Integrated Agent-based and System Dynamics Modeling of the Spatial Diffusion of Home-based Decentralized Water Technologies and the Impacts on the Water System

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1 Introduction

Cities are facing increasing water stress due to climate change and population growth. Although urban water use efficiency was improved, total water use continuously increases especially in the rapidly urbanized areas. Ensuring water availability and security has become an urgent concern to most cities in face of climate change. Centralized water systems dominate the urban water services in major cities and are important in ensuring sufficient water supply, sanitation, and drainage services to urban communities. However, such systems are considered inadequate to address future water challenges and the aspiration of ecologically sustainable development considering their high energy dependence and infrastructure aging problems. Upgrading the urban centralized water infrastructure is critical for a city to achieve the transition towards more sustainable and resilient water and sanitation services. However, considering the socio-technical lock-in effects and the strong path dependency of legacy water infrastructures, the upgrading and extension are costly and complicated.

Considering the challenges faced by centralized water systems, decentralized water technologies are recently emerging as potential alternatives to strengthen the reliability of urban water supply. By recovering and utilizing diverse local water sources to supplement urban water demands, these technologies can mitigate the pressure of water scarcity. Social preferences and choices of decentralized water technologies are critical to the level of mitigation. The demand-side investigation is important for water utilities and the government to make an investment and better plan the deployment. While past studies evaluated the critical socio-economic and technical factors that explain the household preference [1–3], there is a limited understanding of the spatial adoption and diffusion pattern of decentralized water technologies in a city and its impact on the water system. By answering this research question, our study can help the city develop an actionable plan to promote decentralized water technologies.

2 Methodology

We developed an integrated framework to explore the adoption and diffusion pattern of rainwater harvesting (RWH) and greywater recycling (GWR) systems in the city of Boston, and the impact on the water system that supplies water to the whole Metropolitan Boston (MB) region. In the framework, we first built a spatial agent-based model (ABM) to simulate the adoption of home-based decentralized water technologies by single-family households in the city. We used a system dynamics model (SDM) to evaluate the impact of decentralized water supply on reservoir water availability, hydropower generation, and carbon emission for water supply and wastewater treatments. The percentage of carbon reduction was used as the environmental benefit to update household adoption decisions of RWH and GWR in the spatial ABM. By exchanging "potable water supply" and "carbon reduction" between the ABM and the SDM (Fig.1), a hybrid model was thus established.

We validated our model integration by comparing the simulated places where early adoptions emerge with the validated installations (Fig.2), and the simulated reservoir elevations with historical records in the reference year (Fig.3). Several water drops (i.e., Feb. and Nov.) in Wachusett Reservoir were caused by precautionary measures that the SDM did not capture [4]. Nevertheless, the results are basically in line with the reported data in both simulations, and thus can validate the effectiveness of using our integrated model in predicting the spatial adoption and diffusion pattern of RWH and GWR, and evaluating the impacts of two decentralized water technologies on the centralized water system.

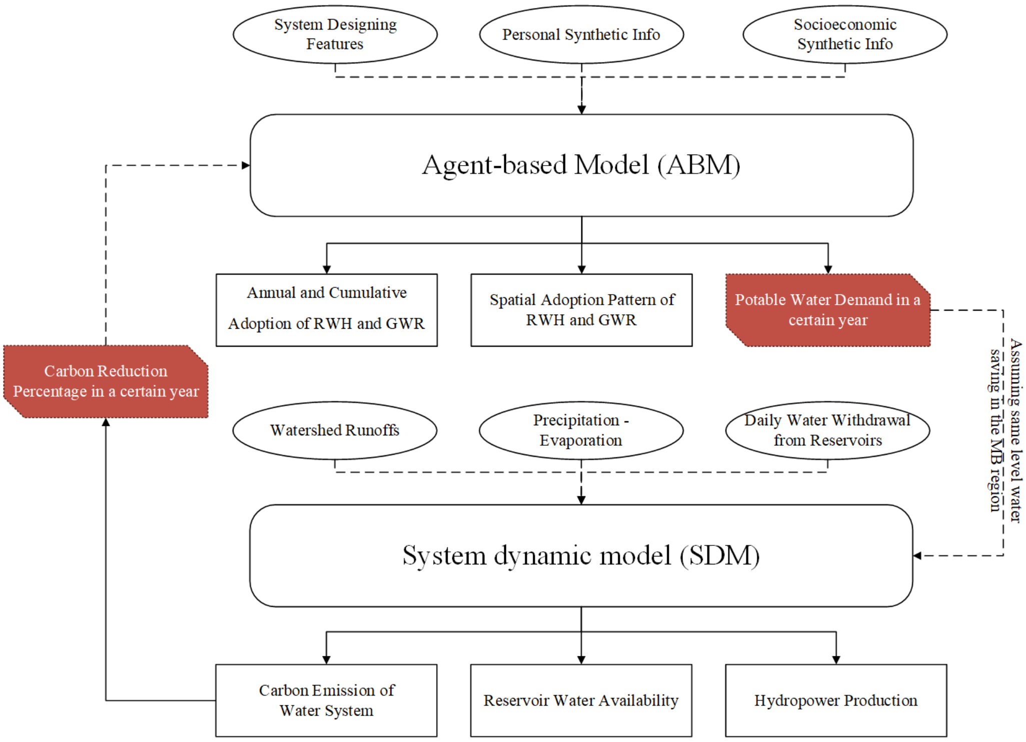

Fig. 1. Integration between the ABM and the SDM.

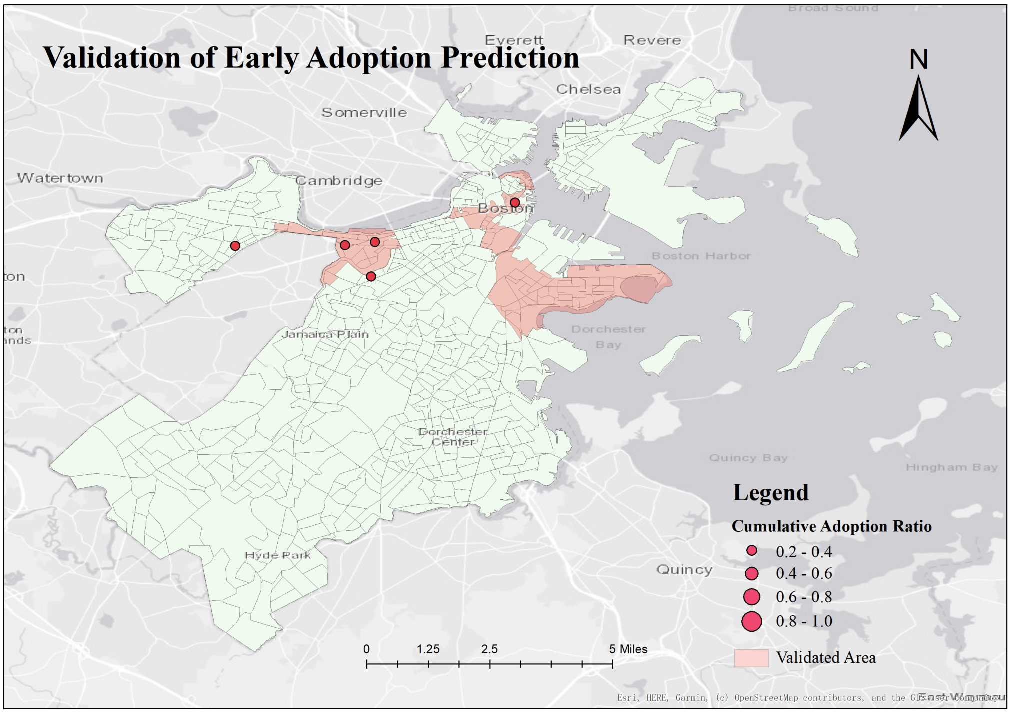

Fig. 2. Validation of early adoption predictions.

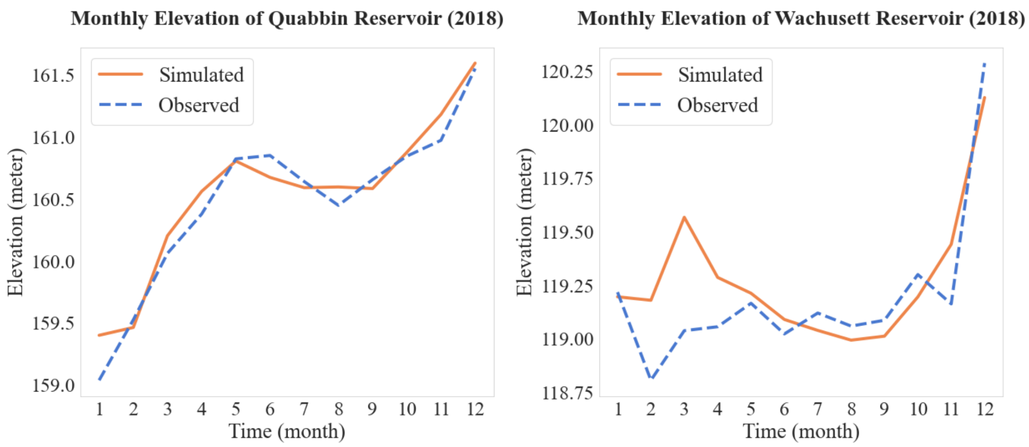

Fig. 3. Validation of monthly reservoir elevations in the reference year.

3 Results and Discussions

In the results, we first examined the sensitivity of RWH and GWR adoptions to market promotion, neighbor's influence, economic performance, and environmental benefits. Our ABM results revealed a much higher adoption and faster diffusion of RWH than GWR. The diffusion of both technologies starts from north downtown to southern suburban in the city. Spatial heterogeneity emerges in adopting two technologies with some communities having much higher adoptions of RWH versus some other communities that have more adoptions of GWR than the average. Our SDM results show that water availability increases in reservoirs with the adoption of RWH and GWR. However, hydropower generation from the water supply becomes less as water transfer between reservoirs decreases. More water is released from reservoirs to downstream rivers for safety purposes. Utilization of the increased water availability should be explored to produce more hydropower. Moreover, we did not find a significant reduction in carbon emission of water systems due to the high carbon intensity of GWR as compared to the centralized system. Reducing the impact of GWR energy consumption is critical to the benefits of large-scale implementations of decentralized water technologies.

4 Relevance for the ABMUS Workshop Themes (Multi-level Modelling)

Our paper is fully in line with the ABMUS overarching theme of multi-level modelling of urban system. The relevance is highlighted in the following aspects:

(1) ABM simulates both the spatial adoption pattern and the temporal diffusion pattern of decentralized water technologies in *a city-wide level*.

(2) SDM quantifies the impact of adoption on water system by assuming *the MB region* has the same level of water saving as single-family households in the city of Boston, which is acceptable because 53% of housing units in MB served by the centralized water system are single-family houses [5].

(3) By integrating the ABM and the SDM, the hybrid-modelling framework can provide systematic solutions for planning and evaluating the decentralized water technologies *at the nexus of human-infrastructure-environment* across *spatial and temporal scales*.

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