A Novel Integrated Decision Support Tool for Sustainable Water Resources Management in Singapore: Synergies Between System Dynamics and Analytic Hierarchy Process

Xi Xi · Kim Leng Poh

Abstract In order to alleviate the risks of urban flooding and diversify Singapore's sources of water supply, an innovative idea of underground reservoirs was proposed. This infrastructure could have significant long-term impacts on the water resources system in Singapore. In addition, among various alternatives to augment water supply, decision makers need to know which ones are the more sustainable plans to pursue. This research proposes a novel integrated decision support tool that synergizes System Dynamics (SD) and a multi-criteria decision-making method called Analytic Hierarchy Process (AHP). First, a SD model takes in real-world data and simulates the consequences of different alternative plans under various scenarios of future population growth. Second, AHP is applied to compare different alternatives based on their performance as revealed by the SD simulation and the judgment of decision makers. Through the SD modeling we found that the proposed underground water storage system is not going to have a profound impact on Singapore's adequacy and self-sufficiency in water, mainly because of its limited capacity and long construction time. Decision analysis through AHP reveals that if the population increases rapidly or mildly, then the order of priorities are: 1) seawater desalination; 2) NEWater (brand name for reclaimed water); 3) local water catchments; 4) underground water storage; 5) status quo. This novel integrated decision support tool, together with real-world data, could be applied to many other similar situations around the world in which policy makers need to make critical decisions with significant long-term implications, both in water systems and beyond.

X. Xi (✉) · K. L. Poh
Department of Industrial and Systems Engineering, National University of Singapore, 10 Kent Ridge Crescent, 119260 Singapore, Singapore
e-mail: shine.xixi@yahoo.com.sg

K. L. Poh
e-mail: pohkimleng@nus.edu.sg

Present Address:
K. L. Poh
Environmental Sciences and Engineering, California Institute of Technology, 1200 E. California Boulevard, 91125 Pasadena, CA, USA

1 Introduction

The growing scarcity of quality water is a global concern in the 21st century (Simonovic 2002b). On the demand side, rapid population growth and economic development will lead to even higher demand for fresh and clean water (Amarasinghe and Smakhtin 2014; Padowski and Gorelick 2014). On the supply side, climate change has caused the rainfall to be less predictable and natural sources of water less reliable (Piao et al. 2010; Hall et al. 2014). 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 resources management, in alignment with the United Nations' broader definition of sustainability (World Commission on Environment and Development 1987).

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 context. With limited land area and water resources, the Republic has been purchasing water from Malaysia under two water agreements (Public Utilities Board (PUB) 2011a). This dependency on imported water is widely perceived to be a threat to Singapore's sovereignty and well-being (Chia and Pin 2008).

Furthermore, as extreme storms become more intense and frequent, several incidents of urban floods have occurred in the country's premier residential and business districts (AsiaOne 2011; Channel NewsAsia 2011; Lur 2011; PUB 2013). In order to alleviate the risks of flooding and diversify water supplies, Singapore's former Chief Defense Scientist, Professor Lui Pao Chuen, proposed an underground water storage system in 2012. This large-scale infrastructure allows extra rainwater to be stored in underground rock caverns and be pumped up in times of water stress (Chua 2012). As there are already similar rock cavern projects completed in Singapore and Japan (Nordmark 2002; Parker 2004; Tezuba and Seoka 2003), building more rock caverns for the dual-purpose of storm-water storage and water supply augmentation seems to be a technically feasible project. 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 need to know which ones are the more sustainable plans to pursue.

To facilitate holistic, long-term planning and decision-making, this paper proposes a novel integrated decision support tool that synergizes System Dynamics (SD) and a multi-criteria decision-making method called Analytic Hierarchy Process (AHP). It also demonstrates the usefulness of this innovative approach in helping to achieve sustainable water resources management in Singapore. Section 2 shows the synergies between SD and AHP and how these two methods complement each other to provide new insights. Section 3 presents the SD simulation results and discusses the priorities of five alternative development plans, as revealed by AHP. Section 4 summarizes main research contributions of this study.

2 A Novel Integrated Decision Support Tool

Figure 1 shows a schematic overview of a novel integrated SD-AHP decision support tool. First, a SD model takes in real-world datasets and simulates the consequences of alternative development plans under various population scenarios. Second, AHP is applied to compare

different alternatives based on their performance as revealed by the SD simulation and the judgment of decision makers. This approach enables synergies between SD and AHP and helps to reach more informed decisions.

2.1 *SingaporeWater* System Dynamics Model

2.1.1 Justification for the Application of SD

System Dynamics (SD) is an approach to understand the behavior of complex systems over time and to capture internal feedback loops and time delays that affect the behavior of the entire system. This method has been widely used in water resources planning and management (Winz et al. 2009 and references therein). For example, SD has been used to study water resources in Canada (Simonovic 2002a, b; Simonovic and Rajasekaram 2004; Ahmad and Simonovic 2006), in China (Dai et al. 1992; Xu et al. 2002; Yang et al. 2014), in Spain (Fernandez and Selma 2003), and in Iran (Madani and Mariño 2009; Ghashghaei et al. 2013; Ghashghaie et al. 2014). Its capabilities to quantitatively simulate the dynamic consequences of various policies make it an ideal decision support tool for strategic policy testing and selection. Here we use SD to study the long-term demand and supply of water in Singapore and to explore alternative pathways to achieve sustainable water resources management.

2.1.2 Model Formulation and Development

Figure 2 illustrates the key components in Singapore's water sector. The city-state has invested heavily in desalination, wastewater reclamation (branded as NEWater), water catchment management and other similar projects (PUB 2005, 2010a, b, 2011c, 2012a, b). The Public Utilities Board, Singapore's 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
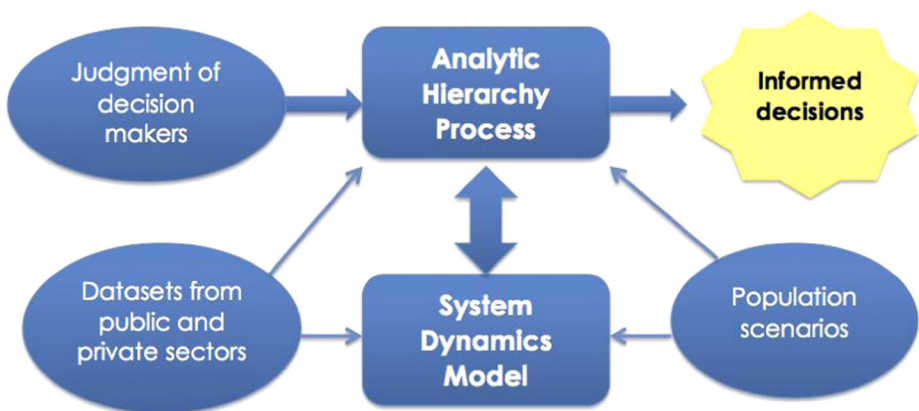

Fig. 1 Schematic overview of a novel integrated SD-AHP decision support tool that helps decision makers to reach more informed decisions

water (PUB 2011b). The concerted efforts to close this loop demonstrate the country's sheer determination to maximize the use of all the water resources available.

Based on a basic demand and supply framework, we developed a system dynamics model called *SingaporeWater*. It runs from year 2000 to 2100, so as to reveal the long-term impacts of proposed plans. This is necessary because Singapore's second water agreement with Malaysia will expire in 2061 (PUB 2011a) and the proposed hydrological infrastructures, such as underground reservoirs and water treatment plants, have long useful lives. On the demand side, population level and economic growth determine the total demand for water. On the supply side, the Four National Taps—local catchment water, imported water, NEWater, and desalinated water—provide water for both domestic and non-domestic consumptions.

A Causal Loop Diagram in Fig. 3(a) captures these key factors. The polarity of the link (+/-) indicates the change in one variable induced by a cause. A positive sign indicates that the two variables change in the same direction: an increase/decrease in one variable induces an increase/decrease in another variable. Conversely, a negative sign indicates change in the opposite direction. For example, an increase in total domestic demand will induce an increase in total demand, if other variables are kept constant. The ‖ sign indicates a time delay. For instance, when government funding for the water sector increases, it will take a few years to build seawater desalination plants. Thus, the positive link between government funding and the capacity of desalination plants has a known time delay.

We identified adequacy of water, self-sufficiency in water, and economic sustainability as the three most important aspects of sustainable water resources management in Singapore. They are quantified by three key indices (Eqs. 1 to 3). To have adequate water means that the total water supply must be higher than or equal to 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 met by
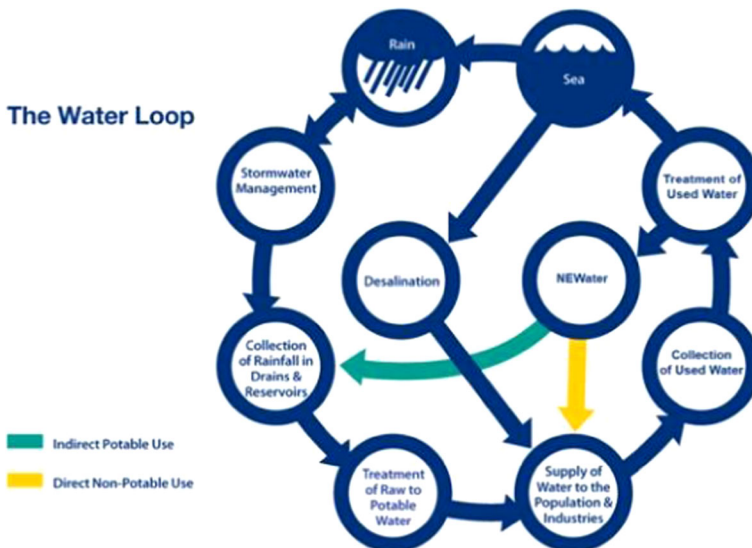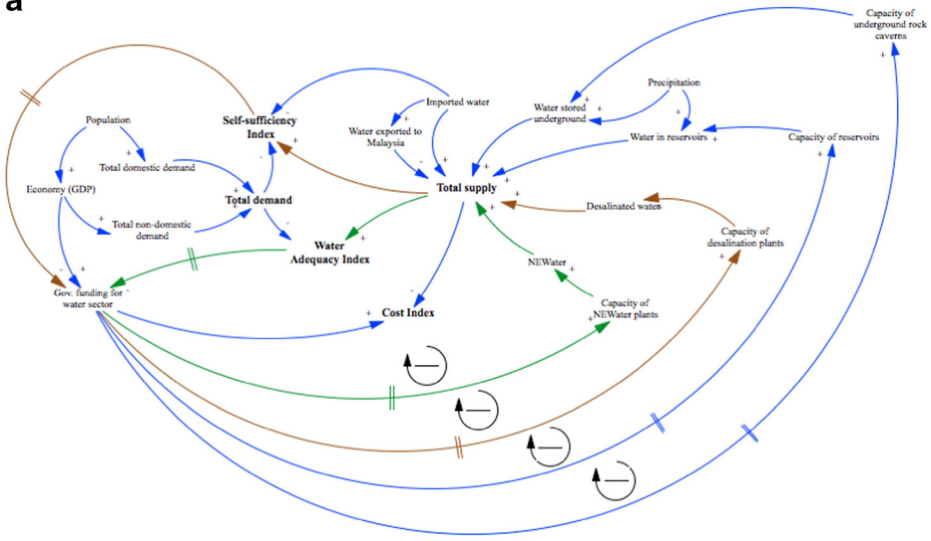

Fig. 2 Singapore's closed water loop managed by Public Utilities Board (PUB)
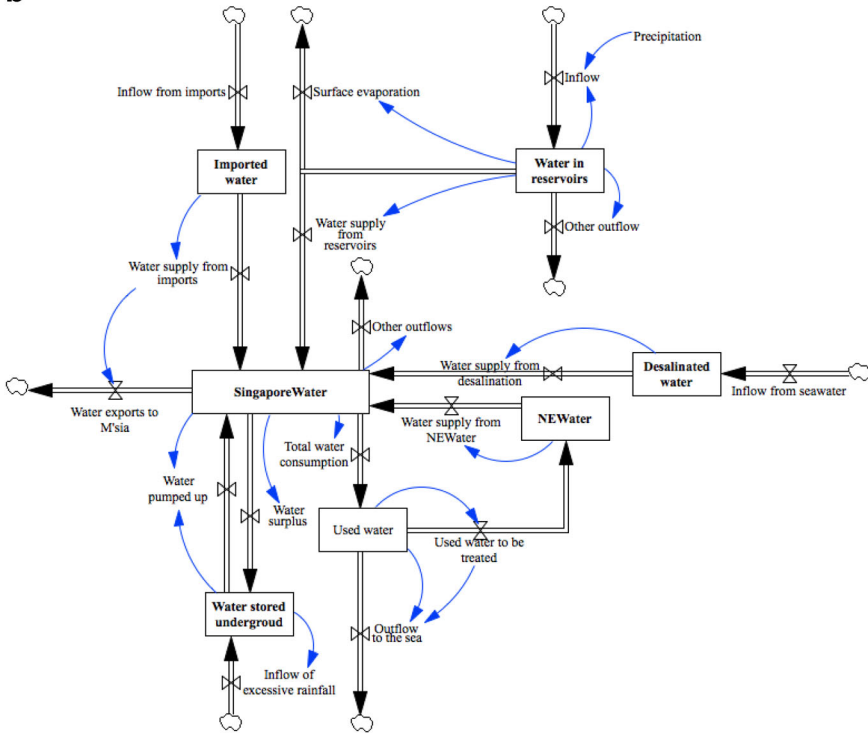
a

b

Fig. 3 **a** Causal Loop Diagram capturing key demand and supply factors in Singapore's water sector. The *black round arrows* with negative signs in the centre indicate negative feedback loops that tend to promote a settling to equilibrium and dampen the effects of perturbations. Two negative feedback loops are highlighted in *brown* and *green*. **b** Key stocks and flows in *SingaporeWater* system dynamics model. The stocks are shown in the *rectangles* and the flows are shown in the *black arrows*. Sources of water supply are highlighted in *bold*

Singapore's own water, excluding imported water. It should be greater than or equal to one in order to reach self-sufficiency in water. Economic sustainability in the water sector is captured by the cost index. It gives a sense of how much investments have been used to sustain a particular level of water supply. Generally, the higher the cost index, the less cost-effective the development plans are.

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

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

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

Figure 3(b) shows the key stocks and flows in the model, including the proposed underground reservoir. It is assumed that excessive rainfall and water surplus will flow into the underground rock caverns. The stored water could then be pumped up whenever the need arises. Fig. S1 in Supplementary Materials shows the complete stock and flow diagram. Comparing the diagram and the system description by PUB leads to the conclusion that the SD model does capture the key components of Singapore's integrated water resources system.

Most of the input data are obtained from open sources published by 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 reservoirs, NEWater plants, and local water catchments are estimated from those of similar projects in Singapore. Key information about these water-related projects are tabulated in Table S1. All model input data, formulae, and detailed explanations are provided in Supplementary Materials. 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. A further simplification is that all the estimated costs in this study are in current dollars.

2.1.3 Assumptions in SingaporeWater

Because of limited information and the inherent uncertainties in almost all real-world systems, 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 in which the need for investments might be more urgent.

Secondly, it is assumed that there is a limit to reservoir expansions and the constructions of underground rock caverns. As Singapore's land area is limited, both reservoirs and underground rock caverns could not expand infinitely. In this model, the limits of underground storage and surface reservoirs are set at 100 and 500 million m^3 respectively. These conservative estimates could be updated when more information are available.

Thirdly, water supply from all Four National Taps is assumed to be of superb quality. This means that every drop of water meets the quality standard for drinking water. Although NEWater is mainly for industrial uses, it could also be used as portable drinking water (PUB 2012b). Therefore, the SD model did not distinguish water supply for industrial or domestic consumptions.

Fourthly, the per capita water demand is assumed to be constant throughout the 21st century. When there is a better way to model per capita water demand in Singapore, it could be easily implemented in the model.

2.1.4 Model Calibration and Validation

To increase confidence in *SingaporeWater*, we performed model calibration, direct structural tests, and sensitivity analysis. Model calibration is the process of estimating the model parameters to obtain a match between observed and simulated behavior (Oliva 2003). Direct structural tests assess the validity of the model structure, by directly comparing the simulated reference mode with knowledge about the real system. Sensitivity analyses of some uncertain parameters are "strong" behavior tests that can help uncover potential structural flaws (Barlas 1996).

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. As shown in Fig. S2, the simulated population level matches the real data satisfactorily when the net immigration level is estimated at 163,000 persons per year.

Besides calibration, direct structural tests also help to improve the validity of the model. Figure 4(a) shows the demand forecasts in *SingaporeWater*. It captures the situation in which the population level grows at the same rate as that of the 2000s. On the demand side, as the population grows rapidly, both domestic and non-domestic demands for water increase significantly throughout the century. Figure 4(b) shows the water supplies from the Four National Taps. Imported water decreases drastically in 2011 and in 2061 because of the expirations of two water agreements with Malaysia. Water from local reservoirs is stable with natural variations due to fluctuations in rainfalls. Water supplies from desalination plants and NEWater plants increase as new plants start operation. However, as the existing plants close down after their useful life, the supply of water from these two National Taps drops to zero from the 2030s onwards.

Because of the availability of imported water and the addition of desalinated water and NEWater, Singapore will continue to enjoy high adequacy of water until early 2030s (Fig. 4(c)). The model demonstrates that Singapore has achieved full self-sufficiency in water in 2010 and will continue to be self-sufficient till 2030. This is cross-validated with Dr. Lee Poh Onn's research results, which concluded that Singapore should no longer be in a "water scarce" condition by 2011 (Lee 2010). As there are no future investments in the reference mode, the cost index, not featured here, is consistently zero.

However, due to the termination of imported water and closing down of existing water plants, the adequacy of water and self-sufficiency in water drop drastically from the 2030s onwards (Fig. 4(c)). The results of these structural tests are consistent with the situations in the real system and research results of other studies. Thus, it could be concluded that the SD model is structurally valid.

Stronger than the direct structural tests are the structure-oriented behavior tests, such as sensitivity analysis. It asks if the real system would exhibit high sensitivity to one particular
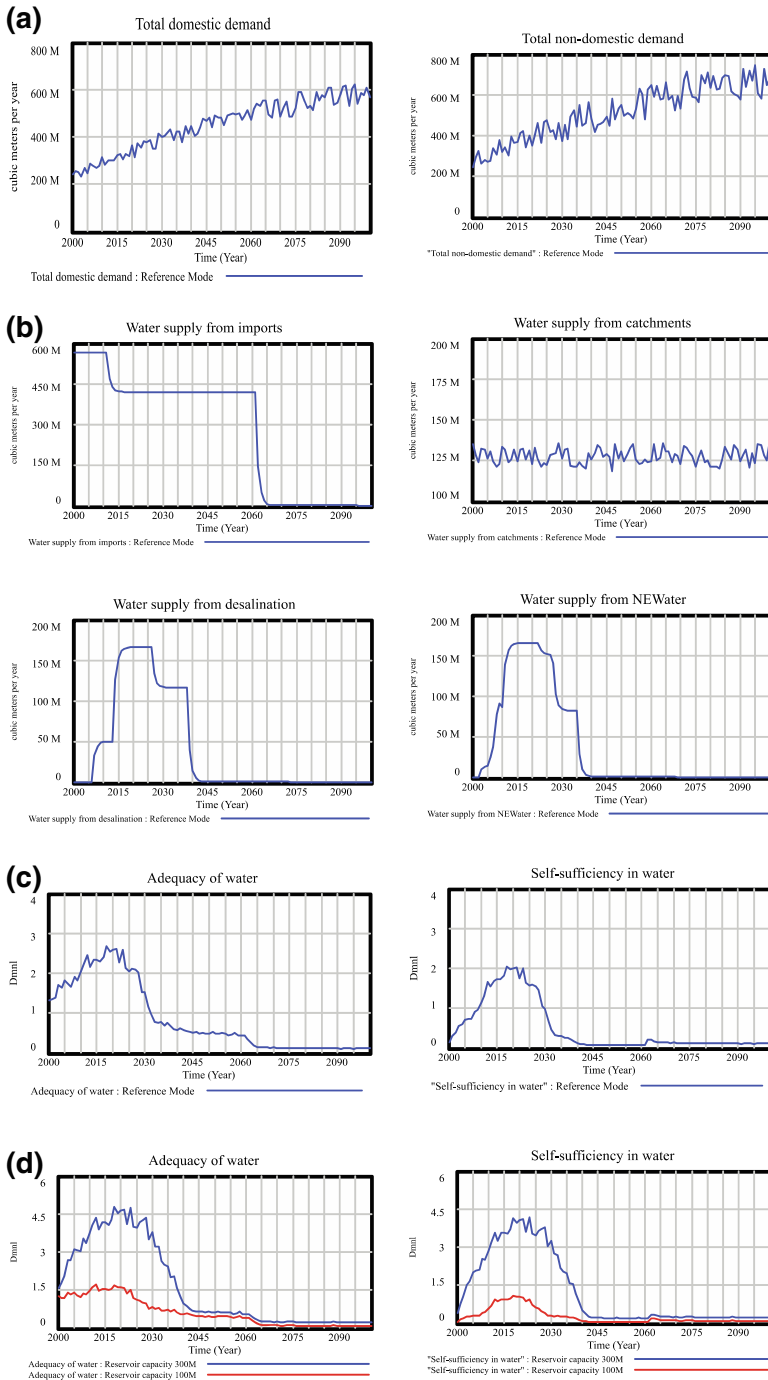
Fig. 4 **a** Demand forecasts in *SingaporeWater*. **b** Four National Taps captured in *SingaporeWater*. **c** System responses in the reference mode of *SingaporeWater*. **d** System responses with different total reservoir capacity. On the y-axis, M stands for Million and Dmnl stands for dimensionless

parameter with uncertain values (Barlas 1996). One such parameter in *SingaporeWater* is the total capacity of the surface reservoirs. We conducted sensitivity analysis of the reservoir capacity.

Figure 4(d) shows the system responses when the total reservoir capacity is estimated at 100 million m^3 (red lines) and 300 million m^3 (blue lines). The general patterns of the adequacy index and self-sufficiency index are similar in both cases. They both increase to a peak in 2020 before dropping to below 1 from 2030 onwards. Seasoned researchers know that "a well-structured model will generate the same general pattern despite the great uncertainty in parameter values" (Ford 1999). Therefore, this is demonstrated that the dynamic hypotheses in *SingaporeWater* are valid.

Furthermore, when the total capacity is set at 300 million m^3, the adequacy index and self-sufficiency index are both unrealistically high (Fig. 4(d)). This implies that a lower estimate at around 100 to 200 million m^3 seems to be more realistic. Based on this observation, the final reservoir capacity is estimated at 150 million m^3.

In a nutshell, the results of the validation process have established a high model confidence. Driven by credible real-world data, the SD model captures the essence of Singapore's water system. It can then be used to test various development plans.

2.2 Analytic Hierarchy Process for Decision Support

As Singapore strives for high adequacy of water and full self-sufficiency in water, it is also concerned about economic sustainability in the water sector. For example, although seawater desalination seems to be promising, at the current level of technology, it is still energy-intensive and costly (Elimelech and Phillip 2011). Thus, there is an apparent trade-off among these three key aspects of sustainable water management. This calls for multi-criteria decision-making (MCDM) tools, such as AHP, to help solve this complex problem with multiple conflicting and subjective criteria. The following sections briefly explain the rationale of applying AHP, how it works, and the basic structure of the decision hierarchy used in this study.

2.2.1 Justification of the Application of AHP

The strength of AHP lies in its ability to structure a complex, and multi-attribute problem hierarchically, and then to investigate each level of the hierarchy separately. Incorporating both qualitative and quantitative information, AHP educes a relative ordering of immeasurable subjective preferences by pair-wise comparison. Compared to other MCDM methods, AHP generates a *ranking* of all alternatives, instead of the most favorable alternative. In this way, it provides more information to the decision-makers rather than simply reporting the "best" alternative (Liu 2004).

Although AHP has been criticized for the possibility of rank reversal, it is still a useful and powerful tool because of its simplicity and its ability to translate subjective judgements into quantitative ratios (Stewart 1992). The user-friendly supporting software, Expert Choice, has certainly contributed to the widespread use of the method. AHP has been successfully applied in strategic water resources planning and management (e.g., Wang 2008; Young et al. 2009; Ennaouri and Fuamba 2011; Han et al. 2012; Chowdary et al. 2013; Srdjevic and Srdjevic 2014).

2.2.2 AHP Explained

AHP provides a comprehensive framework to structure a decision problem, represent and quantify decision criteria, relate these criteria to overall goals, and then evaluate alternative

plans through pair-wise comparisons. The application of AHP mainly consists of four steps: 1) set up a decision hierarchy by breaking down the decision problem into goal, criteria, sub-criteria, and decision alternatives; 2) collect input data for pair-wise comparisons of the decision elements; 3) use the eigenvalue method to estimate the relative weights of the decision elements, and determine the consistency of the judgements; 4) aggregate the relative weights of the decision elements to rank the decision alternatives (Liu 2004). For more details about the method, please refer to Saaty (1990).

2.2.3 Basic Structure of the Decision Hierarchy

Although defining and measuring sustainability is a major challenge, water resources managers should still try to identify and quantity the multiple facets of sustainability (Loucks 2000; Harmancioglu et al. 2012). This section presents the basic decision hierarchy with the overall goal of achieving sustainability in water resources manage-ment. As shown in Fig. 5, the three key criteria for sustainability in Singapore's case are defined as adequacy of water, self-sufficiency in water, and cost. The third level in the hierarchy consists of the five long-term development plans the public and private sectors could choose to pursue. Plan 1 is not to invest in the water sector so as to keep the status quo. The other four plans are about investing 0.5% to 1% of the nation's Gross Domestic Product solely into one of the four development plans.

2.3 Two-Attribute Trade-Off Analysis

The basic decision hierarchy in Fig. 5 has included the cost factor into decision analysis, thus pre-committing the cost constraint into the process of decision-making. However, sometimes decision makers might want to see how the system could perform with respect to the cost factor. Another way to analyze the situation is to isolate the cost factor from other factors and then conduct a two-attribute trade-off analysis between cost and another critical decision criterion.

To better visualize the trade-off between two decision criteria, we conducted a simple two-attribute trade-off analysis by plotting the average self-sufficiency index against the average cost index. This trade-off analysis aims to complement the AHP analysis and offers an
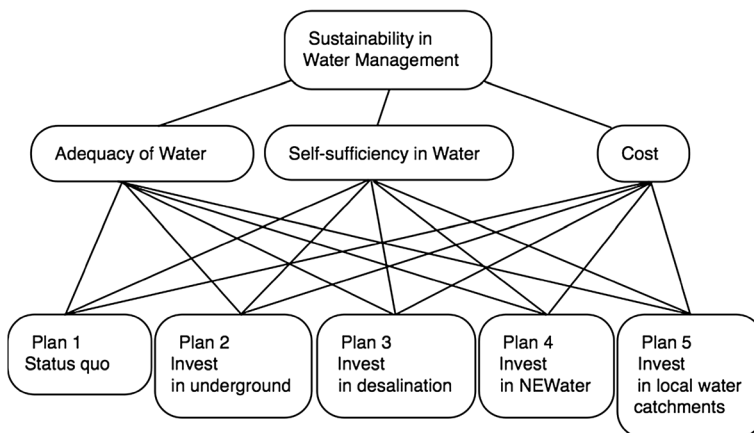

Fig. 5 Basic decision hierarchy for sustainable water resources management in Singapore

alternative way to visualize the trade-offs that might not be clearly noticeable in the AHP results.

3 Results and Discussions

This section presents the simulation results from *SingaporeWater* SD model and the priorities of the five plans under three population scenarios as listed below.

Scenario 1:   Singapore's population continues to grow rapidly at the same rate as that of the 2000s.

Scenario 2:   The population grows gradually from five million to six million people over the 21st century.

Scenario 3:   The population shrinks steadily with no intake of immigrants and the current level of birth rate and death rate.

3.1 SD Simulation Results from *SingaporeWater*

3.1.1 Simulation Results Under Scenario 1

In Scenario 1 Singapore's population keeps increasing at the rate of the 2000s. Figure 6(ai) shows that the population grows from about 4 million in 2000 to about 10 million in 2100. Because of the rapid population growth, the total demand for water also increases steadily, reaching 1.3 billion m^3 per year in 2100. If Singapore adopts Plan 1, which is 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, as shown in the reference mode in Fig. 4(c).

If Singapore invests in underground water storage, due to shortage of water from the 2030s onwards, water stored underground will be pumped up continuously (Fig. 6(aii)). However, it is insufficient to meet the increasing demand for water: adequacy and self-sufficiency indices 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. 6(aii)).

If the Republic invests in seawater desalination as and when there is inadequacy of water, then the water supply from desalination (Fig. 6(aiii)) will be oscillating drastically. Due to the time delay associated with the constructions of new desalination plants, the adequacy and self-sufficiency indices will follow a cyclic pattern: in each cycle, it falls below 1 for about 5 years before shooting up to almost 2 in the subsequent 5 years (Fig. 6(aiii)).

If Singapore invests in NEWater instead, then the water supply from NEWater (Fig. 6(aiv)) will also be oscillating from the 2030s to the 2060s. As the shortage of water 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 5 years of water shortage followed by another 5 years of water abundance (Fig. 6(aiv)).

If the city-state invests in local water catchments in early 2030s, in about 6 years' time, the limit of reservoir expansions will be reached. This means that, even if there are more investments into it, the water supply from catchments will always stay constant (Fig. 6(av)). As the increase in water supply could not meet the rapid increase in water demand, both adequacy and self-sufficiency indices are consistently below 1 after 2030. The merit of this plan is that it is least costly among all the investment plans (Fig. 6(av)).

Fig. 6 (*ai*) Growth of population and water demand under Scenario 1. (*aii*) Long-term impacts of investments in underground under Scenario 1. (*aiii*) Long-term impacts of investments in seawater desalination under Scenario 1. (*aiv*) Long-term impacts of investments in NEWater under Scenario 1. (*av*) Long-term impacts of Investments in local water catchments under Scenario 1. On the y-axis, M and B stands for Million and Billion respectively. (**b**) same as (**a**), but for Scenario 2. (**c**) same as (**a**), but for Scenario 3
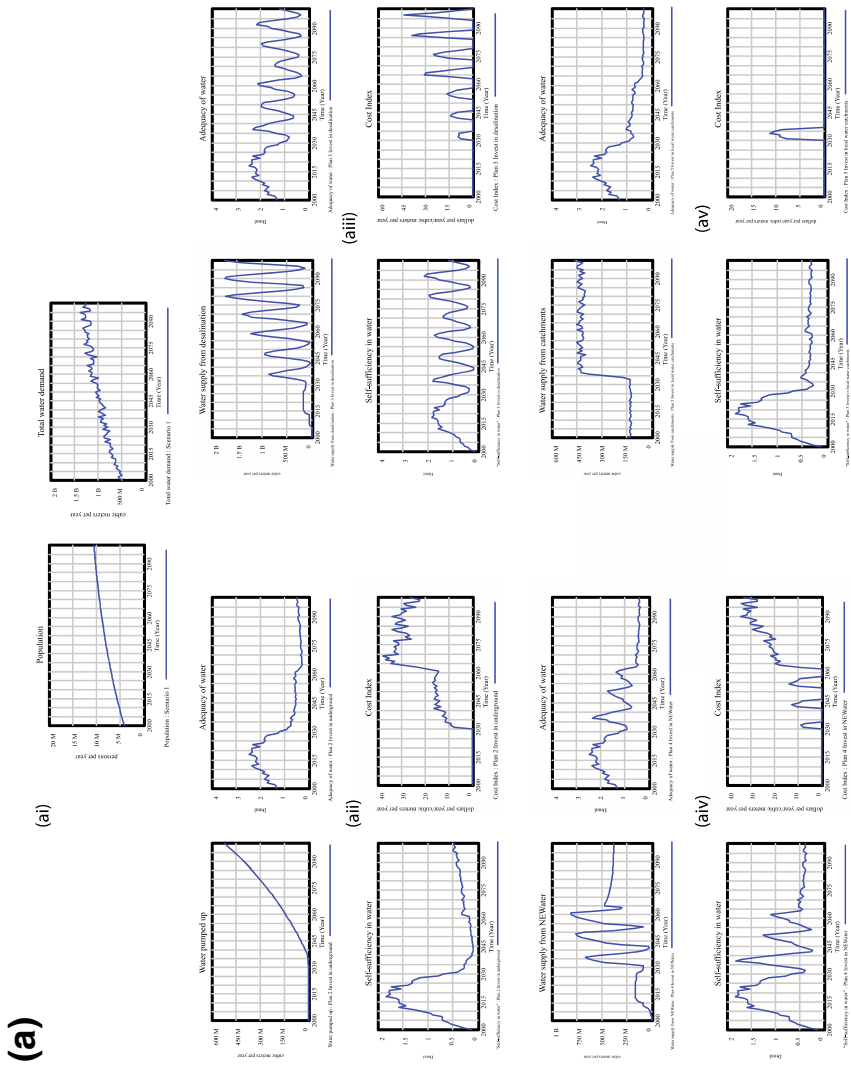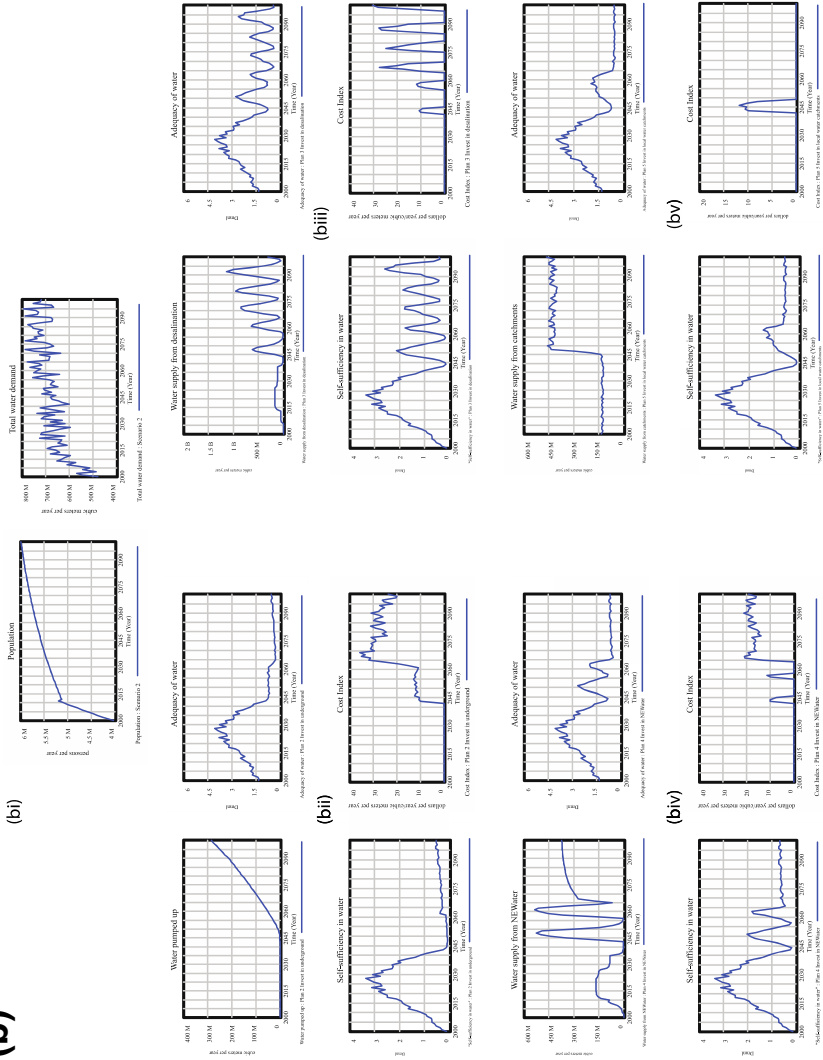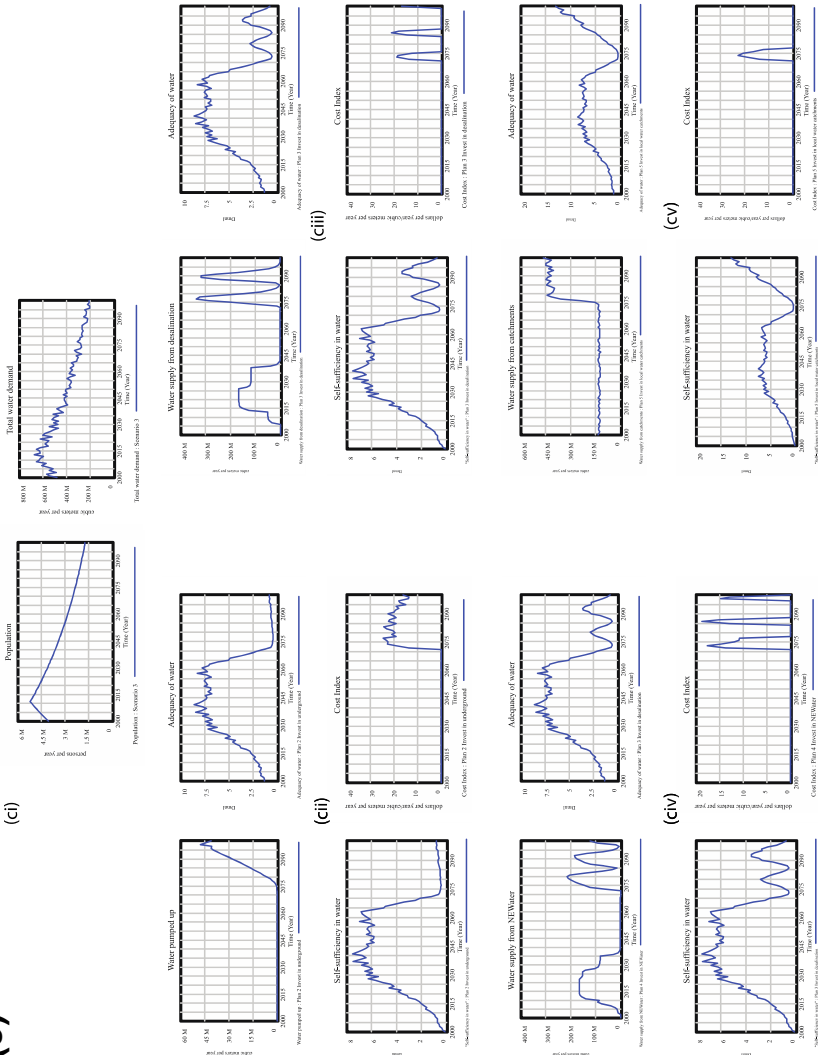
Fig. 6 (continued)

Fig. 6 (continued)

In conclusion, if the population continues to grow rapidly, then investing in underground or local water catchments is not sufficient to help Singapore achieve adequacy and self-sufficiency in water. Under the assumption that investments will only come to the water sector when there is inadequacy of water, investing in desalination or NEWater would result in about 5 years of water shortage followed by another 5 to 6 years of water abundance. The cyclic patterns are mainly due to the construction time of desalination or NEWater plants.

3.1.2 Simulation Results Under Scenario 2

In Scenario 2 Singapore's population increases gradually from about 4 million in 2000 to 6 million in 2100 (Fig. 6(bi)). This is simulated in model by setting the net immigration level at 80,000 per year from 2012 onwards. The total demand for water increases from about 500 million m^3 in 2000 to about 750 million m^3 in 2100. Because of the milder demand compared to that in Scenario 1, the adequacy index peaks at about 4 in late 2020s, meaning that the supply of water is four times more than the demand of water (Fig. 6(bii)). In this case, Singapore enjoys high adequacy in water and full self-sufficiency of water from 2010 to 2040 (Fig. 6(bii)). Shortage of water will only set in after 2040, 10 years later than that of Scenario 1.

If Singapore invests in underground water storage from 2040 onwards, then it needs to continuously pump up water. The water supply from this source reaches about 280 million m^3 in 2100 (Fig. 6(bii)). Similar to Scenario 1, underground water alone is not sufficient to meet Singapore's increasing water demand. The adequacy and self-sufficiency indices stagnate at about 0.5 to 0.8 after 2040. 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 country invests in seawater desalination, then the annual supply from this National Tap could reach more than one billion m^3 in the 2090s (Fig. 6(biii)). The long-term impacts will be similar to those in Scenario 1: Singapore will experience water shortage for about 5 years before enjoying high water abundance for another 5 to 6 years. As we assume that investments will only come to the water sector when there is inadequacy of water, the cost index has periodic peaks. The four peaks after 2040 are much higher than others, implying that the unit cost of water supply is more expensive after the supply from imported water stops.

The system responses are rather different when investments go to NEWater. From 2040 to 2060, the supply from NEWater follows a cyclic pattern, reaching about 500 million m^3 per year in later 2040s and early 2060s (Fig. 6(biv)). After 2061, because of the water shortage, investments keep coming into NEWater, as shown by the steady cost index in the later part of this century. This results in a steady increase in water supply in the same period. However, the total water supply is still not sufficient to meet the total demand: after 2061, adequacy and self-sufficiency indices are both at around 0.7 to 0.8 (Fig. 6(biv)).

Lastly, if Singapore invests in local water catchments in early 2040s, then in about 8 years' time, the limit of reservoir expansions will be reached (Fig. 6(bv)). Note that in Scenario 1 only 6 years' of investments are needed expand the reservoirs to the fullest. This time difference is due to the GDP level in each scenario. In Scenario 2 the population growth is slower. This leads to a lower GDP level and, consequently, a lower amount of investments into the water sector. Again, the supply from local water catchments is not sufficient to meet Singapore's water demand: in later part of the century, both adequacy and self-sufficiency indices stay at about 0.7 (Fig. 6(bv)).

In conclusion, the population growth in Scenario 2 is much more realistic than that in Scenario 1. The total water demand is milder. The long-term impacts of all four plans include higher adequacy and self-sufficiency indices compared to those in Scenario 1.

3.1.3 Simulation Results Under Scenario 3

In Scenario 3 it is assumed that there are no immigrants into Singapore and the country's birth and death rates remain constant. In this case, population will decrease steadily from more than 5 million in 2011 to about 1.6 million in 2100 (Fig. 6(ci)). The total demand for water will drop to 200 million m^3 in 2100. Because of this steady drop in water demand, adequacy index will increase to 7.5 in 2030 and stays constant till 2061 (Fig. 6(cii)). Similarly, self-sufficiency index will stay at 6 from 2030 to 2061, before dropping to below 1 in early 2070s (Fig. 6(cii)). In other words, from 2010s to late 2060s, Singapore will have extremely high adequacy of water and full self-sufficiency of water.

If Singapore invests in underground water storage, then 45 million m^3 of water stored underground would lift the self-sufficiency index to almost one (Fig. 6(cii)). If the investments go to seawater desalination, then the system will again exhibit a cyclic pattern after 2070 (Fig. 6(ciii)). If resources go to expanding NEWater's capacities, then 200 million m^3 of used water could be reclaimed, leading to high adequacy and self-sufficiency indices in the later part of the century (Fig. 6(civ)). If Singapore chooses to expand its local water catchments to the fullest, then the adequacy and self-sufficiency indices will both shoot up to more than 10 by the end of the century, indicating over-supply of water (Fig. 6(civ)).

Even though Scenario 3 is an extreme case and is unlike to happen, it still gives us new insights into the water resources system. Water management policies depend heavily on the population policies. If Singapore chooses to have a declining population, then there is no need to invest too much resources into the water sector because there will be over-abundance of water supply till the 2070s.

3.2 Alternative Selection Using AHP

By using AHP, decision makers could quantify their judgment through pair-wise comparisons of the criteria and the alternatives. In all three scenarios, the priorities of the criteria are the same: the relative weights of adequacy, self-sufficiency, and cost are 0.467, 0.467, and 0.067 respectively (Table S2). For each scenario, the local and global weights of each plan are presented (Table S3, S5, and S7). Results of the sensitivity analysis are also discussed.
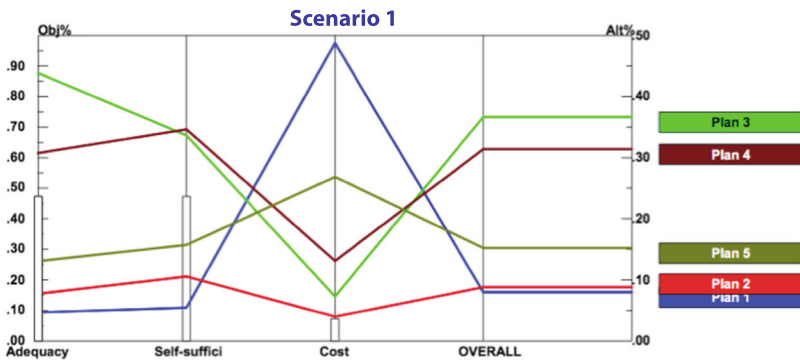
3.2.1 AHP Results Under Scenario 1

In order to strive for sustainable water resources management, Singapore should pursue development plans in the following order of priorities: 1) seawater desalination; 2) NEWater; 3) local water catchments; 4) underground water storage; 5) status quo (Table S4 and Fig. 7(a)). It is worth to note that the relative weight of investing in underground water storage (0.088) is almost equal to that of the status quo (0.080). This implies that, under the assumptions in *SingaporeWater*, investing in underground is inconsequential in the pursuit of adequacy and self-sufficiency in water.
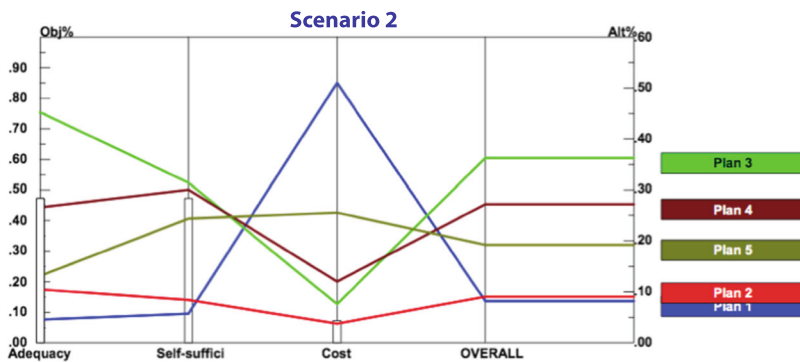
Results of sensitivity analysis are illustrated in Fig. 7(a). With respect to adequacy in water, desalination ranks higher than NEWater. However, with respect to self-sufficiency, NEWater has a small edge over desalination. In terms of costs, keeping status quo ranks the highest and
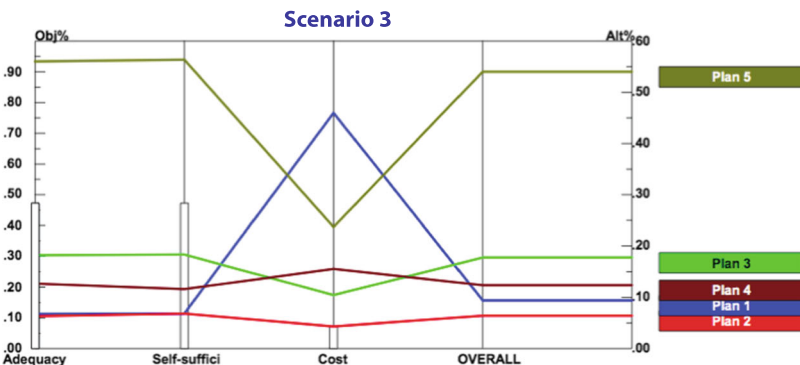
Fig. 7 **a** Performance sensitivity under three population scenarios. The terms "Adequacy", "Self-suffici", and "Cost" are the criteria for the overall goal of sustainable water resources management. The left y-axis represents the relative priority of each criterion, as shown by the *vertical bars*. The right y-axis represents the priority of each alternative with respect to each criterion. The "OVERALL" axis shows the overall priority of each alternative. **b** The efficient frontier under three population scenarios: the preferred direction is the one with lower cost index and higher self-sufficiency index
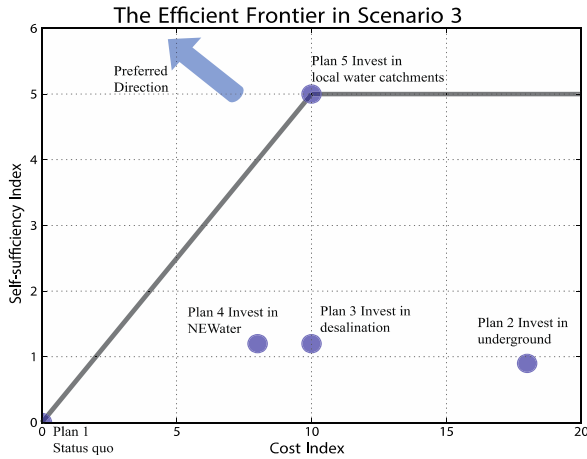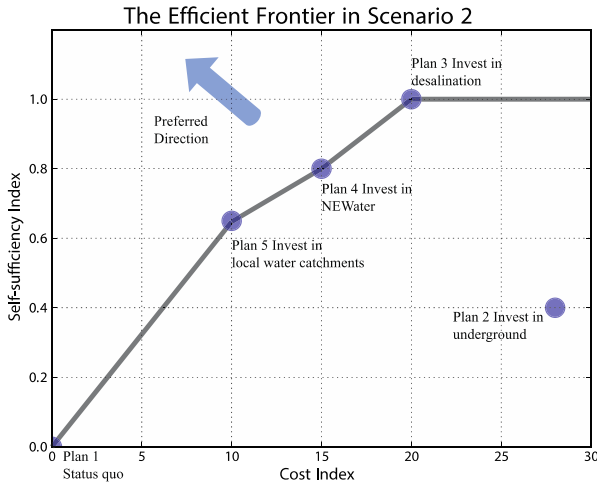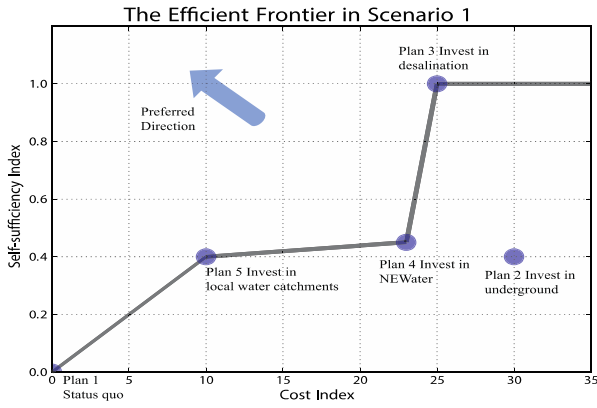
(b)

Fig. 7 (continued)

investing in underground ranks the lowest. With respect to the overall goal of sustainability, investments in seawater desalination and NEWater are ranked much higher than the other three plans.

3.2.2 AHP Results Under Scenario 2

The priorities of the five plans under Scenario 2 are similar to those in Scenario 1: investing in seawater desalination and NEWater are of higher priorities compared to other three plans (Table S6 and Fig. 7(a)).

In Scenario 1, desalination and NEWater are ranked much higher than local water catchments and underground water storage. However, in Scenario 2, the gap between them gets narrower (Fig. 7(a)). This means that in the case of milder population growth, investing in water catchments and underground becomes slightly more favorable. In other words, if the demand for water is milder, then it is less attractive to invest in more costly projects such as desalination and NEWater.

3.2.3 AHP Results Under Scenario 3

The situations in Scenario 3 are completely different. The AHP results suggest that Singapore should pursue development plans in the following order of priorities: 1) local water catchments; 2) NEWater; 3) desalination; 4) status quo; 5) underground water storage (Table S8 and Fig. 7(a)). In particular, the global weight of local water catchments is higher than that of the other four plans combined. This means that investing in local water catchments is of ultimate importance. When the demand for water declines, the most sustainable development plan is to expand the local water catchments. Other plans become much less attractive in the case of the population decline. Interestingly, Plan 1 is of higher weight than Plan 2. This means that it is more sustainable to keep the status quo rather than investing in the costly underground water storage.

3.3 Two-Attribute Trade-Off Analysis

The average self-sufficiency index and cost index under Scenario 1 to 3 are tabulated in Table S9, S10, and S11 respectively. These averages are obtained from SD simulation results for 2061 and onwards. This time period is chosen because 2061 is a critical year in which the imported water will be terminated.

In a plot of the efficient frontier, the preferred direction is one with increasing self-sufficiency in water and decreasing costs, as indicated by the blue arrow in Fig. 7(b). Decision makers could start with the least cost alternative, and then decide if investing more resources to reach the next best alternative is worthwhile.

In Scenario 1, the efficient solutions, on the efficient frontier, are "Plan 3 Invest in desalination", "Plan 4 Invest in NEWater", and "Plan 5 Invest in local water catchments". "Plan 2 Invest in underground" is clearly dominated by the three efficient solutions. This is consistent with the AHP results, which demonstrates that the proposed underground water storage system is of a much lower priority compared to other plans. In Scenario 2, the efficient solutions are still Plan 3, Plan 4, and Plan 5. Similar to the situation in Scenario 1, these three plans also dominate Plan 2 by a large margin. In Scenario 3, a case of declining population, the most efficient plan is "Plan 5 Invest in local water catchments". All other plans become less efficient because the demand of water is declining in this scenario.

4 Conclusion

Driven by real-world data, *SingaporeWater* SD model adequately captures the essence of the integrated water resources system in Singapore. AHP takes in the judgment of the decision makers and helps to quantify the priorities of various development plans. This novel integrated SD-AHP decision support approach has provided new insights for sustainable water resources management. More specifically, this study provides the following key research findings:

(1) The proposed underground water storage could store extra rainfall, alleviate the risk of flooding in urban areas, and diversify sources of water supply. However, because of its limited capacity and long construction time, it cannot be the country's main source of water supply. Furthermore, if it is built in 10 million m^3 only, as suggested by Prof. Lui, then it is not going to have a profound impact on Singapore's adequacy and self-sufficiency in water.

(2) If investments only go into the water sector when there is inadequacy of water, then there will be periodic and drastic oscillations in water supply, mainly due to the constructions of new water plants. For instance, the long-term impacts of investing in seawater desalination is that Singapore will experience 5 years of water shortage followed by another 5 to 6 years of water abundance. This highlights the need to plan well in advance. *SingaporeWater* SD model is able to simulate when and how much capacity expansions are most suitable for Singapore.

(3) The situations in the water sector depend heavily on the population policies. This is shown in the AHP results for three population scenarios. If the population increases rapidly or mildly (Scenarios 1 and 2), then the priorities of plans are: 1) seawater desalination; 2) NEWater; 3) local water catchments; 4) underground water storage; 5) status quo. In fact, the global weight of underground water storage is almost equal to that of the status quo. This implies that it is almost as inconsequential as status quo. If Singapore chooses to have a declining population (Scenario 3), then there is no need to invest too much resources into the water sector because there will be over-abundance of water till the 2070s. Therefore, policies for sustainable water resources management should be tailored to the country's long-term population policies, so as to optimize resource allocations.

This study has provided new insights for sustainable water resources management in Singapore and other countries who want to analyze and manage their water resources holistically. The novel integrated decision support tool, together with real-world data, could be applied to many other similar situations around the world in which policy makers need to make critical decisions with significant long-term implications, both in water systems and beyond.

References

Ahmad S, Simonovic S (2006) An intelligent decision support system for management of floods. Water Resour Manag 20:391–410. doi:10.1007/s11269-006-0326-3

AsiaOne (2011) Flash floods hit Liat Towers and other parts of Orchard Road. Singapore Press Holdings. http://www.asiaone.com/News/Latest+News/Singapore/Story/A1Story20111223-317945.html

Amarasinghe UA, Smakhtin V (2014) Global water demand projections: past, present and future. Int Water Manag Inst Sri Lanka. doi:10.5337/2014.212

Barlas Y (1996) Formal aspects of model validity and validation in system dynamics. Syst Dyn Rev 12:183–210. doi:10.1002/(SICI)1099-1727(199623)12:3<183::AID-SDR103>3.0.CO;2-4

Channel NewsAsia (2011) Heavy rain causes flash floods in Singapore. MediaCorp. http://www.channelnewsasia.com/stories/singaporelocalnews/view/1133302/1/.html. Accessed 22 Sept 2012

Chia ES, Pin FK (2008) A large-scale systems engineering perspective of water management in Singapore INCOSE

Chowdary VM, Chakraborthy D, Jeyaram A, Murthy YVNK, Sharma JR, Dadhwal VK (2013) Multi-criteria decision making approach for watershed prioritization using analytic hierarchy process technique and GIS. Water Resour Manag 27:3555–3571. doi:10.1007/s11269-013-0364-6

Chua G (2012) Why not underground reservoirs? The Straits Times 23 March, 2012

Dai D, Lu X, Guo Y, Xu X (1992) Research/application of system engineering to water resources systems. J Water Resour Plan Manag 118(3):337–349. doi:10.1061/(asce)0733-9496(1992)118:3(337)

Elimelech M, Phillip WA (2011) The future of seawater desalination: energy, technology, and the environment. Science 333:712–717. doi:10.1126/science.1200488

Ennaouri I, Fuamba M (2011) New integrated condition-assessment model for combined storm-sewer systems. J Water Resour Plan Manag 139(1):53–64. doi:10.1061/(asce)wr.1943-5452.0000217

Fernandez JM, Selma MAE (2003) The dynamics of water scarcity on irrigated landscapes: mazarron and Aguilas in south-eastern Spain. Syst Dyn Rev 20(2):117–137

Ford A (1999) Modeling the environment: an introduction to system dynamics modeling of environmental systems. Island Press, Washington

Ghashghaei M, Bagheri A, Morid S (2013) Rainfall-runoff modeling in a watershed scale using an object oriented approach based on the concepts of system dynamics. Water Resour Manag 27:5119–5141. doi:10.1007/s11269-013-0457-2

Ghashghaie M, Marofi S, Marofi H (2014) Using system dynamics method to determine the effect of water demand priorities on downstream flow. Water Resour Manag 28:5055–5072. doi:10.1007/s11269-014-0791-z

Harmancioglu NB, Barbaros F, Cetinkaya CP (2012) Sustainability issues in water management. Water Resour Manag 27:1867–1891. doi:10.1007/s11269-012-0172-4

Han M, Qingwang R, Wang Y, Du J, Hao Z, Sun F, Cheng L, Qi S, Li D (2012) Integrated approach to water allocation in river basins. J Water Resour Plan Manag 139(2):159–165. doi:10.1061/(asce)wr.1943-5452.0000255

Hall JW, Grey D, Garrick D et al (2014) Coping with the curse of freshwater variability. Science 346(80-):429–430. doi:10.1126/science.1257890

Lee PO (2010) The four taps: water self-sufficiency in Singapore. In: Chong T (ed) Management of success: Singapore revisited. ISEAS Publishing, Singapore, pp 417–442

Liu R (2004) Using system dynamics in decision support for sustainable waste management. National University of Singapore

Loucks DP (2000) Sustainable water resources management. Water Int 25(1):3–10

Lur X (2011) Floods worse than breakdowns for economy. Yahoo News. http://sg.news.yahoo.com/blogs/singaporescene/floods-worse-breakdowns-economy-044720977.html. Accessed 22 Sept 2012

Madani K, Mariño M (2009) System dynamics analysis for managing Iran's Zayandeh-Rud River Basin. Water Resour Manag 23:2163–2187. doi:10.1007/s11269-008-9376-z

Nordmark A (2002) Overview on survey of water installations underground: underground water-conveyance and storage facilities. Tunn Undergr Space Technol 17:163–178

Oliva R (2003) Model calibration as a testing strategy for system dynamics models. Eur J Oper Res 151:552–568. doi:10.1016/S0377-2217(02)00622-7

Padowski JC, Gorelick SM (2014) Global analysis of urban surface water supply vulnerability. Environ Res Lett 9:104004. doi:10.1088/1748-9326/9/10/104004

Parker HW (2004) Underground space: good for sustainable development, and vice versa. Paper presented at the World Tunnel Congress, Singapore

Piao S et al (2010) The impacts of climate change on water resources and agriculture in China. Nature 467:43–51. doi:10.1038/nature09364

PUB (Public Utilities Board) (2005) PUB Expands NEWater Plants and Builds MBR Demo Plant. http://www.pub.gov.sg/mpublications/Pages/PressReleases.aspx. Accessed 15 Sept 2012

PUB (2010a) Sea! Another source of water. Pub. http://www.pub.gov.sg/LongTermWaterPlans/wfall_4thtap.html. Accessed 20 Aug 2012

PUB (2010b) Water for all: meeting our water needs for the next 50 years. http://www.pub.gov.sg/LongTermWaterPlans/wfall.html. Accessed 22 Sept 2012

PUB (2011a) Imported water. http://www.pub.gov.sg/water/Pages/ImportedWater.aspx. Accessed 22 Sept 2012

PUB (2011b) PUB Annual Report 2010/2011: a complete makeover. http://www.pub.gov.sg/annualreport2011/

PUB (2011c) Marina barrage. http://www.pub.gov.sg/Marina/Pages/3-in-1-benefits.aspx#wc

PUB (2012a) Local catchment water. http://www.pub.gov.sg/water/Pages/LocalCatchment.aspx. Accessed 10 Aug 2012

PUB (2012b) NEWater. http://www.pub.gov.sg/water/newater/Pages/default.aspx. Accessed 20 Aug 2012

PUB (2013) Recent flash floods. http://www.pub.gov.sg/managingflashfloods/Pages/recent.aspx. Accessed 26 Jun 2013

Saaty TL (1990) How to make a decision: the analytic hierarchy process. Eur J Oper Res 48:9–26

Simonovic SP (2002a) Assessment of water resources through system dynamics simulation: from global issues to regional solutions. In: the 36th Hawaii International Conference on System Sciences, Hawaii, 2002. IEEE

Simonovic SP (2002b) World water dynamics: global modeling of water resources. J Environ Manag 66:249–267

Simonovic SP, Rajasekaram V (2004) Integrated analyses of Canada's water resources: a system dynamics approach. Can Water Resour J 29(4):223–250

Srdjevic Z, Srdjevic B (2014) Modelling Multicriteria decision making process for sharing benefits from the reservoir at Serbia-Romania border. Water Resour Manag 28:4001–4018. doi:10.1007/s11269-014-0723-y

Stewart T (1992) A critical survey on the status of multiple criteria decision making theory and practice. Omega 20:569–586. doi:10.1016/0305-0483(92)90003-P

Tezuba M, Seoka T (2003) Latest technology of underground rock cavern excavation in Japan. Tunn Undergr Space Technol 18(2–3):127–144

Wang X (2008) A proposal and application of the integrated benefit assessment model for urban water resources exploitation and utilization. Water Resour Manag 23:1171–1182. doi:10.1007/s11269-008-9321-1

Winz I, Brierley G, Trowsdale S (2009) The use of system dynamics simulation in water resources management. Water Resour Manag 23:1301–1323. doi:10.1007/s11269-008-9328-7

World Commission on Environment and Development (1987) Report of the World Commission on Environment and Development: Our Common Future. In. Oxford University Press, Oxford, p 383

Xu ZX, Takeuchi K, Ishidaira H, Zhang XW (2002) Sustainability analysis for yellow river water resources using the system dynamics approach. Water Resour Manag 16:239–261

Yang J, Lei K, Khu S, Meng W (2014) Assessment of water resources carrying capacity for sustainable development based on a system dynamics model: a case study of Tieling City, China. Water Resour Manag. doi:10.1007/s11269-014-0849-y

Young K, Kibler D, Benham B, Loganathan G (2009) Application of the analytical hierarchical process for improved selection of storm-water BMPs. J Water Resour Plan Manag 135(4):264–275. doi:10.1061/(asce)0733-9496(2009)135:4(264)