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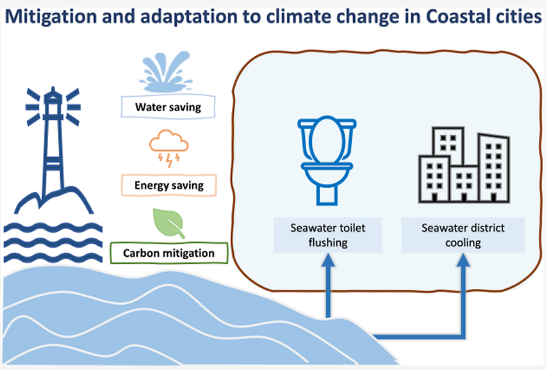
ABSTRACT: Exploring alternative water sources and improving the efficiency of energy uses are crucial approaches to strengthening the water−energy securities and achieving carbon mitigations in sub(tropical) coastal cities. Seawater use for toilet flushing and district cooling systems is reportedly practical for achieving multiaspect benefits in Hong Kong. However, the currently followed practices are yet to be systematically evaluated for scale expansions and system adaptation in other coastal cities. The significance of using seawater to enhance local water−energy securities and carbon mitigations in urban areas remains unknown. Herein, we developed a high-resolution scheme to quantify the effects of the large-scale urban use of seawater on a city's reliance on non-local and non-natural water and energy supplies and its carbon mitigation goals. We applied the developed scheme in Hong Kong, Jeddah, and Miami to assess diverse climates and urban characteristics. The annual water and energy saving potentials were found to be 16−28% and 3−11% of the annual freshwater and electricity consumption, respectively. Life cycle carbon mitigations were accomplished in the compact cities of Hong Kong and Miami (2.3 and 4.6% of the cities' mitigation goals, respectively) but not in a sprawled city like Jeddah. Moreover, our results suggest that district-level decisions could result in optimal outcomes supporting seawater use in urban areas.



KEYWORDS: *climate change, seawater, municipal services, carbon mitigation, coastal cities*

INTRODUCTION

Over 50% of the world's greenhouse gas (GHG) emissions originate from urbanized coastal areas (<100 km from the sea) that are home to over 40% of the global population.[1−3] The high population densities, anthropogenic activities, and natural climatic conditions in these regions render them sensitive to climate change.[4] Increased water stress is one of the most significant repercussions of climate change in coastal regions.[5−7] Cross-boundary water transportation, seawater desalination, and wastewater reclamation are the primary strategies to relieve water stress;[8] however, these strategies are energy-intensive.[9−12] For example, cross-boundary water transportation from Guangdong Province in mainland China meets 70−80% of Hong Kong's (HK) freshwater needs. However, this process consumes more than 200 GW h of electricity and releases up to 0.2 $MtCO_2e$ annually.[13,14] Seawater desalination is used to deliver 50% of Saudi Arabia's water demand, which consumes up to 14 TW h of electricity and releases more than 7 $MtCO_2e$ annually.[15] Similarly, saltwater intrusion caused by groundwater overexploitation has resulted in Florida having the highest annual volume of wastewater reclamation (1.14 million m^3) among all US states;[16] however, the energy intensity for wastewater reclamation (0.5−1.0 kW h/m^3) is much higher than that required for traditional groundwater supply (0.03−0.15 kW h/m^3).[17] This shows that current alternative water sources ensure local water security but increase energy consumption, thereby increasing GHG emissions.

Another extreme consequence of climate change is the alteration in global temperatures. A 1 °C increase in the global average temperature by 2050 (compared with current temperatures) is expected to increase the average number of cooling degree days (CDDs) by 25%.[18] Considerable increases in CDDs and population growth result in tremendous demands for space cooling.[19,20] The International Energy Agency has predicted that the space cooling demands of (sub)tropical regions worldwide will increase from 14,000 to

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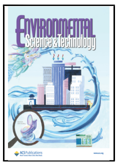

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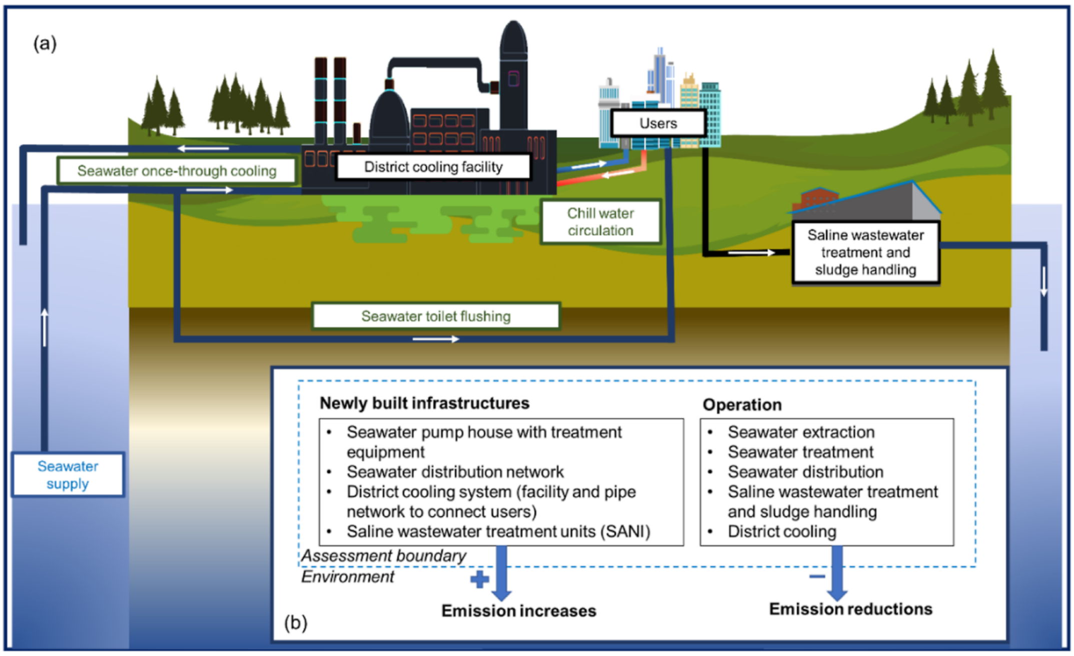


Figure 1. Illustration of the seawater-involved systems and the system boundary of the life cycle assessment. (a) Graphical demonstration of the seawater-involved systems, including seawater supply for toilet flushing and the district cooling system; (b) defined boundary of the life cycle assessment, including the required new infrastructures for the seawater-involved systems and system operations. The newly built infrastructures resulted in increased emissions to the environment, and the seawater-involved systems' operations resulted in emission reductions to the environment.

30,000 GW by 2050, challenging the energy supply in these regions. Water-cooled air-conditioning systems typically require 40 to 50% less energy than conventional air-cooled systems. Thus, for the 30,000 GW cooling load, compared with a traditional air-cooled system, the most efficient water-cooled air-conditioning system could yield more than 8000 TW h of electricity savings annually.[18,21,22] However, if the cooling demands increase as predicted, the water consumed by water-cooled systems will exceed 400 billion m^3 by 2050, almost equal to the national annual water consumption in China.[18,23−26] Therefore, although highly efficient water-cooled systems save energy, they exacerbate water stress and jeopardize local water security.

Climate change, therefore, threatens water and energy security in hot coastal regions such as HK. To solve this problem, 90% of the population in HK has been using seawater for toilet flushing since the 1950s. The seawater is passed through a 5−10 mm coarse screen and subjected to electrochlorination for nonpotable municipal services. This achieves the cobenefits of water−energy−GHG emission savings; the freshwater savings from using seawater for toilet flushing alone amount to 300 million cubic meters annually.[27,28] Moreover, the most extensive seawater district cooling system has been in operation in the Kai Tak District in HK to serve 1.73 million m^2 floors since 2013,[29] where approximately 20.3 million kW h of electricity was saved from 2013 to 2020, equivalent to a reduction of 14,210 tCO_2e.[30] The successful use of seawater for municipal services in HK suggests that this approach can strengthen the water−energy securities and achieve carbon mitigations for ensuring the sustainability and resilience of coastal urban areas worldwide.

However, comprehensive insights into how such seawater-involving systems can be expanded or applied to other coastal cities are not yet available. Understanding the spatial distributions of water and energy savings and life cycle environmental impacts of large-scale application in a coastal city is urgently warranted as seawater-involving systems require additional operations and infrastructure. Herein, we developed a universally applicable high spatial resolution scheme to quantify the consequences of the wide application of seawater-involving systems (for toilet flushing and district cooling) in water−energy savings and carbon mitigations and provide generalized guidance for application (seawater-involving systems are shown in Figure 1a). Our scheme includes (i) time series to project the engineered water demands (defined as any non-local and non-natural water supply), energy imports, and carbon reduction goals from 2022 to 2050, (ii) bottom-up models to calculate the water and energy demands, with life cycle environmental impacts of the seawater-involving systems and the baseline systems (the baseline systems are context-specific in case cities, see descriptions in Table S1) and (iii) performance analysis conducted by normalizing the water, energy, and carbon consequences of the seawater-involving systems by projected engineered water demands, energy imports, and carbon reduction goals. These performances were then aggregated into a joint indicator to reflect the context-specific effects of the seawater-involving systems on the water−energy securities and carbon mitigations in a city. We applied our scheme to three coastal cities: HK, Jeddah (Saudi Arabia), and Miami (USA); all these cities have a hot climate and high living standards, suffer from water stress, and possess similar demographic features but different urban characteristics.

■ METHODOLOGY

Time Series Models for Predicting Engineered Water Demands and Energy Imports. A city's reliance on engineered water and energy imports reflects its local water and energy securities.[31,32] In this study, engineered water is defined as non-locally and non-naturally supplied water. Since 1965, HK has been importing 70−80% of its water from the Dongjiang river (Guangdong Province, China).[33] Jeddah meets 60% of its water demand through seawater desalination.[34] Although Miami is not currently facing a water shortage, the existing water supply is unable to meet the projected water demands due to the overexploitation of the Biscayne Aquifer and saltwater intrusions. Therefore, alternative water supplies such as seawater or brackish water desalination and rainwater harvesting are being explored.[35,36] For HK and Jeddah, we collected historical imported water and desalinated seawater data from government records.[34,37] The historical data for the water imported from Guangdong Province were recorded from 1990 to 2021. We established an autoregression integrated moving average (ARIMA) model to predict the imported water demand from 2022 to 2050. For Jeddah, the historical desalinated seawater data from 2010 to 2018 are available. Although the data volume was limited, we were able to establish a Holt model with a good R^2. For Miami, the inferred water supply shortages (potential imbalance between the projected demand and the currently inferred supply) were predicted by the Office of Economic and Demographic Research of Florida.[36] The predictions were extrapolated into one-year intervals (from 2022 to 2050) as the accessible predictions were presented in five-year intervals.

The future energy imports of HK and Miami were predicted. HK has no local energy resources and thus relies entirely on external sources. Therefore, we obtained the historical energy import data[37] and built the ARIMA model to predict the energy imports from 2022 to 2050. Nearly 100% of natural gas consumed by Florida is obtained from outside the state.[38] Therefore, for Miami, we used the data on natural gas delivered to Florida through interstate pipelines and calculated the portion assigned to Miami based on the population of Miami as the historically imported energy data.[39] Winters' multiplicative model was built to predict the energy imports in Miami from 2022 to 2050. In contrast, Saudi Arabia entirely relies on local energy;[40] the energy import predictions for Jeddah were ignored (the detailed model parameters, statistics, and selection criteria are summarized in Table S2).

Grid-Level Water and Energy Demands of the Seawater-Involving Systems and BAU Systems. Grid-level gross floor areas (GFAs) and effective population were calculated from satellite data [see details of grid-level (1 km^2) GFAs and population calculations in the Supporting Information]. In seawater-involving systems, freshwater is replaced with seawater for toilet flushing. Therefore, the freshwater savings from seawater-involving systems equal the water demands for toilet flushing. The water demands for toilet flushing depend on the population, frequency of flushing, and flushing volumes (eq 1). To determine the flushing frequency, we referred to existing studies and used the Poisson distributions to account for uncertainties. Moreover, different parameters (λ) were set for domestic and non-domestic buildings.[41,42] Uniform distribution was assumed for the flushing volume as the flushing volume depends on the type of toilet, with minor variations. The ranges of toilet flushing volume used for domestic and non-domestic buildings were comparable[43−45] (see Table S5 for details). The Monte Carlo simulation was used to propagate the uncertainties from different parameters.

The energy demands of the seawater-involving systems include energy use for water processing, such as pumping seawater, seawater treatment, seawater distribution, saline wastewater treatment, sludge handling, and district cooling system operations. Compared with seawater-involving systems, BAU systems have water processing demands, including freshwater treatment and distribution, wastewater treatment and sludge handling, and existing air-conditioning system operations. The energy used for water processing depends on the flow rate required by the user and the energy intensity of each process. The energy used by the cooling system depends on the user's space cooling demands, which are related to the GFA, floor height, air exchange rate, CDDs, and the coefficient of performance (COP) of the cooling system. The energy demands of the seawater-involving systems, BAU systems, and energy savings were calculated using eqs 2−5. The uncertainties related to COP were accounted for by uniform distributions for water-cooled and air-cooled systems and for domestic and non-domestic buildings.[46] The explanations of energy use of processes in the seawater-involving systems can be found in the Supporting Information (water and energy intensities of processes in a seawater-involving system). The detailed parameters for calculating the energy use of the water-processing components and air-conditioning systems are summarized in Tables S6 and S7.

$$\mathrm{WS}_{i,j} = \sum_{k=1}^{2} \mathrm{WD}_{\mathrm{TF}_{i,j,k}} = \sum_{k=1}^{2} \mathrm{Pop}_{i,j,k} \times N_{\mathrm{TF}_k} \times V_{\mathrm{TF}} \tag{1}$$

where i is the city; j is the grid; k is the land use type (domestic or non-domestic); WS is the water savings (m^3); $\mathrm{WD}_{\mathrm{TF}}$ is the toilet flushing water demand (m^3); Pop is the population; N_{TF} is the toilet flushing frequency (number of flushings/day/person); and V_{TF} is the toilet flushing water volume (m^3/flushing).

$$\mathrm{WD}_{\mathrm{DCS}_{i,j}} = \sum_{k=1}^{2} \frac{C_{\mathrm{air}}\rho_{\mathrm{atm}} n_k \mathrm{GFA}_{i,j,k} h_k \Delta T_{\mathrm{air}_i}}{C_{\mathrm{w}} \Delta T_{\mathrm{cw}} \rho_{\mathrm{w}}} \tag{2}$$

where $\mathrm{WD}_{\mathrm{DCS}}$ is the district cooling system seawater demand (m^3); C_{air} and C_{w} are the specific heat of air and water, respectively [kJ/(kg·°C)]; ρ_{atm} and ρ_{w} are the density of air and water, respectively (kg/m^3); ΔT_{air} is the annual CDDs (°C·days); n is the number of air exchanges per day (times/day); ΔT_{cw} is the cooling range of cooling water (°C); h is the height of the floors (m); and GFA is the GFAs that need cooling.

$$\mathrm{ED}_{\mathrm{SW}_{i,j}} = \sum_{k=1}^{2} \Bigg(\mathrm{WD}_{\mathrm{TF}_{i,j,k}} \sum_{a=1}^{6} \mathrm{EUI}_a + \mathrm{WD}_{\mathrm{DCS}_{i,j,k}} \sum_{c=1}^{2} \mathrm{EUI}_c + \frac{(C_{\mathrm{air}}\rho_{\mathrm{atm}} n_k \mathrm{GFA}_{i,j,k} h_k \Delta T_{\mathrm{air}_i})}{\mathrm{COP}_{\mathrm{water}}}\Bigg) \tag{3}$$

where $\mathrm{ED}_{\mathrm{SW}}$ is the energy demands of the seawater-involving systems; EUI is the energy use intensity (kW h/m^3); $\mathrm{COP}_{\mathrm{water}}$ is the COP of a water-cooled cooling system (dimensionless); a represents the processes related to seawater supply for toilet flushing (seawater extraction, treatment, mains distribution, lifting to the storage tank, sulfate reduction autotrophic denitrification and nitrification, and sludge handling); and c represents the processes related to seawater supply for the cooling of district cooling systems (seawater extract and treatment).

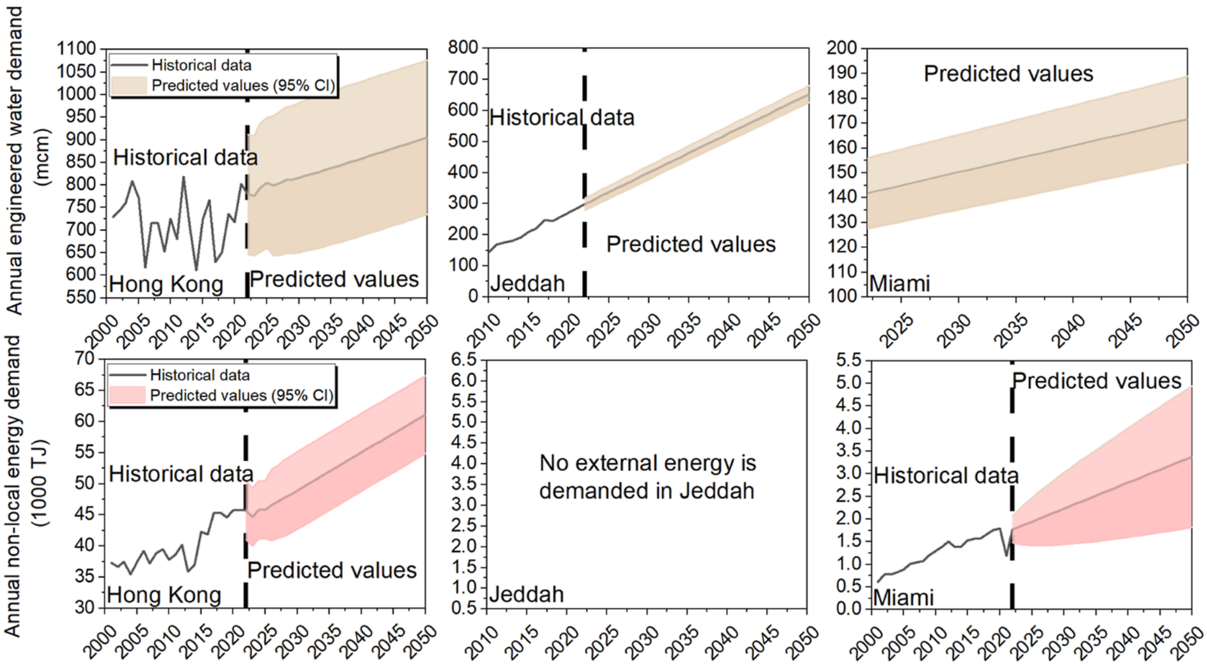


Figure 2. Historical and predicted annual engineered water demands and non-local energy (import energy) demands in Hong Kong, Jeddah, and Miami. Data on the historical transported water to Hong Kong, energy imports to Hong Kong, desalinated seawater in Jeddah, and natural gas imports to Florida were collected from the government or institution archive.[34,37,39] The historical data were used to build time series models to predict the annual engineered water demands and energy imports from 2022 to 2050. The predictions of the engineered water demands in Miami were based on the inferred water supply shortages modeled by the Office of Economic and Demographic Research of Florida.[36] Jeddah did not have energy imports. The shaded areas in the figures show the 95% confidence intervals for the predictions. mcm = million cubic meters; CI = confidence interval.

$$\mathrm{ED}_{\mathrm{BAU}_{i,j}} = \sum_{k=1}^{2} \Big(\mathrm{WD}_{\mathrm{TF}_{i,j,k}} \sum_{b=1}^{5} \mathrm{EUI}_b + \frac{C_{\mathrm{air}}\rho_{\mathrm{atm}} n_k \mathrm{GFA}_{i,j,k} h_k \Delta T_{\mathrm{air}_i}}{\mathrm{COP}_{\mathrm{air}}}\Big) \tag{4}$$

where $\mathrm{ED}_{\mathrm{BAU}}$ is the energy demands of the baseline systems; $\mathrm{COP}_{\mathrm{air}}$ is the COP of a conventional air-cooled cooling system (dimensionless); and b represents the processes related to freshwater supply for toilet flushing (freshwater treatment, mains distribution, lifting to the storage tank, anaerobic/oxic wastewater treatment, and sludge handling).

$$\mathrm{ES}_{i,j} = \mathrm{ED}_{\mathrm{BAU}_{i,j}} - \mathrm{ED}_{\mathrm{SW}_{i,j}} \tag{5}$$

where ES is the energy savings of the seawater-involving system (kW h).

$$\mathrm{CS}_{i,j} = \mathrm{ES}_{i,j} \times \mathrm{CI}_j \tag{6}$$

where CS is the carbon reduction of the seawater-involving system (kg CO_2e) and CI is the carbon intensity of electricity (kg CO_2/kW h).

LCA of the Seawater-Involving Systems. The functional unit has been defined as the environmental impacts (calculated as per year) related to the operation and infrastructure for supplying toilet flushing water and space cooling to all existing buildings in the city (infrastructures' impacts were averaged by their lifetimes). In this study, we assessed the life cycle environmental impacts of the seawater-involving systems, including the impacts from infrastructure manufacturing and construction (emission increases) and system operation (emission reductions). The quantities of the new infrastructures required on the grid-level were determined based on the space cooling load, toilet flushing water demands, and the distance from the coastline to buildings in each tile. The detailed inventory development processes are summarized in in the Supporting Information (inventory of the newly built infrastructures and uncertainties accounts for the life cycle assessment). We did not consider the retrofitting of in-building plumbing systems since the existing studies indicate that their environmental impacts are much lower than water mains.[47,48] The newly built infrastructures in each tile were normalized by their corresponding life expectancy. The operation inventory involves the annual energy savings by seawater-involving systems and chemical inputs in the seawater-involving systems. Subsequently, the corresponding life cycle impact assessment metrics, including all entries in the life cycle inventory, were generated using the ReCiPe Midpoint (H) method in the SimaPro platform. The life cycle impacts of the seawater-involving system at the grid level were calculated by multiplying the life cycle inventory and the life cycle impact assessment metrics matrixes (detailed life cycle inventories are available in Tables S8−S11).

Indicators for Reflecting Context-specific Effects of Seawater-Involving Systems on Water−Energy Securities and Carbon Mitigations. Water-saving, energy-saving, and carbon-mitigation indicators were developed to quantify the effects of seawater-involving systems on the water and energy securities and carbon mitigations in a city. Specifically, the water savings, energy savings, and carbon reductions of the seawater-involving systems were normalized by the projected annual engineered water demands, energy imports, and carbon mitigation goals of the city. The normalized dimensionless values were then aggregated into a single indicator to reflect the overall significance of the seawater-involving systems in a

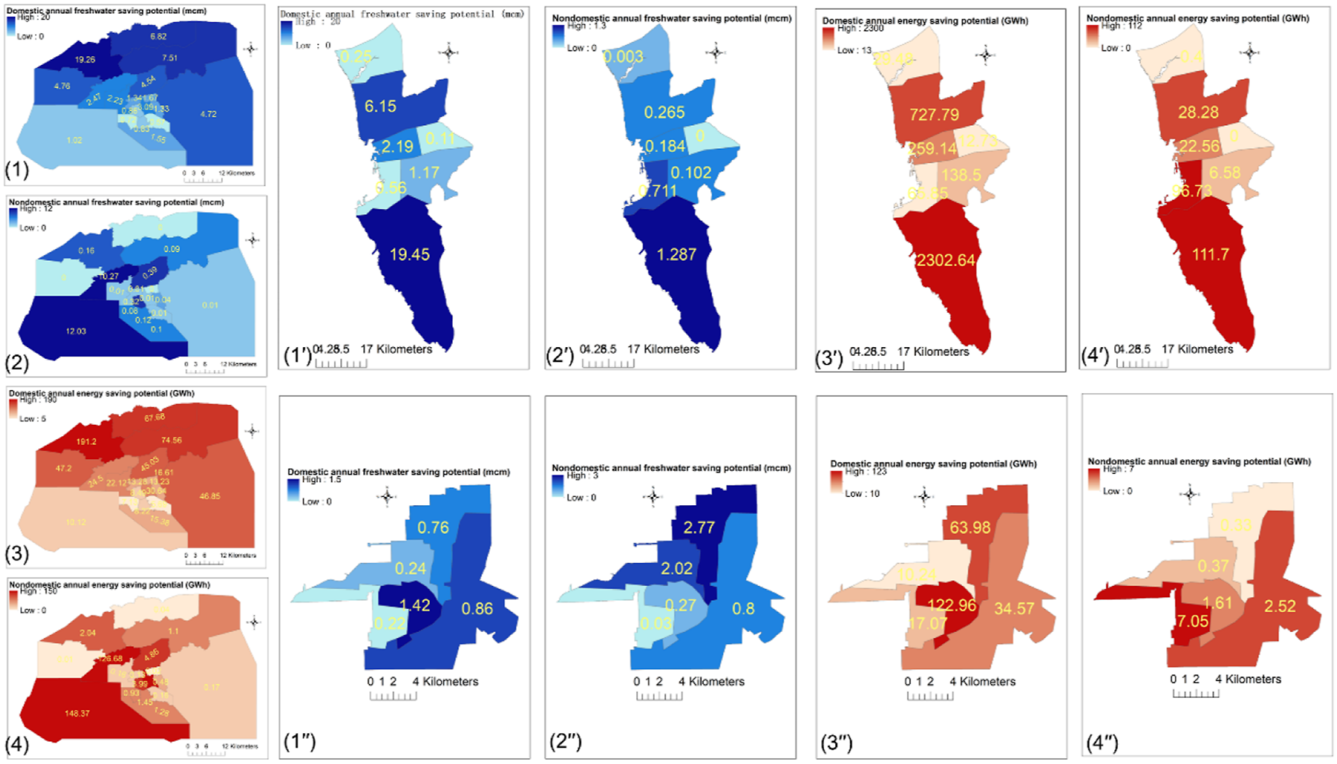


Figure 3. District-level annual water and energy saving potentials in domestic and non-domestic buildings. (1−4), (1′−4′), and (1″−4″) represent domestic annual freshwater saving potential, non-domestic annual freshwater potential, domestic annual energy saving potential, and non-domestic annual energy saving potential in Hong Kong, Jeddah, and Miami.

city. A positive value indicates overall positive outcomes, whereas a negative value indicates net negative effects. A greater absolute value of the joint indicator indicates greater positive or negative effects.

We further used Spearman's correlation analysis to elaborate on the statistical relationship between the joint indicator of the seawater-involving systems and the distance from the user site to the coastline and the effective population of the user site. Spearman's rank correlation coefficient is a nonparametric (distribution-free) statistic used to measure the strength of association between two variables. Thus, this method was suitable for our dataset.[49] The GenerateNearTable function in ArcMap 10.6 was utilized to determine the distance from the coastline to each building. This tool measures the distance between the input feature and the near feature, which can be set as land use and coastline layers, respectively. The population in each tile was calculated as described in the previous section. All statistical calculations were performed using SPSS Statistics 26 (IBM, New York).

$$\mathrm{WE}_{i,d} = \frac{\sum_{j=1}^{n} \mathrm{WS}_{i,j}}{\mathrm{WD}_{\mathrm{eng}_{i,t}}} \tag{7}$$

where n is the number of grids in district d; $\mathrm{WE}_{i,d}$ is the effects of the seawater-involving system on local water security in district d; and $\mathrm{WD}_{\mathrm{eng},i,t}$ is the engineered water demands in the city i in year t.

$$\mathrm{EE}_{i,d} = \frac{\sum_{j=1}^{n} \mathrm{ES}_{i,j}}{\mathrm{ED}_{\mathrm{import}_{i,t}}} \tag{8}$$

where $\mathrm{EE}_{i,d}$ is the effect of the seawater-involving system on local energy security in district d and $\mathrm{ED}_{\mathrm{import}_{i,t}}$ is the energy imports in the city i in year t.

$$\mathrm{CE}_{i,d} = \frac{\sum_{j=1}^{n} \mathrm{CS}_{i,j}}{\mathrm{CD}_{\mathrm{mtg}_{i,t}}} \tag{9}$$

where $\mathrm{CE}_{i,d}$ is the effects of the seawater-involving system on local carbon mitigation in district d and $\mathrm{CD}_{\mathrm{mtg}_{i,t}}$ is the carbon mitigation goal in the city i in year t.

$$\mathrm{SI}_{i,d} = \mathrm{WE}_{i,d} + \mathrm{EE}_{i,d} + \mathrm{CE}_{i,d} \tag{10}$$

where $\mathrm{SI}_{i,d}$ is the synergy indicator of the seawater-involving systems in district d in city i.

■ RESULTS AND DISCUSSION

External Water and Energy Demand by 2050 and Regional Carbon Mitigation Goals. Increasing trends of engineered water demands and energy imports were observed in all three cities (Figure 2). For HK, the predicted annual engineered water demands were 779 million m^3 [95% confidence interval (CI): 646−912] in 2022. This value is expected to increase to 905 million m^3 by 2050 (95% CI: 734−1075). Besides, the annual energy imports were predicted to be approximately 45,660 TJ (95% CI: 40,980−50,340) in 2022 and expected to reach 61,151 TJ (95% CI: 54,925−67,377) by 2050. In Jeddah, the annual demand for desalinated water in 2022 was predicted as 299 million m^3 (95% CI: 280−319), and by 2050, the demand would reach 653 million m^3 (95% CI: 624−680). For Miami, the annual demand for non-conventional water (including desalinated seawater, brackish

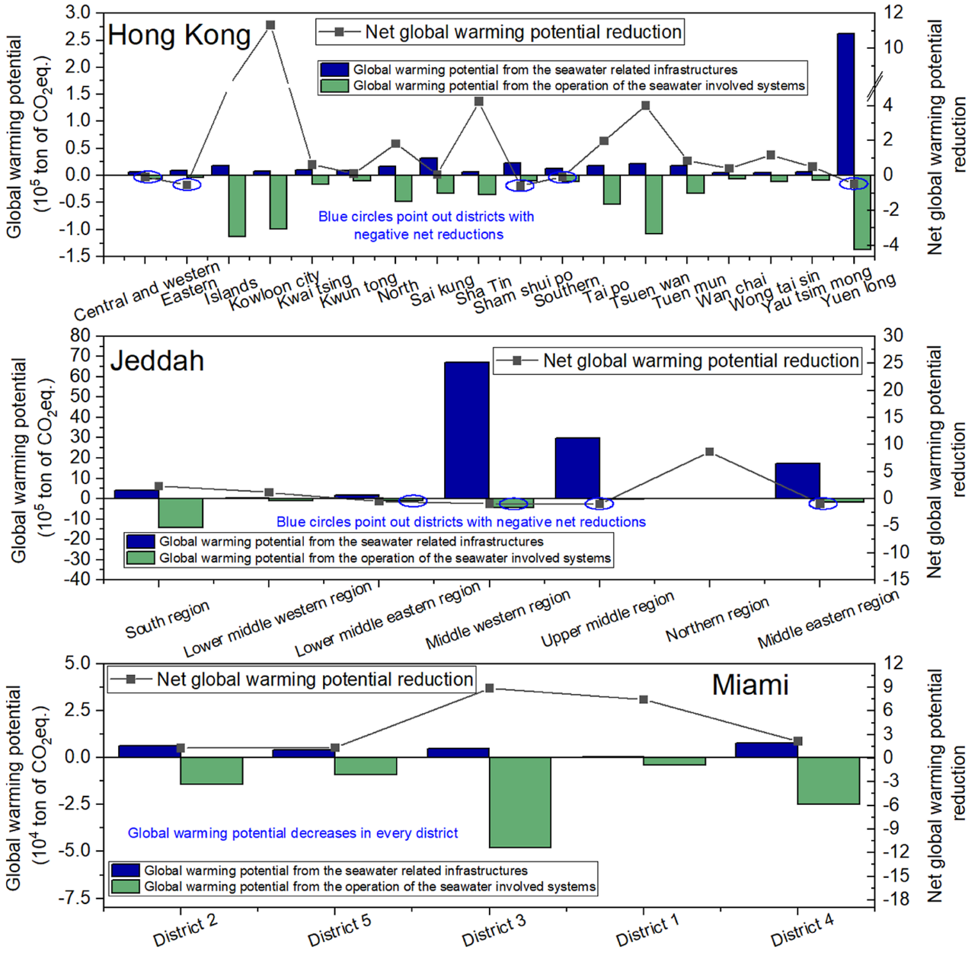


Figure 4. District-level life cycle environmental impacts of the seawater-involved system. The results are GWP. The left *Y*-axis indicates the increases in the environmental impacts resulting from infrastructure manufacturing and construction and the reductions in the environmental impacts resulting from the more efficient operation of the seawater-involved systems. The right *Y*-axis shows the net environmental impacts of the seawater-involved systems calculated as (reduction − increase)/increase. A positive value indicates overall positive environmental consequences, whereas a negative value indicates negative environmental consequences. A larger absolute value represents a greater increase or reduction in environmental impacts.

water, and harvested rainwater) was 142 million m^3 (95% CI: 128−156) in 2022. The rate of the annual increase in the engineered water demand was lower in Miami (0.6−0.7%) than in HK and Jeddah. The annual non-conventional water demands were expected to amount to 172 million m^3 (95% CI: 154−189) by 2050 in Miami. The energy imports in Miami were projected as 1772 TJ (95% CI: 1481−2063) in 2022, and this value was expected to increase to 3380 TJ (95% CI: 1814−4946) by 2050. The governments of HK and Miami have explicitly defined their regional carbon mitigation goals. HK is determined to reduce its carbon intensity by 65−70% by 2030, relative to the value recorded in 2005 (i.e., 11.2 $MtCO_2e$ per year), and Miami aims to reduce its city-wide carbon emissions by 60% by 2035, relative to the levels recorded in 2018 (i.e., 1.69 $MtCO_2e$ per year).[50,51] However, Jeddah has no explicit city-level carbon mitigation goals. Therefore, we used the Nationally Determined Contributions of Saudi Arabia to estimate the population-averaged carbon reduction goals in Jeddah, which is 14.9 $MtCO_2e$ annually[52] (Table S13).

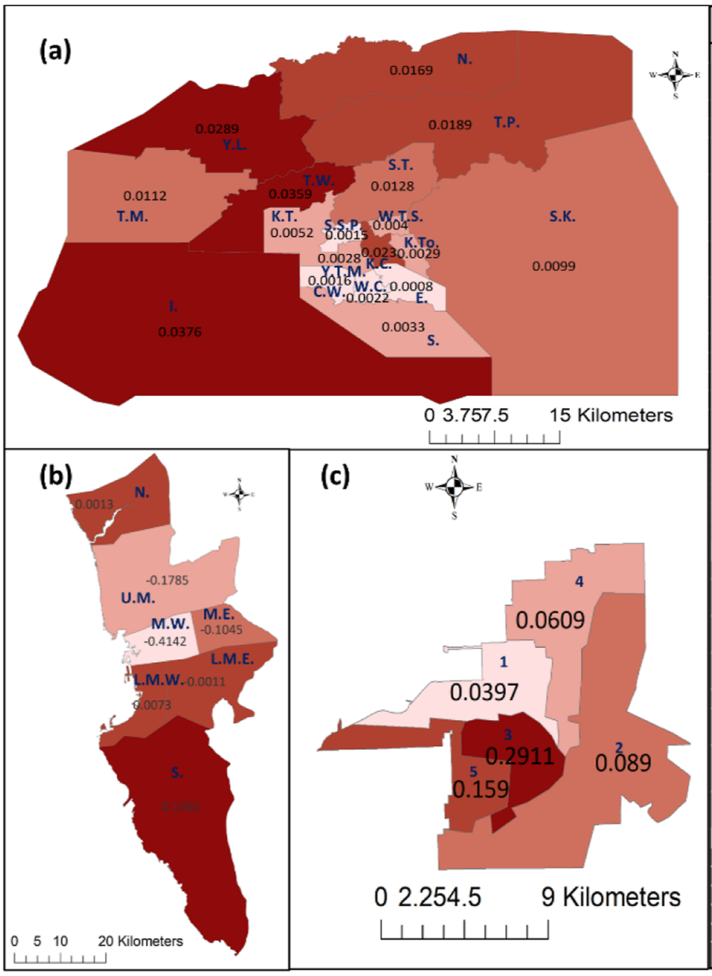
Water−Energy Savings Using Seawater-Involving Systems. We developed a bottom-up model to quantify the potential freshwater and energy savings with seawater toilet flushing and district cooling. The annual city-level freshwater saving potentials in HK, Jeddah, and Miami were calculated as 296 (95% CI: 268−326), 32.5 (95% CI: 29.7−35.3), and 9.4 (95% CI: 5.6−13.2) million m^3, respectively, accounting for approximately 28, 16.3, and 20.4% of their respective annual freshwater consumption. Energy savings are derived from highly efficient seawater-cooled district cooling systems (i.e., seawater-cooled district cooling systems have a higher COP than air-cooled air conditioning systems) and the low energy intensity of seawater treatment compared with that of freshwater treatment (i.e., 90% less electricity than freshwater supply). Moreover, saline wastewater treatment (anaerobic sulfate reduction and sulfide autotrophic denitrification) consumes less energy than conventional wastewater treatment (heterotrophic denitrification and nitrification) (0.31 vs 0.50 kW h/m^3).[53] The annual city-level energy saving potentials in HK, Jeddah, and Miami were 1047 (95% CI: 757−1337), 3806 (95% CI: 3356−4256), and 261 (95% CI: 177−345) GW h, respectively, accounting for 3.0, 11.4, and 4.2% of the cities' relevant annual electricity consumption.

Figure 3 presents the estimated district-level annual freshwater and energy savings in domestic and non-domestic buildings in three cities in 2022. Facilitated by seawater-involving systems, domestic buildings generally have higher water and energy saving potentials than non-domestic buildings. Seawater systems save 65.3 and 23.7 million m^3 of freshwater in domestic and non-domestic buildings in HK, respectively. Yuen Long and North districts have the highest water-saving potentials from domestic buildings (19.2 and 6.8 million m^3, respectively), whereas Tsuen Wan and Island districts have the highest freshwater-saving potentials from non-domestic buildings (10.3 and 12.0 million m^3, respectively). Overall, Yuen Long and Island districts are the two regions with the highest water-saving potentials at 19.4 and 13.0 million m^3, respectively. The annual energy saving potentials from domestic and non-domestic buildings in HK amount to 648 and 399 GW h, respectively. Yuen Long and Tai Po districts have the highest energy-saving potentials from domestic buildings (191 and 74.6 GW h, respectively). Moreover, Island and Tsuen Wan districts have the highest annual energy-saving potentials from non-domestic buildings (148 and 127 GW h, respectively). In Jeddah, 30.0 and 2.6 million m^3 of water could be saved annually in domestic and non-domestic buildings. The Southern and Middle Western regions of Jeddah have the highest water-saving potentials from domestic and non-domestic buildings, that is, 6.15 and 2.19 million m^3 and 1.29 and 0.71 million m^3, respectively. Furthermore, the annual energy saving potentials in Jeddah (3540 and 266 GW h in domestic and non-domestic buildings, respectively) were significantly higher than those in HK and Miami. The Southern region of Jeddah has a total of 2414-GW h energy saving potential from domestic and non-domestic buildings. The Middle Eastern region of Jeddah has the lowest energy-saving potential, amounting to 12.7 GW h annually. Miami has the smallest population among the three cities, and its annual water-saving potentials from domestic and non-domestic buildings are 3.5 and 5.89 million m^3, respectively. Districts 3 and 5 in Miami have the highest water-saving potentials from domestic and non-domestic buildings (1.42 and 1.61 million m^3, respectively). Moreover, the annual energy saving potentials from Miami are 249 and 12 GW h from domestic and non-domestic buildings, respectively. District 3 accounts for 49% of the total saving potential from domestic buildings, whereas District 4 accounts for 59% of the total saving potential from non-domestic buildings.

Life Cycle Environmental Impacts of the Seawater-Involving Systems. The previous section presents the water and energy saving potentials of seawater-involving systems. However, additional infrastructure is required for seawater-involving systems, and upstream emissions from the manufacturing and construction processes lead to unknown environmental impacts. Therefore, a life cycle assessment (LCA) should be conducted to fully assess the consequences of the broad implementation of seawater-involving systems. In this study, we focused on five environmental indicators: global warming potential (GWP), ozone formation potential for human health (OFP), fine particulate matter formation potential (FPFP), marine eutrophication potential (MEP), and marine ecotoxicity potential (METP). We quantified the environmental burdens due to newly built infrastructures, including seawater intake pipes, seawater distribution pipes (without in-building plumbing) for toilet flushing, seawater cooling pipes and chill water loops in district cooling systems, centralized chillers in district cooling facility, and SANI units in wastewater treatment plants. Although we ignored the retrofitting pipes in buildings, we overestimated the seawater mains by geoprocessing tools in ArcGIS and offset the environmental impacts from the in-building pipes to a certain extent.

The equivalent annual GWP of the infrastructures was 0.488 $MtCO_2e$, whereas the annual GWP reduction of the system was 0.744 $MtCO_2e$; therefore, the overall GWP reduction in HK was 0.256 $MtCO_2e$. However, the consequences of GWP vary significantly from district to district. The Central and Western, Eastern, Sham Shui Po, Southern, and Yuen Long districts yielded negative net GWP reductions. Therefore, considering GWP alone, seawater-involving systems may not be feasible for these districts. Meanwhile, regarding GWP, Kowloon City, Island, and Tsuen Wan districts are the preferred regions for seawater-involving systems (Figure 4). Besides GWP, in most districts, positive net reductions are seen in FPFP, except in the Eastern, Sham Shui Po, and Yuen Long districts. However, most districts yielded negative net reductions in the OFP, MEP, and METP (13/18, 18/18, and 12/18, respectively; Figure S2). For Jeddah, the city-wide net reductions in the five environmental indicators were negative: −9.86 $MtCO_2e$, −32.5 kt NO_xe, −16.1 kt PM2.5, −1.81 kt Ne, and −1.08 Mt 1,4-DCB for GWP, OFP, FPFP, MEP, and METP, respectively. The increase in GWP from the infrastructures was 12.1 $MtCO_2e$. However, the reduction in GWP upon the use of the seawater systems was only 2.24 $MtCO_2e$ (Figure 4). The Southern, Lower Middle Western, and Northern regions had positive net reductions in the GWP and FPFP (0.997, 0.0461, and 0.00672 $MtCO_2e$ for GWP and 3.06, 0.16, and 0.019 kt PM2.5 for FPFP, respectively). Moreover, the Southern and Northern regions had positive net reductions in OFP (316 and 6.08 kg NO_x, respectively). All regions resulted in a negative net reduction in MEP; only the Southern and Northern regions had positive net reductions of 9.06 and 0.189 kt 1,4-DCB in METP, respectively (Figure S2). Compared with Jeddah, the net reductions in the environmental impacts of seawater-involving systems are better in Miami. The reductions in the GWP, OFP, FPFP, MEP, and METP were 76.9 $ktCO_2e$, 86.8 ton NO_xe, 36 ton PM2.5, 7.02 ton Ne, and 2.04 kt 1,4-DCB in Miami, respectively. Districts 1 and 4 had negative net reductions in the OFP and METP. All other districts had positive net reductions in each environmental indicator (Figures 4 and S2).

Compared with HK and Miami, Jeddah had the highest environmental burden from the seawater-involving systems, possibly because Jeddah is a more sprawled urban region.[54−57] The population and building densities are lower in Jeddah than in HK and Miami, resulting in a less efficient infrastructure than in compact cities. Based on the LCA results, the broad implementation of seawater-involving systems in HK and Miami seems favorable, considering that the city-scale net reductions in most environmental indicators are positive (3/5 in HK and 5/5 in Miami). Although the city-wide implementation of seawater-involving systems in Jeddah resulted in net negative environmental impacts for specific regions, in the Southern and Northern regions, most net reductions in the environmental indicators were positive (4/5 in both regions). We conducted an uncertainty analysis in LCA to assess the inventory data uncertainties using the Monte Carlo simulation model. Based on the uncertainty assumptions of the indicators (see details in Tables S10 and S11), the uncertainty analysis revealed that the coefficients of variation were 13−34% for the GWP results, 13−33% for the OFP results, 13−28% for the FPFP results, 11−18% for the MEP results, and 28−41% for the METP results (Table S12).



(d)

District	Abbreviation	Effect on water security	Effect on energy security	GHG mitigation effect
		Hong Kong		
Kowloon City District	K.C.	0.0040	0.0109	0.0081
Wan Chai District	W.C.	0.0012	0.0008	0.0002
Eastern District	E.	0.0008	0.0005	-0.0004
Yau Tsim Mong District	Y.T.M.	0.0015	0.0010	0.0003
Sham Shui Po District	S.S.P.	0.0017	0.0011	-0.0012
Kwun Tong District	K.T.	0.0018	0.0011	0.0001
Central and Western District	C.W.	0.0010	0.0006	0.0000
Kwai Tsing District	K.T.	0.0029	0.0018	0.0005
Wong Tai Sin District	W.T.S.	0.0022	0.0013	0.0006
Tai Po District	T.P.	0.0098	0.0060	0.0032
Islands District	I.	0.0167	0.0125	0.0084
Yuen Long District	Y.L.	0.0249	0.0152	-0.0112
Sha Tin District	S.T.	0.0063	0.0039	0.0026
Tsuen Wan District	T.W.	0.0163	0.0119	0.0077
Southern District	S.	0.0021	0.0013	-0.0001
North District	N.	0.0088	0.0053	0.0028
Sai Kung District	S.K.	0.0061	0.0037	0.0002
Tuen Mun District	T.M.	0.0061	0.0037	0.0014
City-level effects		**0.1142**	**0.0825**	**0.0228**
		Jeddah		
South region	S.	0.0692	0	0.0672
Lower middle eastern region	L.M.E	0.0042	0	-0.0053
Lower middle western region	L.M.W	0.0042	0	0.0031
Upper middle region	U.M	0.0214	0	-0.1999
Northern region	N.	0.0008	0	0.0004
Middle eastern region	M.E	0.0003	0	-0.1048
Middle western region	M.W.	0.0079	0	-0.4221
City-level effects		**0.1085**	**0**	**-0.6616**
		Miami		
1		0.0160	0.0216	0.0021
2		0.0117	0.0725	0.0048
3		0.0119	0.2537	0.0255
4		0.0018	0.0491	0.0100
5		0.0249	0.1310	0.0031
City-level effects		**0.0663**	**0.5280**	**0.0455**

Figure 5. (a−c) District-level synergy indicator regarding water and energy savings and carbon mitigations in Hong Kong, Jeddah, and Miami; (d) district-level water-saving effects, energy-saving effects, and carbon mitigation effects in three cities.

Significance of the Seawater-Involving Systems to the Local Water−Energy Securities and Carbon Mitigations. From previous sections, we understand that the water and energy savings and environmental impacts of the seawater-involving systems varied significantly from district to district and from city to city. However, these exact results cannot reflect the context-specific effects of the systems in different cities. It is necessary to develop explicit indicators to reflect the performance of the seawater-involving systems in terms of water−energy savings and environmental mitigations, specifically carbon mitigation. Herein, we developed the water-saving, energy-saving, and carbon mitigation indicators to demonstrate the water−energy−carbon consequences of the seawater-involving systems on the local water−energy securities and carbon mitigations. Moreover, the three dimensionless indicators were aggregated into a synergy indicator to compare the coeffects of the seawater-involving systems in different cities and to demonstrate the coeffects in different districts within a city.

Among the three cities, HK achieved the highest water-saving effects (0.114), followed by Jeddah (0.108). Miami had the highest energy-saving effects (0.528), while HK achieved the limited energy-saving effects (0.083). Regarding carbon mitigation, Miami achieved the highest benefits (0.046), followed by HK (0.023); however, Jeddah got negative effects (−0.662) (Figure 5d). Overall, Miami got the best coeffects from the seawater-involving systems (0.640), and HK achieved moderate coeffects (0.220). The coeffects in Jeddah were negative (−0.553). For district-level effects, in HK, the three districts with the highest joint indicators were Island (0.0376), Tsuen Wan (0.036), and Yuen Long (0.0290); these districts should be prioritized for building seawater-involving systems to enhance the water−energy securities and carbon mitigations (Figure 5a). In Jeddah, three regions had positive joint indicators: Southern (0.136), Lower Middle Western (0.0074), and Northern (0.0013). In Miami, all five districts had positive joint indicators in the following order: District 3 (0.291) > District 5 (0.159) > District 2 (0.089) > District 4 (0.061) > District 1 (0.0397). Accordingly, we concluded that when resources are limited, the prioritized implementation of seawater-involving systems in District 3 will lead to the most significant enhancement of water−energy securities and carbon mitigations.

Implications. Mitigation and adaptation are keys to responding to climate change, which refers to the actions to reduce carbon emissions and increase resilience to the impacts of climate change.[58] Planning the seawater-involving systems at the district level could achieve the reduction of life cycle carbon emissions, which is a potential approach for climate change mitigation. According to the IPCC Sixth Assessment Report, water scarcity and heat impacts due to climate change were observed at an increasing level.[59] Facing the uncertainties of water availability, seawater is a reliable candidate that consistently provides toilet flushing water with fewer energy costs. Moreover, the highly efficient seawater district cooling system prevents human exposure to extreme heat with less energy and water costs. Thus, the seawater-involving systems could strengthen the resilience of cities to adapt to adverse impacts from climate change. Besides mitigation and adaptation to climate change, another superior feature of seawater is that it is safer for humans to use than reclaimed water (centralized wastewater reclamation or greywater reclamation) as a replacement for freshwater in municipal services.[60] This is because seawater salinity serves as a clear warning for the cross-contamination of freshwater with seawater, which may occur due to pipe misconnections. By contrast, the contamination of freshwater with reclaimed water due to pipe misconnections is less easily detectable, posing significant risks to human health and preventing the large-scale application of reclaimed water for toilet flushing. Besides, compared to reclaimed water, seawater is a cheaper option for toilet flushing (less than 0.01 USD/m^3 for seawater vs 0.1−0.9 USD/m^3 for reclaimed wastewater).[61−63]

The most significant challenges of using seawater include seawater main failure and unpredictable source contamination prevention, necessitating well-managed regular maintenance and constant monitoring of seawater at the source. In the 50 years since seawater has been used for toilet flushing in HK, a close number of bursts and much fewer leaks have been reported in the seawater mains than in the parallel freshwater system each year (2022 and 2106 main bursts in the freshwater supply and the saltwater supply, 34,079 and 6392 main leaks in the freshwater supply and saltwater supply).[64] The success of seawater use in HK not only relies on effective water management but also on stringent installation regulations, good audits, and incentive policies.[65−67] Furthermore, a study on 200 years' worth of groundwater chemistry data revealed no significant impacts on groundwater of seawater leakage from pipes supplying seawater to municipal services.[68] Another study also concluded that using seawater to replace freshwater for toilet flushing could be a mitigation approach for the detrimental effects of wastewater on marine organisms.[69]

More than 50% of the 17 United Nations Sustainable Development Goals of the UN 2030 Agenda for Sustainable Development address social and environmental issues.[70] Efforts to fulfill a water−energy−climate goal typically result in synergy among the three aspects of the goal or a trade-off between one aspect and the others.[71] Considering Jeddah as an example, the population-averaged carbon mitigation goal to combat anthropogenic climate change is 14.85 $MtCO_2eq$/year by 2030.[52] In this context, the city-level implementation of seawater-involving systems, including toilet flushing and district cooling, will realize carbon reductions of 2.24 $MtCO_2eq$/year, that is, 15.1% of the 2030 target, thereby contributing to a significant reduction in carbon emissions and water−energy savings. However, when life cycle emissions are accounted for, the net carbon reduction amounts to −9.86 $MtCO_2e$, indicating that 12.1 $MtCO_2e$ of carbon emissions are transferred to other sectors (e.g., industrial and construction) or other regions around the world. Therefore, when making decisions on sustainable solutions, a broad boundary that accounts for both local and global emissions should be defined. Besides, we observed that the effects of seawater-involving systems significantly differ from city to city. The seawater-involving systems bring significant overall positive effects to Hong Kong and Miami regarding water and energy savings and carbon mitigations. However, they lead to overall negative effects on Jeddah, which suggests that no one solution fits all situations, and site-specific solutions and planning are critical to meet multidimensional goals.

Additional infrastructure required for seawater-involving systems include the pump house, the seawater distribution system, the district cooling system and user connections, and the sulfate-reducing autotrophic denitrification and nitrification units in the wastewater treatment plant. Therefore, it is critical to assess whether such systems are economically feasible. A general payback analysis was conducted to investigate the economic performance of such systems. The benchmark costs of the district cooling system and seawater toilet flushing in HK were utilized. The capital investments in HK, Jeddah, and Miami were estimated at 10.4, 73.4, and 5.23 billion USD (with 50% contingency), respectively. When the annual operational and maintenance costs were assumed to be 1% of the capital investments (an assumption used for the heat, air ventilation, and cooling system in the GHG Abatement Cost Model by the UN Environment Programme), the service price of the district cooling system was comparable to HK's current charges, and the revenues from carbon emission trading were included. The payback period of the seawater systems was found to be 14, 14, and 16 years for HK, Jeddah, and Miami, respectively (see payback analysis assumptions in the Supporting Information for detailed calculations and Table S14 for detailed results).

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c07352.

> Grid-level (1 km^2) GFAs and population calculations; water and energy intensities of processes in a seawater-involving system; inventory of the newly built infrastructure and uncertainties accounts for the life cycle assessment; payback analysis assumptions; correlation between coeffects of the seawater-involving systems and distance from coastline to user buildings and effective population density in user buildings; and supplementary figures and tables (PDF)

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