Multi-objective Spatial Optimisation of Decentralised Water Reuse Implementation and Service Allocation in Hong Kong

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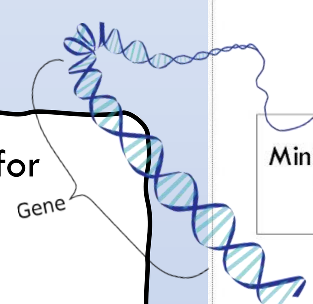
Background

Water Scarcity is a global issue that affects billions of people worldwide. According to the United Nations, over 10% of the world population are suffering from water stress and 67% of them are living in urban areas. With the continued growth of population and climate change, water scarcity is becoming an increasing urgent issue that requires immediate attention and solutions.

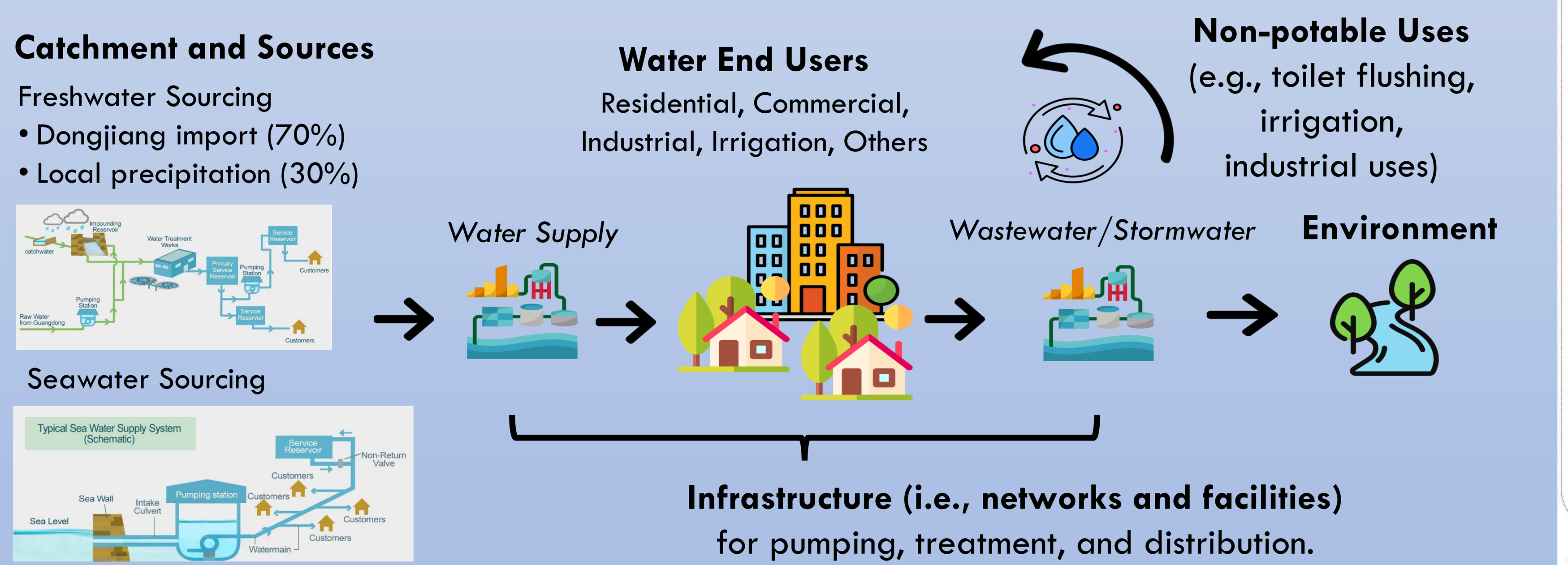
Hong Kong is one of the fast-urbanized cities with over 7.4 million residents, consuming about 21% more freshwater per capita than the global average. The city replies heavily on freshwater import, with less than 30% water supply from local rainfall catchments. To alleviate the challenge of water stress, the government has launched a *Total Water Management Strategy (TWM)* to **diversify its water supply sources**, including using seawater for toilet flushing and recycled water **for non-potable purposes.**

Research Questions?



1. How efficient is the current energy performance of water and wastewater services for urban communities in Hong Kong?
2. What is the optimal approach to integrating the decentralised water reuse technologies (DWR) into the existing urban water infrastructure networks?
3. What are the impacts of water diversification on the urban water systems?

Hong Kong and its Complex Urban Water System



Summary

This paper presents **a multi-objective spatial optimisation framework** to help cities adaptively integrate the **water reuse concepts** into urban water infrastructure planning.

Using Hong Kong as a case study, we modelled the hydraulic flows and energy use for water across various stages from water sourcing, treatment, and distribution to wastewater collection, treatment and discharge. The base scenario analysis identifies **communities with energy-intensive water services.** Our optimisation offers insights into **the design of decentralised water reuse technologies** and their **impact evaluations** to support the water source diversification.

Overall, our research makes a valuable contribution to the advancement of **holistic-integrated solutions** in urban infrastructure planning and water resource management, with the ultimate goal of achieving **a more sustainable and resilient urban future.**

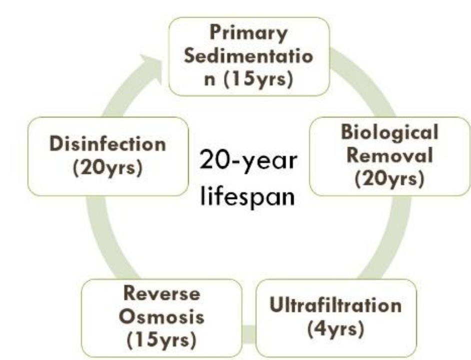
Methods and Materials

Centralised Water Infrastructure Operations

- Estimate Water Demand & Wastewater Generation (based on water use surveys of residential, commercial, and industrial uses)
- Simulate Hydraulic Flow & Electricity Consumption at Different Water Transmission Stages (using back-tracking algorithm)
- Simulate Water Age of Centralised Freshwater Pipes (using EPANET Python Toolkit)

Design of Decentralised Water Reuse Facilities (DWR)

Process Train and Technologies



Tertiary Planning Units (TPU) were considered as potential sites to implement DWR; If a TPU has a pre-existing WWTP, only the supplementary modules will be added.

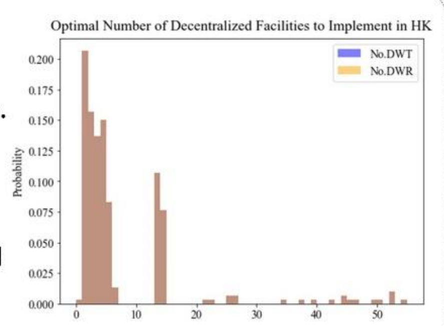
Capital & OM Costs: $f(Treatment\ Capacity)$

Electricity Consumption: $f(Flow\ Rate)$

Multi-objective Spatial Optimisation

Minimize Freshwater Withdrawal | Minimize Electricity for Water | Minimize Investment Costs

Assumptions:
- Based on experiments, a maximum number of 20 DWRs was considered suitable for implementation.
- Urban communities can only receive decentralised services within a radius of 8 kilometres.
- Urban communities tend to prioritize DWRs that are closer, less expensive to construct, and located in areas with high freshwater demand.



Initialisation (Population Size = N) → Fitness Values → Selection → Crossover → Mutation → Pareto-fronts

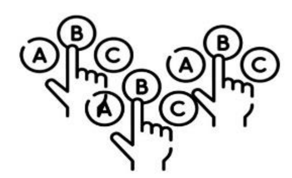
Offspring; Termination?

Step 1: Randomly open a certain number K (K<20) of DWR.

Step 2: Generate N feasible solutions as initial population using an iterative approach.

Decision Variables

Let urban communities make their decisions on whether to receive centralised or decentralised services, regarding:
- Wastewater Treatment
- Water Supply for Nonpotable uses



Termination? No. FS > N

Is it feasible? (Constraints)

The amount of reclaimed water produced should not surpass the volume of wastewater treated by each DWR.

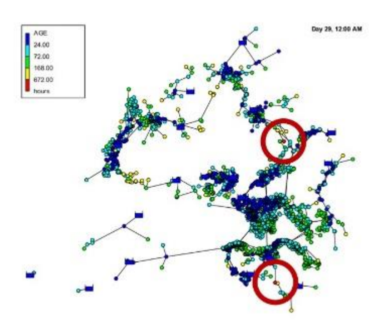
$$RWS_i \leq \mu TC_i, \forall i \in M$$

Where, μ is permeate rate, $\mu = 0.8$ and t represents each DWR facility, $t \in \{1, \ldots, 231\}$

Infeasible / Feasible → Feasible Solutions (FS)

Post-process

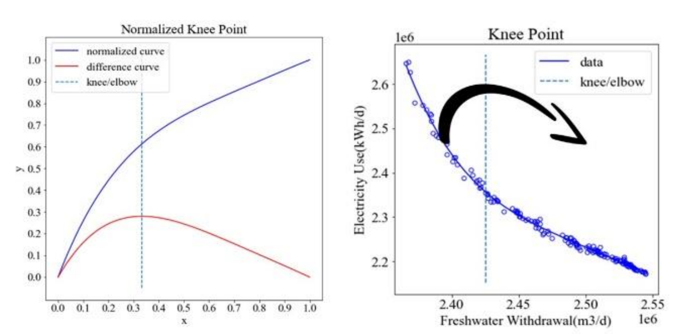
Simulate the Water Quality Changes in the Centralised Freshwater Pipeline Network for Comparison with Base Scenario.



Remove infeasible solutions from Pareto-fronts if:
(1) More than 5% of the water age at the community-end exceeds 672 hours;
(2) The water age at any community is doubled and exceeds 672 hours.

Impact Assessment

Identify the Knee Point with the Maximum Curvature to be the Most-Effective Solution.

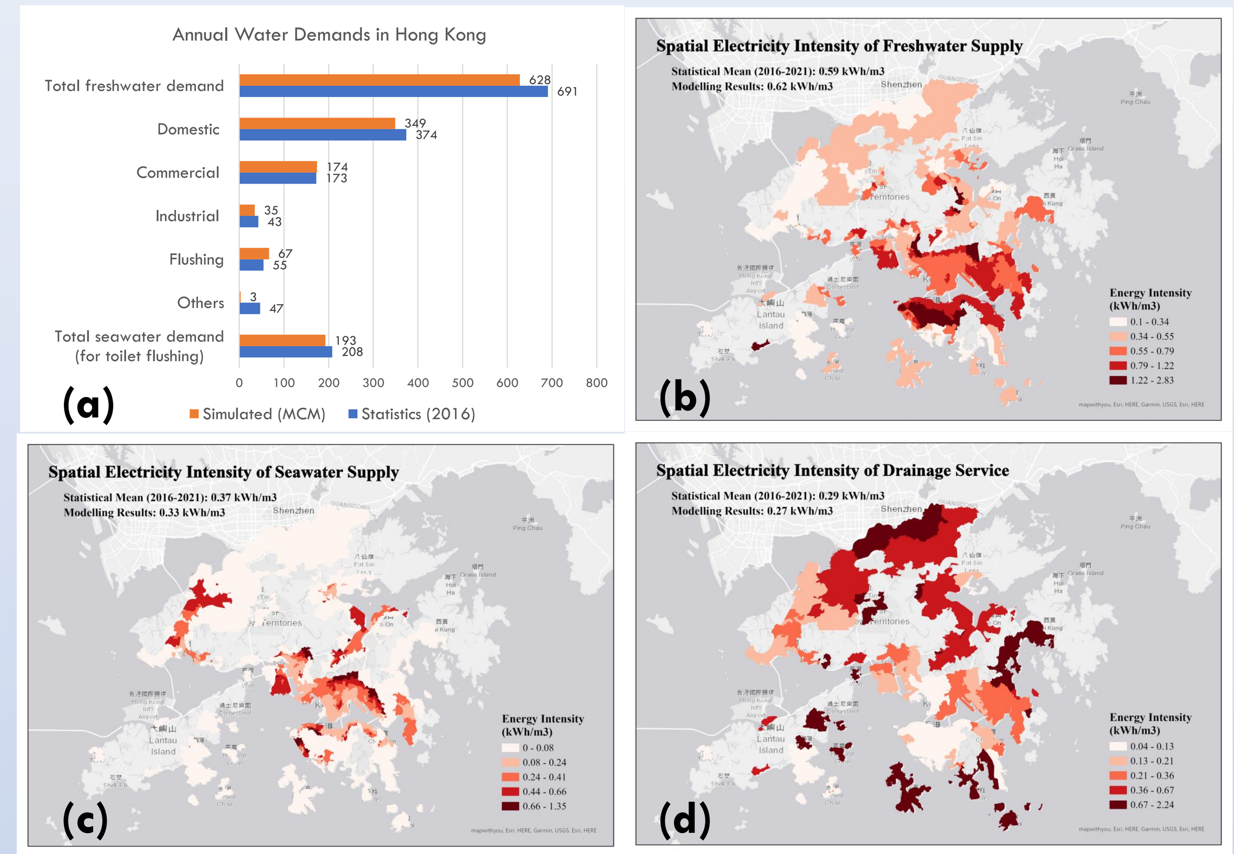


where relative electricity use to reduce freshwater withdrawal is no longer worth the performance/benefits.

To compare with Base Scenario: Freshwater Saving | Seawater Saving | Electricity Increase

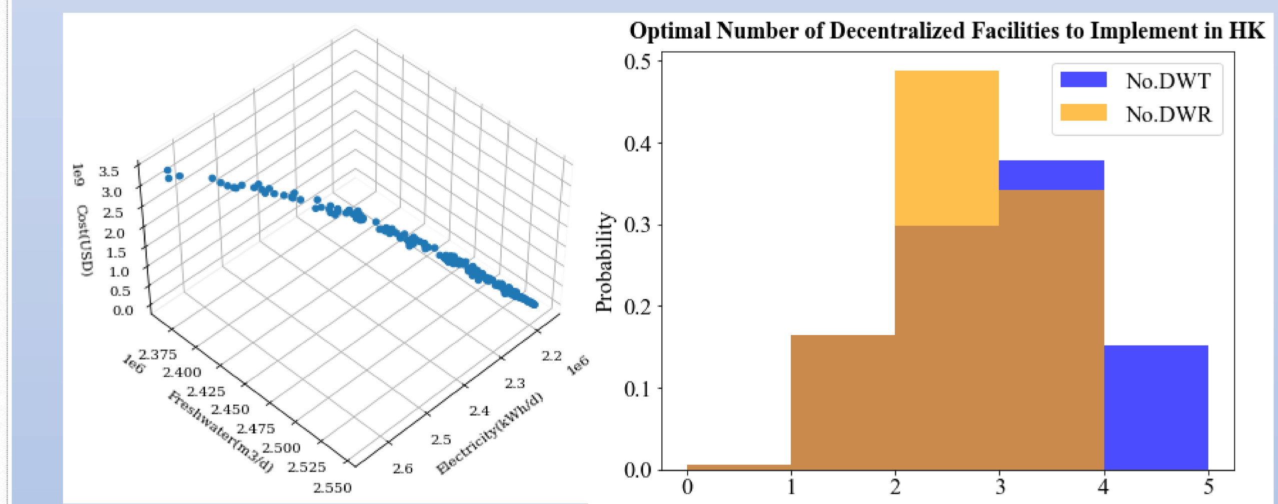
Results

Water-Energy Dependence in Hong Kong (Base Scenario):



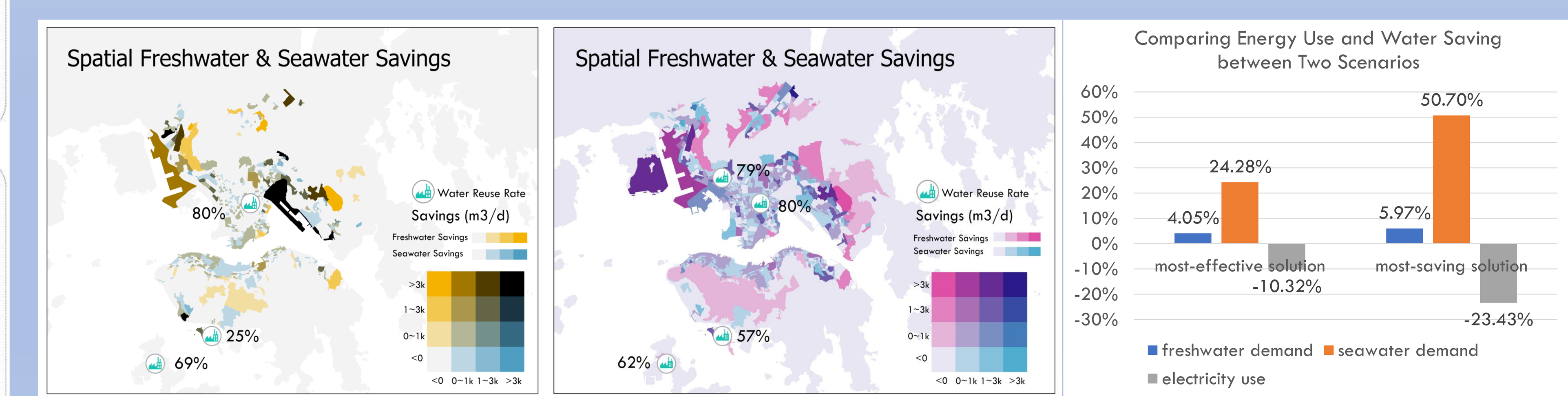
1. We calculated daily freshwater & seawater demands and wastewater production of each urban community based on water consumption surveys of residential, commercial, and industrial uses. Our estimation (a) is basically in line with the statistical reports.
2. We also computed and visualised the energy intensity of providing freshwater, seawater, and drainage services to urban communities (b-d). Our results have been validated by comparing with the statistical mean from 2016-2021.

Pareto-fronts Analysis:



1. The optimisation can produce 230 Pareto fronts, out of which 164 are workable solutions that ensure acceptable quality degradation in the centralized freshwater pipeline network. This quality degradation occurs as freshwater demand decreases due to water diversification.
2. In general, most pareto fronts recommend to implement 2~4 DWR facilities in the city.

Scenario Analysis and Impact Assessments:



Most-effective Solution | Most-saving Solution

We compared two scenarios to analyze their water-saving potential and energy costs. The most effective solution suggests to build three DWR facilities in *Ho Man Tin, Ap Lei Chau Island, and Tai Peng Island*, resulting in a 4% reduction in freshwater withdrawal and a 24% reduction in seawater withdrawal with a 10% increase in electricity use. Another proposal suggests a fourth DWR facility in *Cheung Sha Wan*, which would double the energy consumption and only result in less than 2% further reduction in freshwater usage. The rapid increase in energy consumption is due to the use of recycled water instead of seawater for toilet flushing.