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Using system dynamics for sustainable water resources management in Singapore

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Abstract

To strive to full self-sufficiency in water, Singapore has invested heavily in desalination, wastewater reclamation (branded as NEWater), water catchment management and other similar projects. Among the many alternatives to augment Singapore's water supply, decision-makers need to know which one is the most sustainable plan to pursue. This research project aims to demonstrate the usefulness of System Dynamics (SD) as a decision support tool to help achieve sustainable water management in Singapore. We have developed a system dynamics model called *SingaporeWater* and analyzed the long-term impacts of various investment plans. We discovered that investing in underground water storage or surface water catchments alone is not sufficient to help achieve self-sufficiency in water. If Singapore starts to invest in desalination or NEWater only after there is inadequacy of water, then it will result in about five years of water shortage followed by another five years of water abundance. The results highlight the need to build water infrastructures well in advance in order to meet Singapore's future water demand.

Keywords: sustainability; water resources management; system dynamics; decision support; Vensim

Introduction

Sustainable water resources management

Water is the world's most critical natural resource. The severe scarcity of water is a global concern for now and the future. On the demand side, rapid population growth and economic development have led to even higher demand for water worldwide. On the supply side, climate change has caused the rainfall to be less predictable and natural sources of water less reliable [1]. The demand-supply imbalance in the water sector calls for more innovative water management practices, so as to provide sufficient quality water for present and future generations. This is the ultimate goal of sustainable water management, in alignment with United Nations' broader definition of sustainability [2].

Besides the challenges brought by climate change on the global scale, Singapore, a small city-state at the heart of Southeast Asia, faces many other challenges which are unique to its local contexts. With limited land spaces and

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water resources, the Republic has been purchasing water from Malaysia under two agreements [3]. This dependency on imported water is widely perceived to be a threat to Singapore's sovereignty and well-being [4]. To strive for full self-sufficiency in water, the country has invested heavily in desalination, wastewater reclamation (branded as NEWater), water catchment management and other similar projects. All these have resulted in an integrated and systematic approach towards sustainable water management. Public Utilities Board (PUB), the national water agency, is now managing the whole water cycle, from sourcing to the collection, purification/treatment and supply of drinking water and the management of waste and storm water [5].

In order to reduce flood risk and diversify water supplies, Singapore's former Chief Defense Scientist, Professor Lui Pao Chuen, proposed an underground water storage system that allows extra rainwater to be stored underground and be pumped up in times of water stress [6]. If constructed and put into operation, this new underground infrastructure will have significant long-term impacts on the integrated water resources system in Singapore. In addition, among the many alternatives to augment Singapore's water supplies, decision-makers in both public and private sectors need to know which one is the most sustainable plan to pursue. This research project aims to demonstrate the usefulness of System Dynamics (SD) as a decision support tool to help achieve sustainable water management in Singapore.

System Dynamics (SD) and its applications

System Dynamics (SD) is an approach to understanding the behavior of complex systems over time. It captures internal feedback loops and time delays that affect the entire system. Developed by Professor Jay Forrester in the 1960s [7] and popularized by the Club of Rome's *Limits to Growth* in the 1970s [8], SD has been successfully applied to study demographics [8], economic growth [9], business development [9, 10], water and natural resources management [11, 12, 13, 14], and environmental systems [15, 16]. Its capabilities to quantitatively simulate the dynamic consequences of various policies make it an ideal decision support tool for strategic policy testing and selection.

The current modeling studies of water resources mainly focus on the irrigation system of the agricultural industries. For example, SD has been used to study Yellow River in China [17], water for irrigation in Spain [18], water resources in Canada [12, 13, 14], and water balance in Mono Lake, California [19]. To date, there are no published studies that apply SD as a decision support tool to analyze Singapore's integrated water resources system. This project aims to fill in this gap. The paper is organized as follows. Section 2 describes the *SingaporeWater* system dynamics model. Section 3 discusses the long-term impacts of various investment plans as revealed by the model results. Section 4 concludes with the new insights derived from this modeling study.

***SingaporeWater* System Dynamics Model**

In order to capture the essence of Singapore's water sector, we have developed a system dynamics model called *SingaporeWater*. Since the second water agreement with Malaysia will expire in 2061 and the proposed underground water storage system will have long lifespan, the model runs from the year 2000 to 2100, so as to reveal long-term impacts of the proposed policies. It is developed with Vensim Personal Learning Edition, which helps to conceptualize, build, and test system dynamics models [20].

The SD approach is appropriate for any dynamic system characterized by interdependence, mutual interaction, information feedback, and circular causality [21]. It is an excellent tool to study problems that arise in closed-loop systems. As Singapore's water resources system is highly integrated, SD has been used to capture interdependencies and feedbacks between various sub-systems. In addition, most of the relevant data needed for model building are all readily available from government websites, corporate annual reports, and many other open-access sources. These credible data have significantly enhanced the validity of the model. Hence, SD is proven to be a very useful tool to holistically analyze Singapore's water resources system.

2.1 Model formulation and development

The *SingaporeWater* model is originated from a basic demand and supply framework. On the demand side, population level and economic growth determines the total demand for water. On the supply side, Singapore has built a diversified water supply through the Four National Taps, namely local catchment water, imported water, NEWater, and desalinated water [22]. A Causal Loop Diagram (CLD) in Fig. 1 captures the key elements of the system. The water agreements between Singapore and Malaysia stipulate that a certain portion of the imported water from Malaysia will be treated by Singapore and be exported to Malaysia [3]. It is assumed that Singapore government will invest in water sector when there is an inadequacy of water, as quantified by the water adequacy index. After some delays in planning and constructions, the funding will then be translated into capacity increases in the Four National Taps. Thus, there are four balancing loops in this mechanism.

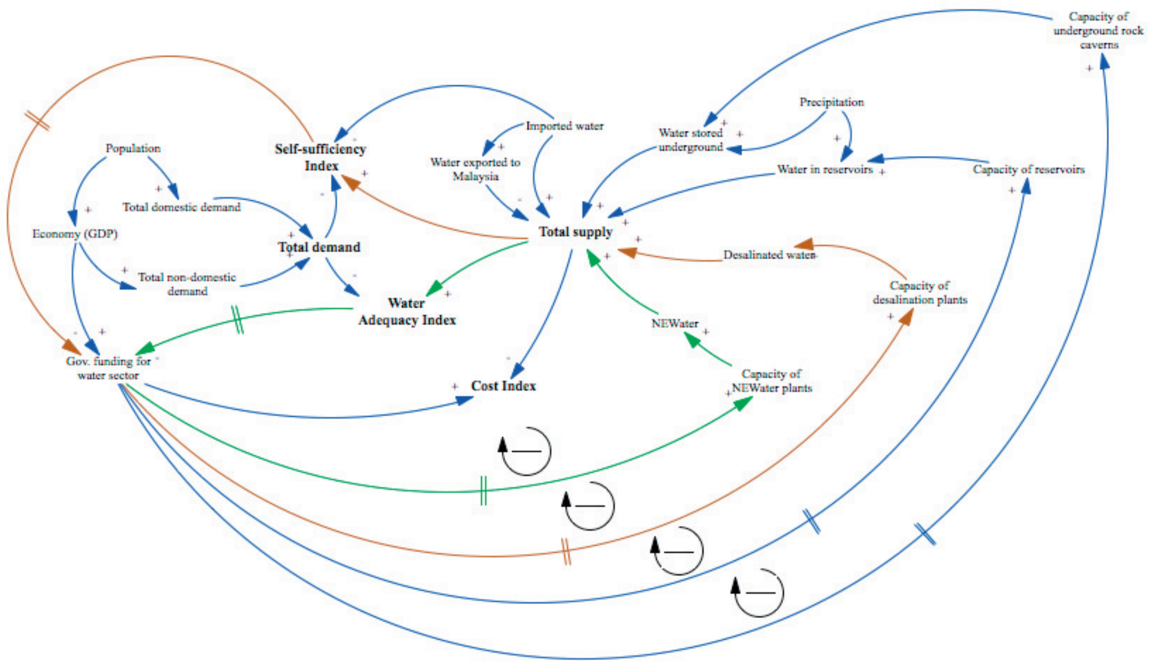

Fig. 1. Causal Loop Diagram (CLD) for *SingaporeWater*

We identified adequacy of water, self-sufficiency in water, and economic sustainability as the three most important aspects of sustainable water management in Singapore. They are quantified by Equations (1), (2), and (3). To have adequate water means that the total water supply must be equal or higher than the total water demand. The goal is to have Adequacy Index larger than one throughout the 21st century. Self-sufficiency Index shows how much water demand is actually met by Singapore's own water, excluding imported water from neighbouring countries. If it is equal or greater than one, then Singapore is considered to be self-sufficient in water. The Cost Index quantifies the extent of economic sustainability in water sector. It gives a sense of how much investments have gone into the water sector in order to have a particular level of water supply in Singapore. Generally, the higher the index, the less cost-effective the investment plans are. Note that the annual investments, from both private and public sectors, refer to the initial investments in building up the infrastructures. They do not include the yearly operational and maintenance costs of the Four National Taps.

$$\text{Adequacy Index}(t) = \frac{\text{Total Water Supply}(t)}{\text{Total Water Demand}(t)} \qquad (1)$$

$$\text{Self-sufficiency Index}(t) = \frac{\text{Total Water Supply}(t) - \text{Imported Water}(t)}{\text{Total Water Demand}(t)} \qquad (2)$$

$$\text{Cost Index}(t) = \frac{\text{Annual Investments}(t)}{\text{Total Water Supply}(t)} \qquad (3)$$

From the CLD in Fig. 1, we developed a Stock and Flow Diagram (SFD) for *SingaporeWater*. The key stocks and flows are shown in Fig. 2. This SFD also includes the proposed underground water storage system. The stored water could be pumped up when the need arises. After comparing the full SFD with PUB's system descriptions we conclude that the SD model indeed captures the key elements of Singapore's integrated water system.

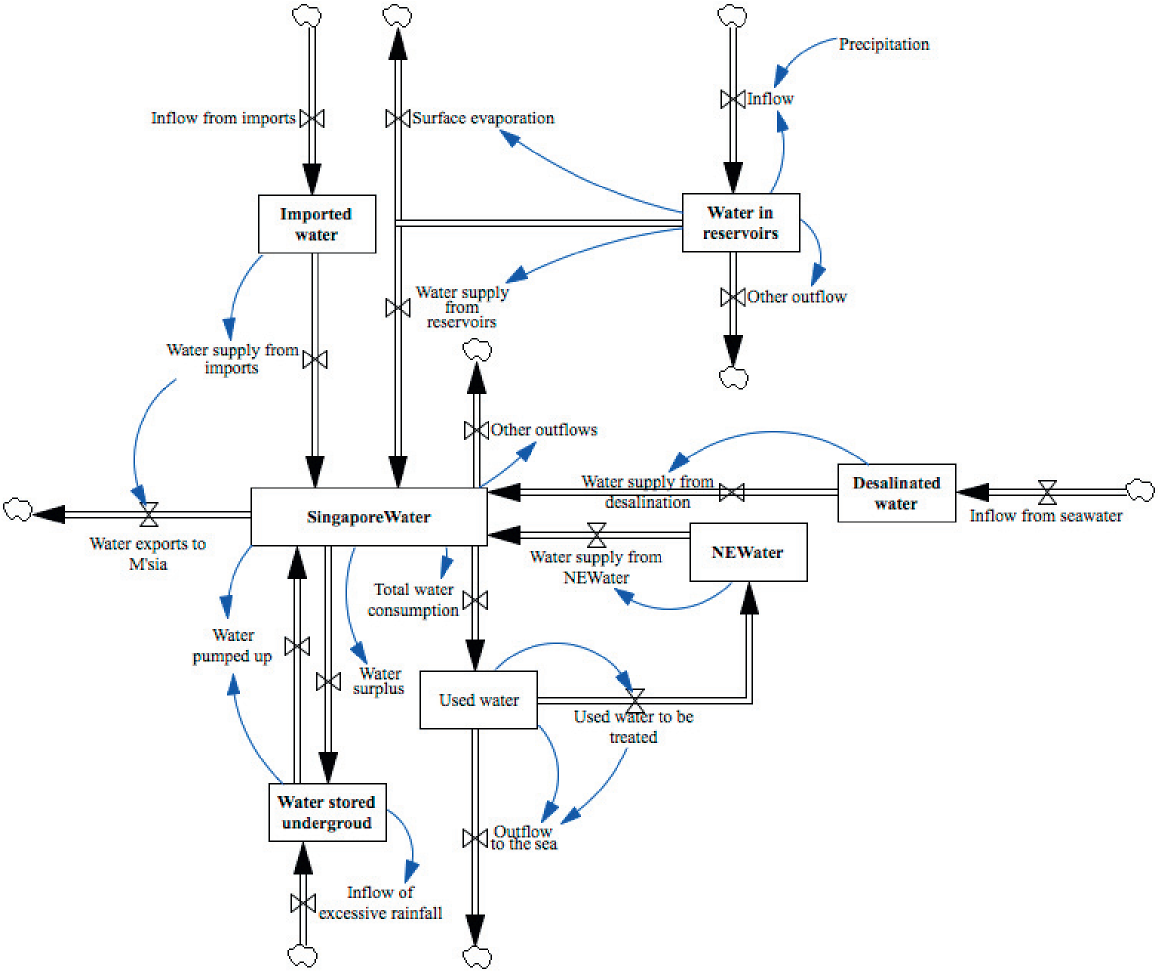

Fig. 2. Key stocks and flows in *SingaporeWater*

Most of the input data are obtained from various governmental agencies such as PUB, Ministry of Environment and Water Resources, Singapore Department of Statistics, and National Environment Agency. The costs of building underground rock caverns, water reclamation plants, and local water catchments are estimated from those of similar projects in Singapore.

Because of limited information and the inherent uncertainties, assumptions have to be made during model building. The first assumption is that both the private and public sectors will only start to invest in the water sector when there is inadequacy of water. This is reasonable because a high adequacy index does not justify the investments of limited resources into the water sector. Instead, the resources could be diverted to other sectors such as education, transportation, and healthcare where the need for investments might be more urgent. Secondly, it is assumed that there is a limit to reservoir expansions and underground rock caverns constructions. As Singapore's land space is limited, both could not expand infinitely. In this model, the limits of underground storage and surface reservoirs are set at 100 million cubic meters and 500 million cubic meters respectively.

2.2 Model calibration and validation

To increase confidence in *SingaporeWater* SD model, we performed model calibration and direct structural tests. Model calibration is the process of estimating the model parameters to obtain a match between observed and simulated behavior [23]. Direct structural tests assess the validity of the model structure, by directly comparing the simulated reference mode with knowledge about the real system [24]. We have also presented the preliminary results to co-workers in systems engineering. They helped to fine-tune the dynamics hypotheses made in the model.

Although most of the population data are made available by Singapore's Department of Statistics, the net immigration level is not publicly accessible. This is an important variable that significantly affects the future population level and, consequently, the future water demand. Its value is estimated through calibrating it with the total population level from 2000 to 2011. When the net immigration level is estimated to be 163,000 persons per year, the simulated population level matches the real data satisfactorily. Besides calibration, direct structural tests also help improve the validity of the model. Fig. 3 shows the reference mode of *SingaporeWater.* It captures the situation when the population increases at the same rate as that of the 2000s and when there are no future investments into the water sector.

On the demand side, as the population grows rapidly, both domestic and non-domestic demand for water increase significantly throughout the century, as shown in Fig. 3(a) and 3(b). Water supplies from the Four National Taps are shown in Fig. 3(c), 3(d), 3(e), and 3(f). Imported water decreases drastically in 2011 and in 2061 because of the expirations of two water agreements with Malaysia. Water supplies from local reservoirs are stable with natural variations due to fluctuations in the rainfall. Water supplies from desalination plants and NEWater plants increase as new plants start operation. However, in the 2030s and 2040s, as the existing plants close down after their useful lives, the supply of water from these two sources will drop to zero.

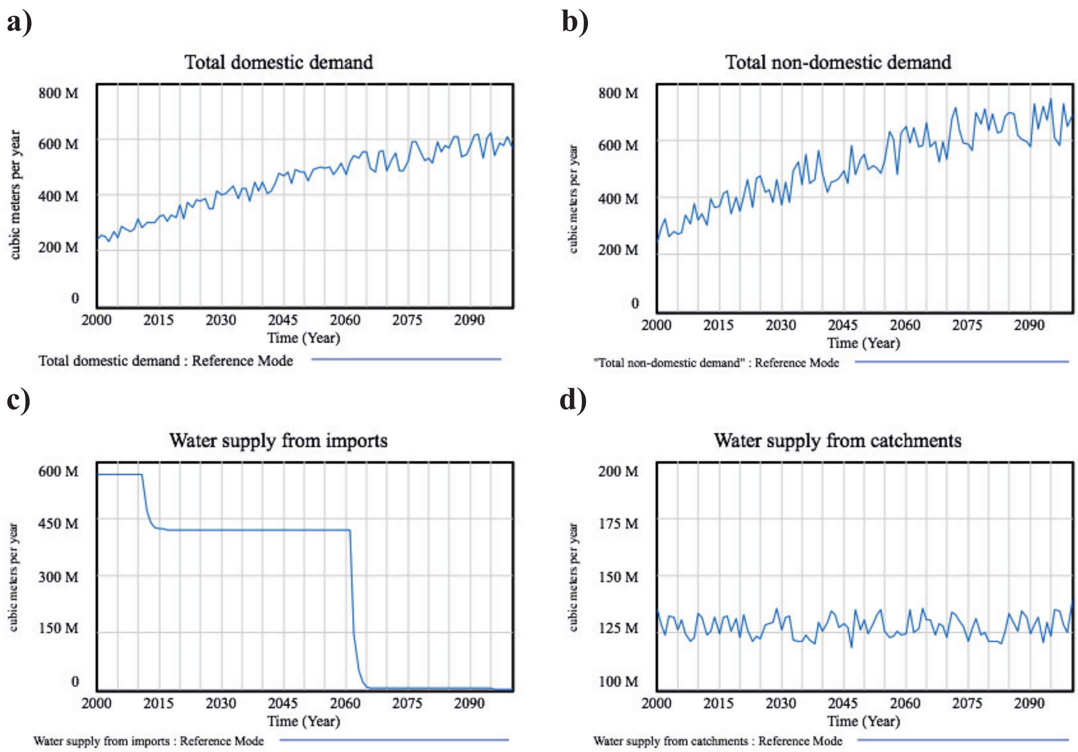

Fig. 3. The reference mode of *SingaporeWater* (continue on next page)

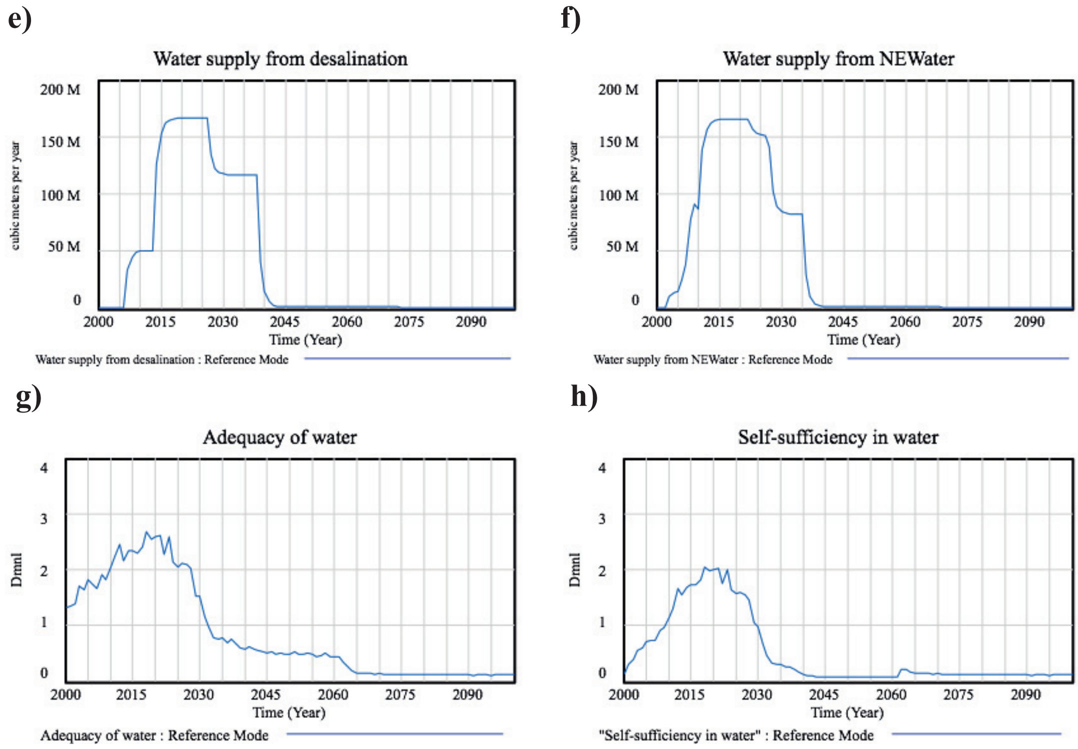

Fig. 3. The reference mode of *SingaporeWater* (continued)

Results and Discussions

If Singapore's population keeps increasing at the current pace it will grow from about 4 million in 2000 to more than 10 million in 2100. Because of the rapid population growth, the total water demand per year also increases steadily, reaching 1.3 billion cubic meters in 2100 (Fig. 3(a) and 3(b)). If Singapore decides not to invest in the water sector and keep the status quo, then it will suffer severe inadequacy of water from the early 2030s onwards (Fig. 3(g) and 3(h)).

If Singapore invests in underground water storage, due to shortage of water from the 2030s onwards, water underground will be pumped up continuously (Fig. 4(a)). However, it is insufficient to meet the increasing demand for water: adequacy and self-sufficiency indices (Fig. 4(b) and 4(c)) are both below 0.5 after 2060. As the initial costs of building underground rock caverns are significantly higher than other infrastructure projects, the Cost Index is consistently at a high level (Fig. 4(d)). The abrupt jump of the Cost Index in 2061 is due to the absence of imported water. This implies that, after 2061, the unit cost of water supply will increase significantly.

If the Republic invests in seawater desalination only after there is inadequacy of water, then the water supply from desalination (Fig. 5(a)) will be oscillating drastically. Due to the time delay associated with the constructions of new desalination plants, the adequacy and self-sufficiency indices (Fig. 5(b) and 5(c)) will follow a cyclic pattern: in each cycle, it falls below 1 for about five years before shooting up to almost 2 in the subsequent five years.

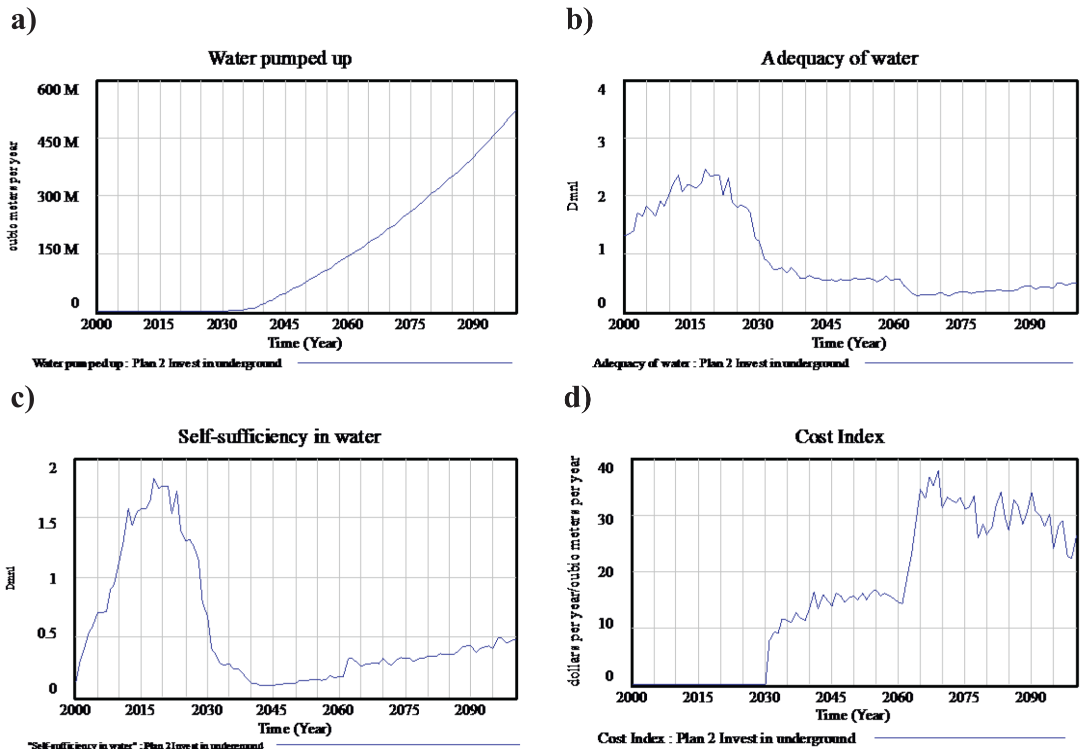

Fig. 4. Long-term impacts of investments in underground

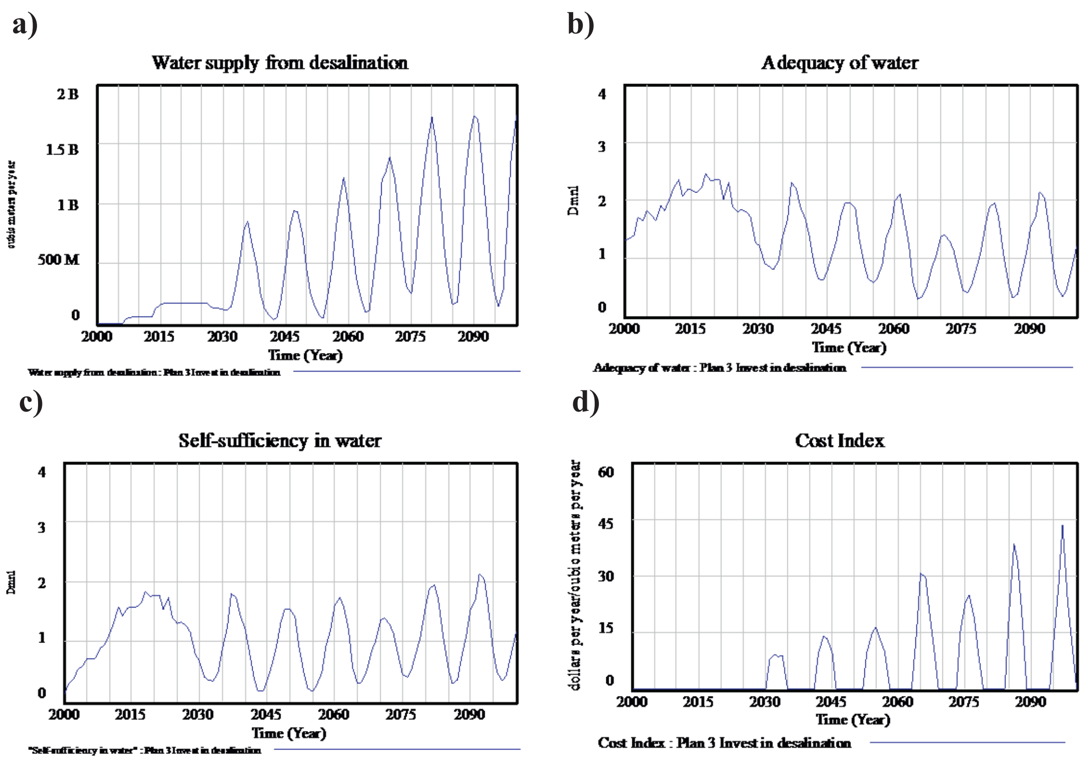

Fig. 5. Long-term impacts of investments in seawater desalination

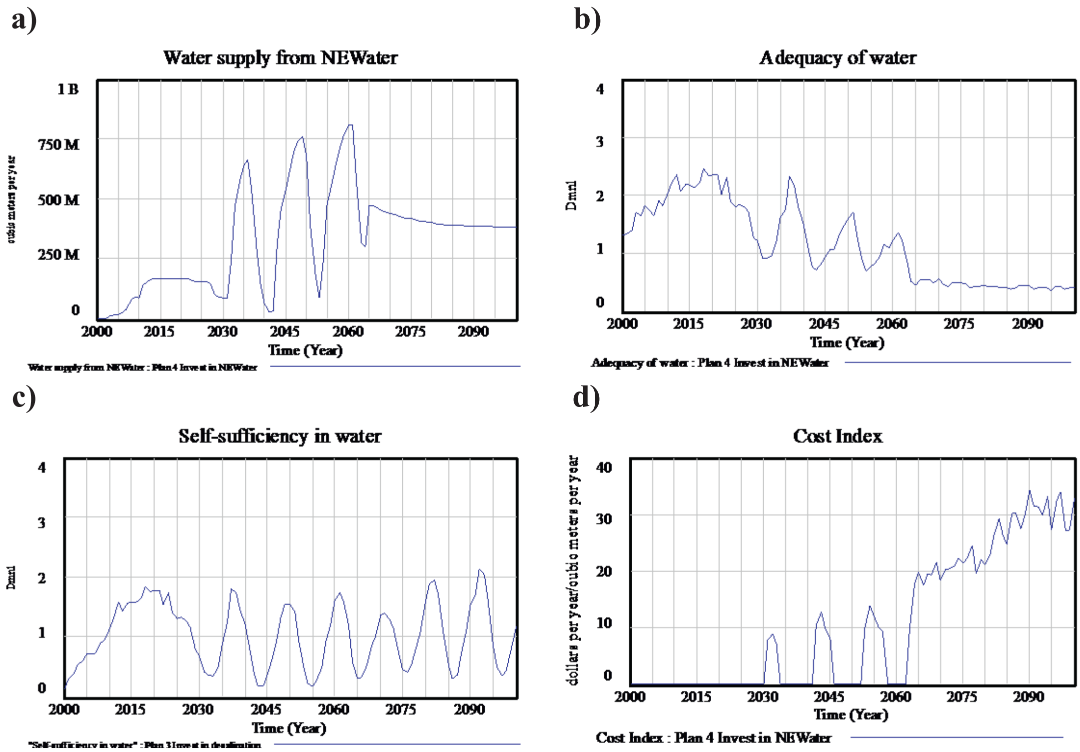

Fig. 6. Long-term impacts of investments in NEWater

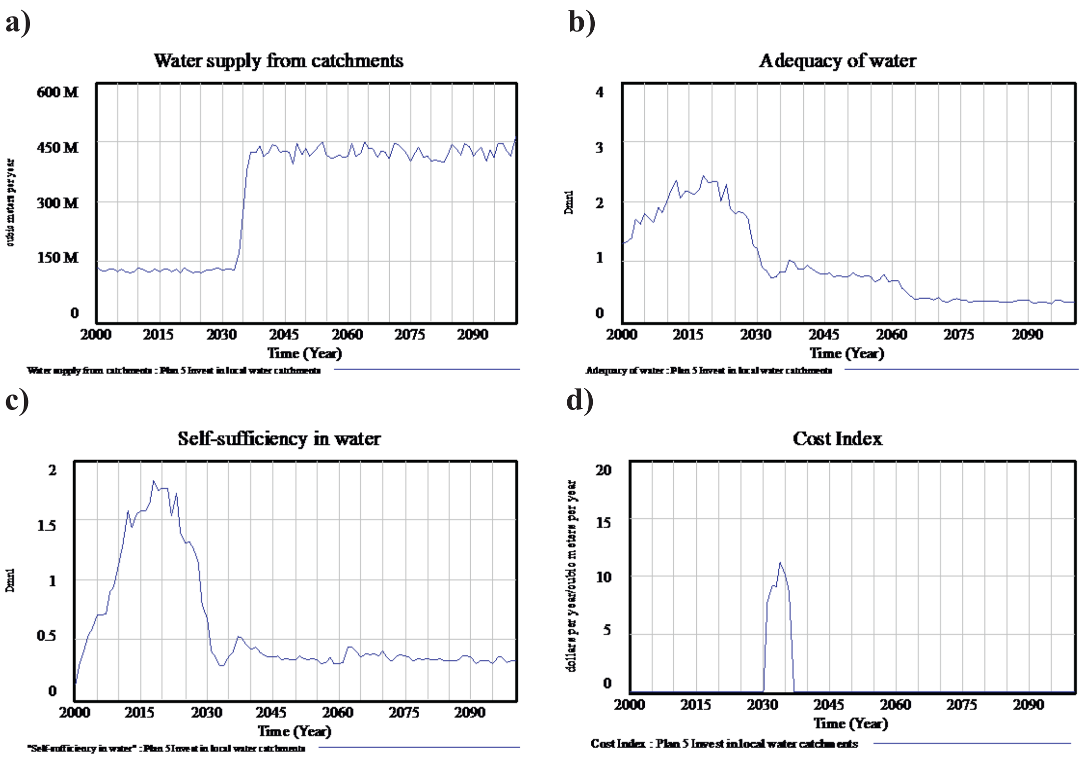

Fig. 7. Long-term impacts of investments in local water catchments

If Singapore invests in NEWater instead, then the water supply from NEWater (Fig. 6(a)) will also be oscillating from the 2030s to the 2060s. As water shortage grows more severe after 2061, the recyclable used water will also decrease sharply. Similar to the case of desalination, the adequacy and self-sufficiency indices follow a cyclic pattern, with about five years of water shortage followed by another five to six years of water abundance (Fig. 6(b) and 6(c)). As there is inadequacy of water after 2061, the model assumes that more investments will go to NEWater plants (Fig. 6(d)). However, as there is insufficient used water to be treated in the first place, the capacity expansions from the 2060s onwards could not lead to any increase in NEWater supplies (Fig. 6(a)).

If the city-state invests in local water catchments in early 2030s, in about six years' time, the limit of reservoir expansions will be reached (Fig. 7(a)). As the increase in water supply could not meet the rapid increase in water demand, both the adequacy and the self-sufficiency indices (Fig. 7(b) and 7(c)) are consistently below 1 after 2030. On the other hand, it is worth to note that investing in local catchments is least costly, compared to others (Fig. 7(d)).

Conclusion

This study has demonstrated that SD is a useful decision support tool for sustainable water resources management. The simulation results have given us new insights into Singapore's integrated water system. We discovered that investing in underground or local water catchments alone is not sufficient to help Singapore achieve adequacy and self-sufficiency in water. If Singapore starts to invest in desalination or NEWater only after there is inadequacy of water, then it will result in about five years of water shortage followed by another five to six years of water abundance. The cyclic patterns are mainly due to the construction time of desalination or NEWater plants. These results highlight the need to plan and build water infrastructures well in advance in order to meet Singapore's future water demand.

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