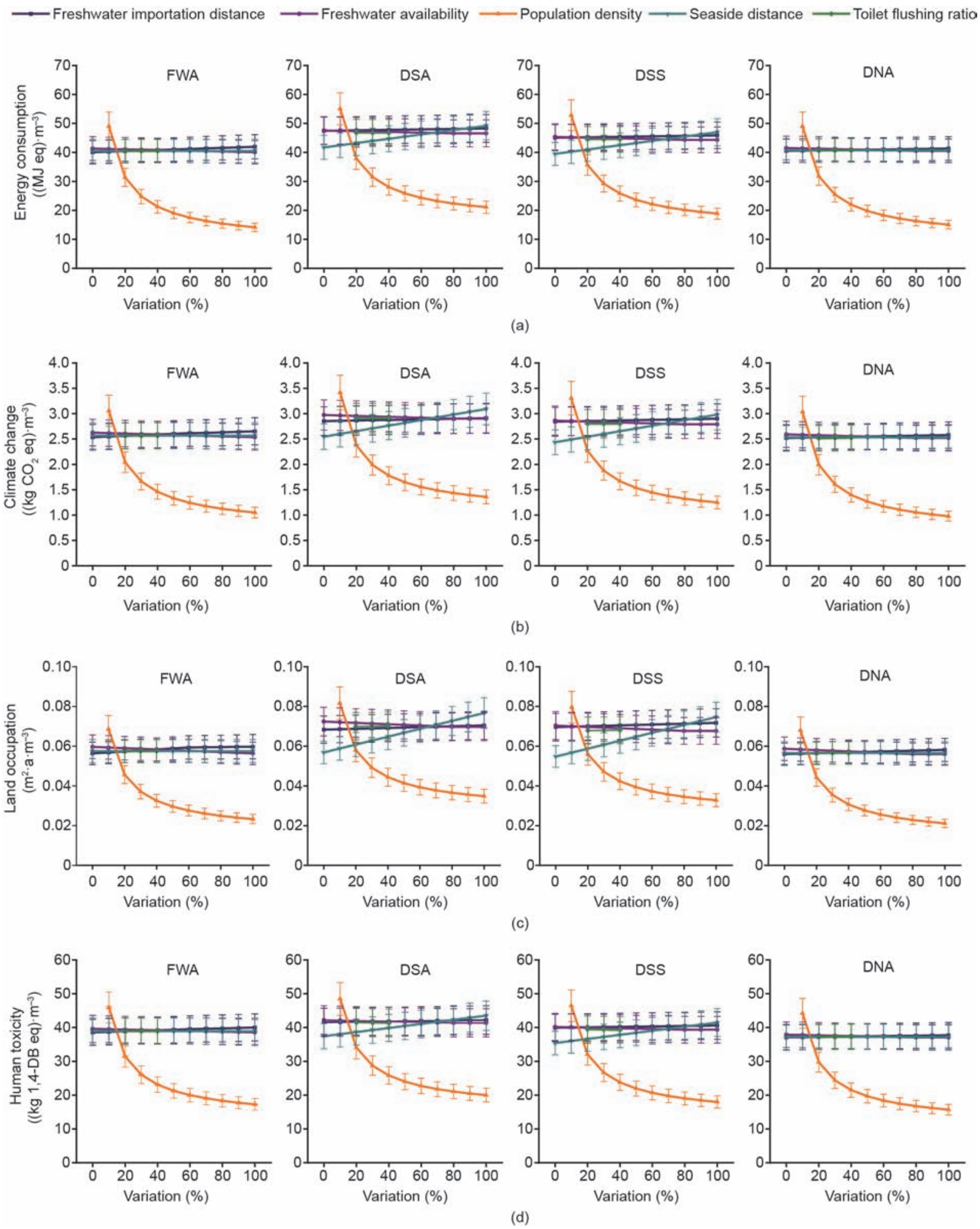

Fig. 4. Sensitivity analyses based on variations in the importing distance of freshwater, availability of freshwater, effective population density, distance from the coast, and ratio of water used for toilet flushing to total water consumption for a city. Results for (a) energy consumption, (b) climate change, (c) land occupation, and (d) human toxicity for the four selected scenarios of the urban water systems (FWA, DSA, DSS, and DNA—see Fig. 1) based on the worst possible conditions for SWTF application.

Based on the results of the sensitivity analysis, effective population density and distance from the coast are confirmed to be the two most important parameters. Hence, they are selected as the major impact factors to evaluate the potential application of the SWTF scenarios under different conditions. In this evaluation, the environmental impact indicators selected are climate change and land occupation, which yielded the highest sensitivities to variations in the above two parameters.

4.2. Potential application of SWTF

Fig. 5 compares the different scenarios on the basis of land occupation. The curved surfaces are plotted as functions of three varying parameters, namely effective population density, distance from the coast, and land occupation. Other parameters were kept constant at their mean values, although this does not favor the application of SWTF. The projected shadow areas on in the *x*-*y* plane reflect the conditions that would favor the application of SWTF as an alternative for water supply, and the equation shows the intersection of the two curved surfaces.

In general, the shadow areas for DSS versus FWA and DSS versus DNA, shown in Fig. 5(b) and (d), are larger than those for DSA versus FWA and DSA versus DNA, shown in Fig. 5(a) and (c), because of the additional environmental benefits from the SANI process, which are mainly related to the lower land occupation. If the conventional activated sludge process is used for saline wastewater treatment, the city should be located within 30 km of the seashore, with limited impact from population density. The application of SWTF still benefits the environment beyond a 60 km distance from the seashore if the SANI process is applied for wastewater treatment. For cities with an effective population density less than 1100 persons·km^{-2}, the application of SWTF is, in general, not environmentally beneficial even if the city is located along the coast. However, as mentioned before, none of the water management approaches considered in this study are environmentally sustainable if the effective population density is at or below 1100 persons·km^{-2}. The land occupation increases 3.5 to 7 fold regardless of the scenarios investigated (Fig. 4(c) and Fig. 5) at population densities below 3000 persons·km^{-2}. The application of SWTF in large coastal cities with high population densities can further reduce humanity's footprint to a more sustainable level.

The application of SWTF is much more environmentally beneficial than the use of a reclaimed water system, as shown in Fig. 5(c) and (d), which can be explained by the fact that the DNA scenario does not show any advantage over the FWA scenario (with the freshwater system as control). This is true for all the environmental impact indicators except freshwater saving. Moreover, the potential for cross-contaminations between the reclaimed water and freshwater systems represents a health risk [33]. It can be avoided by implementing SWTF because residents can easily detect the misconnections from salty taste of seawater.

Fig. 6 illustrates the effects on climate change of the different scenarios. SWTF yields lower effects on climate change than on land occupation. This finding is consistent with the results of the sensitivity analyses. In other words, when the SWTF scenario is evaluated based on land occupation, its potential application appears to be always environmentally sustainable in terms of indicators other than land occupation. In this way, the SWTF scenario is unlike the other scenarios.

Considering the significant reduction in freshwater eutrophication for the SWTF scenario when coupled with marine wastewater discharge, the application of SWTF in inland cities can be

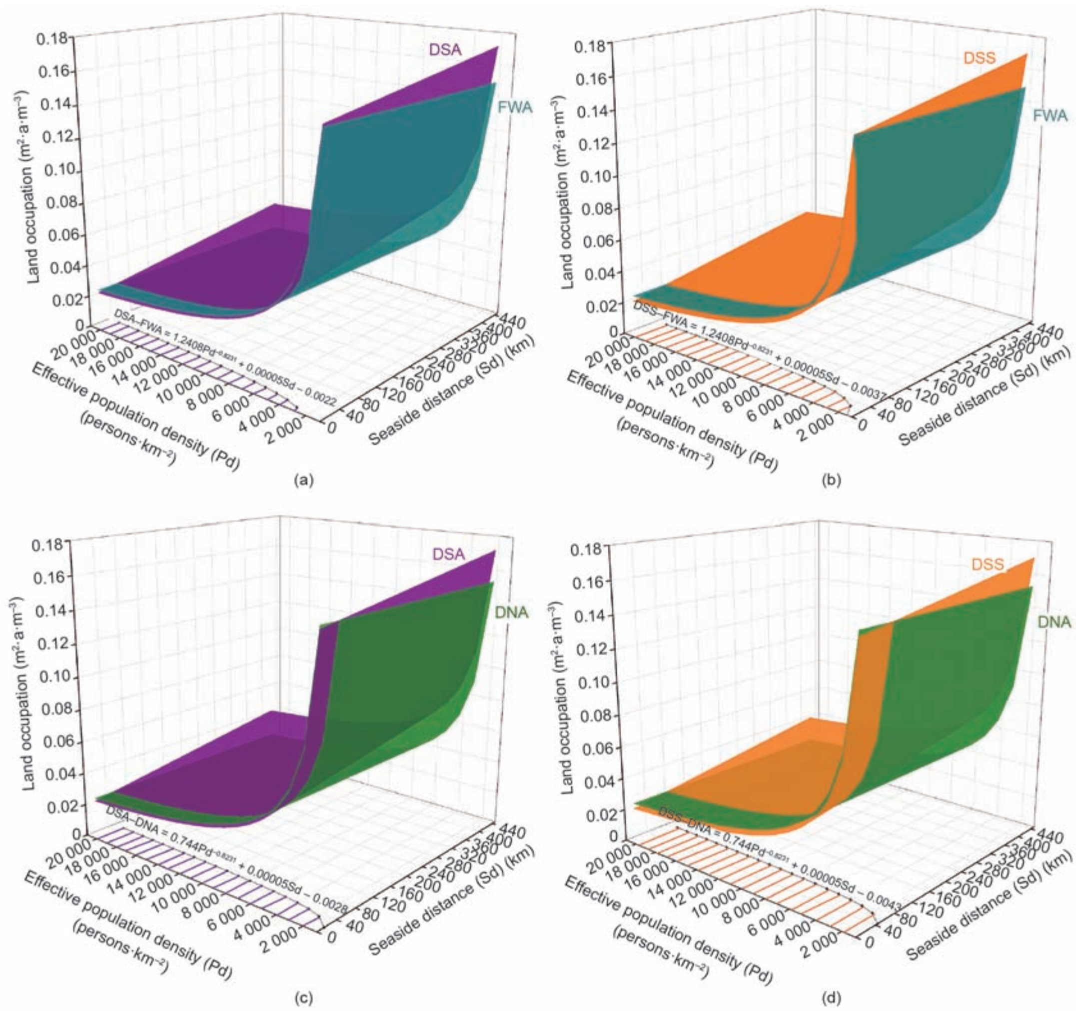

Fig. 5. Comparisons, based on land occupation, between the SWTF scenarios (DSA and DSS), freshwater-only (FWA) scenario, and reclaimed water (DNA) scenario to evaluate the conditions for the potential application of SWTF. (a) DSA versus FWA; (b) DSS versus FWA; (c) DSA versus DNA; (d) DSS versus DNA.

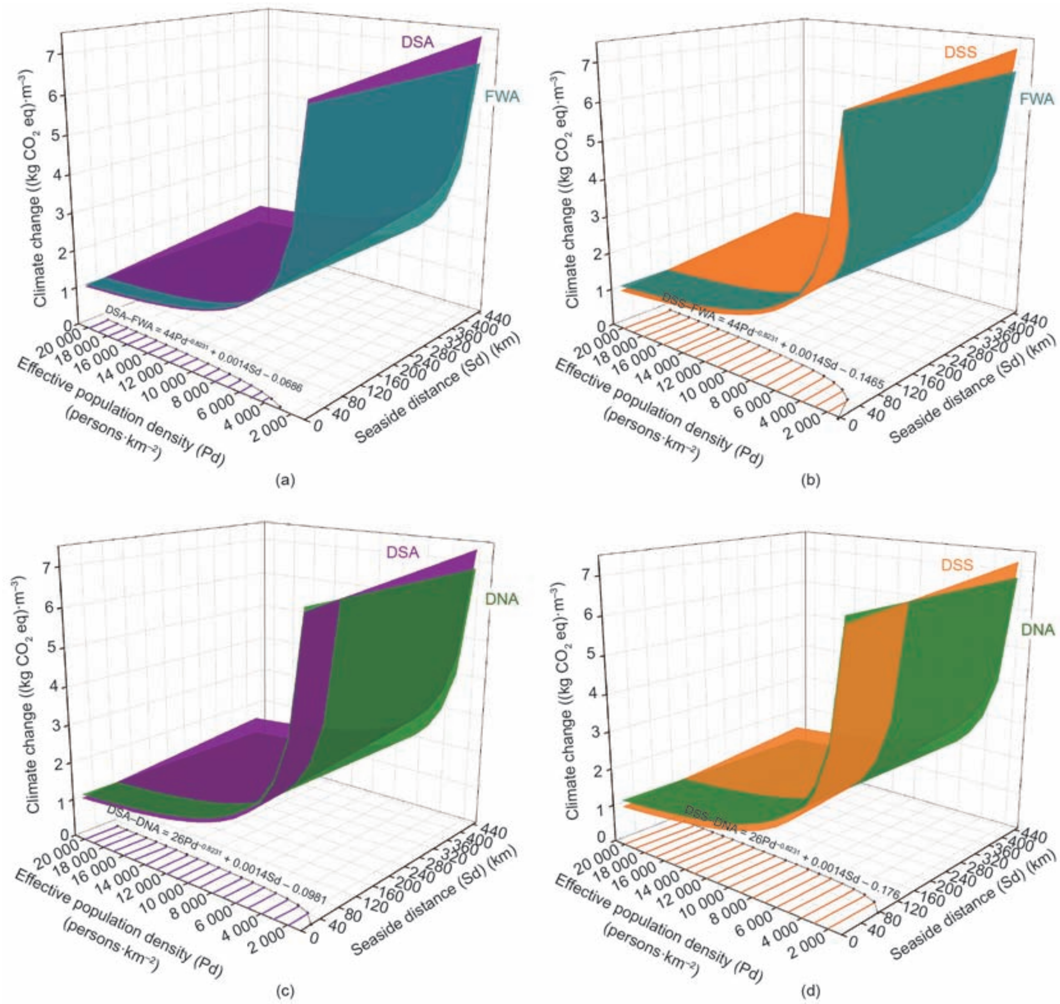

Fig. 6. Comparisons, based on climate change, between the SWTF scenarios (DSA and DSS), freshwater-only (FWA) scenario, and reclaimed water (DNA) scenario to evaluate the conditions for the potential application of the SWTF scenario. (a) DSA versus FWA; (b) DSS versus FWA; (c) DSA versus DNA; (d) DSS versus DNA.

a solution to the water scarcity issue (particularly with regard to water quality). Therefore, the SWTF system and SANI process should be promoted for the development of densely populated modern cities that are within 60 km of the seashore. Examples of such cities include Macau (China), Tokyo (Japan), Singapore, New York (USA), Ningbo (China), Mumbai (India), and L'Hospitalet de Llobregat (Spain). (See also Table S12 in the SI.)

5. Conclusions

In this study, different scenarios of water-wastewater closed loops are compared with each other and with a conventional system in order to assess their potential applications in densely populated and water-stressed cities. The scenarios are seawater desalination, SWTF, RWTF, and the conventional freshwater system. By studying the cases of four representative cities, this study implies that the urban water scenarios with SWTF are more environmentally friendly than other options (i.e., desalination, freshwater importation, and water reclamation) in Hong Kong, Shenzhen, and Qingdao. In addition, the application of SANI technology for wastewater treatment in scenarios with SWTF is more beneficial to the environment. However, SWTF does not perform better than RWTF in Beijing, due to the long seaside distance.

Sensitivity analyses of the environmental impacts—derived from the LCA—are also conducted. The result implies that effective population density and seaside distance are the most responsive impact factors for the application of SWTF. The environmental impacts caused by effective population density show similar effect potential and trend in all the indicators, and these effects will be insignificant when the effective population density is above 12 000 persons·km^{-2}. Seaside distance affects land occupation more than it affects other indicators.

SWTF, as exemplified by the SWTF system that has been practiced in Hong Kong for over 60 years, is a promising water supply alternative for modern cities, and particularly for those that are located within 30 km of the seashore and that have an effective population density higher than 3000 persons·km^{-2}. In addition to its environmentally friendly performance, this approach can help slash freshwater consumption by 20%–30%, which will significantly alleviate water stress problems in most cities. When the SANI process for wastewater treatment is coupled with the SWTF system, the effective population density can be reduced to 1100 persons·km^{-2} and the distance from the seashore can be doubled to 60 km without negatively impacting the environment; this result is unlike the results obtained for the scenarios using freshwater. Most fast-growing metropolitan areas around the world are located on a coast. Hence, a freshwater supply coupled with SWTF, and subsequent use of the SANI process for wastewater treatment, could be the next generation of water-wastewater closed loop systems for more sustainable development.

Acknowledgements

The authors gratefully acknowledge the support from the Hong Kong Innovation and Technology Fund (ITF) (ITS/179/12FP), Water Supplies Department (WSD), Drainage Services Department (DSD), New Epoch Co. Ltd., Sincere World Far East Co. Ltd., Pearl River S&T Nova Program of Guangzhou (2014J2200048), and Guangdong Provincial Science and Technology Planning Project (2015A020215029).

Compliance with ethics guidelines

Xiaoming Liu, Ji Dai, Di Wu, Feng Jiang, Guanghao Chen, Ho-Kwong Chui, and Mark C. M. van Loosdrecht declare that they have no conflict of interest or financial conflicts to disclose.

Supplementary Information

http://engineering.org.cn/EN/10.1016/J.ENG.2016.04.013
Table S1–S12
Inventory analysis and method

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