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An optimization model for determining the degree of decentralization for nonpotable water reuse in Hong Kong

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Abstract: Hong Kong is a densely populated city that faces a significant shortage of freshwater. The mountainous terrain of Hong Kong presents challenges for collecting and storing rainwater, resulting in local yields accounting for only 20~30% of the city's freshwater supply. The remaining 70~80% is imported from the Greater Bay Area, which is also facing the water shortage due to rapid urbanization and climate change. To reduce freshwater consumption, Hong Kong has been using seawater for toilet flushing since the 1950s, which has become an established practice in the city's water conservation efforts. Since 2019, Hong Kong is actively promoting the total water management strategy to improve the climate resilience and environmental sustainability of freshwater supply. Investing in nonpotable water reuse is one of the critical infrastructural solutions in the total water management strategy.

An important aspect of investing in nonpotable water reuse in the context of Hong Kong is determining the number and size of water reuse plants needed. The city can invest in one large central plant or distribute several smaller plants. Treatment of wastewater for nonpotable use is energy-intensive, and the urban water supply and wastewater treatment already consume significant amounts of energy in the city. Despite existing literature studying the optimal nonpotable water supply with fixed choices of wastewater treatment plants, a solution to determine the optimal degree of decentralization is still lacking.

To address this gap, we developed a spatial model to analyze water consumption and energy usage for water in Hong Kong, and formulated a novel optimization model to determine the optimal degree of decentralization for nonpotable water plants. Our spatial model quantifies water consumption for different purposes at the community scale, as well as the energy required to supply water and treat wastewater for each community. Our spatial model is used to evaluate the energy use of introducing nonpotable water plants in the optimization. In the optimization model, each community decides whether to send wastewater for treatment and reuse, and whether to accept treated wastewater. The locations and capacities of nonpotable water plants emerge from the collective decisions of communities in Hong Kong, with objectives including minimizing freshwater withdraw, capital and operation cost of nonpotable water plants, and energy consumption. We applied genetic algorithm to solve the multi-objective optimization model.

Our spatial modeling results highlight a wide range of energy intensities for water services across Hong Kong communities. The highest values reach up to 2.83 kWh/m^3, 1.35 kWh/m^3, and 2.24 kWh/m^3 for freshwater supply, seawater supply and wastewater treatment, respectively. Our optimization model suggests the optimal degree of decentralization ranges from 1 to 5 in the set of pareto-front solutions. Among the optimal solutions, a degree of 2 was the most frequently identified optimal solution. The suggested locations of nonpotable water plants are found to be in Kowloon and Hong Kong Island where nonpotable water demand is significant while the energy for freshwater and seawater is high. We verified the robustness of our optimization model in identifying the pareto-front and the optimal degree of decentralization when evaluating the decisions of more than a thousand of communities across different regions in Hong Kong. Based on solutions near the cost-effective regions of the pareto-front, the city could save about 4.5% freshwater and 18% seawater, while consuming 7% more electricity.

In conclusion, our spatial modeling and optimization model provide valuable insights for cities to determine the optimal degree of decentralization for nonpotable water use, with a holistic evaluation of the water-energy-cost nexus on an urban scale. Our findings also suggest the need for future studies to explore ways of reducing the energy dependence of water reuse, in order to maximize the potential for cities to reduce freshwater consumption.

Keywords: *Nonpotable water reuse, urban water systems, centralization, water-energy-cost nexus, sustainable development*