Should Singapore go ahead with underground reservoirs?

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Abstract: In order to alleviate the risks of flooding and diversify Singapore’s sources of water supply, the country’s former Chief Defence Scientist, Professor Lui Pao Chuen, proposed a novel idea of underground reservoirs in early 2012. This infrastructure could have significant long-term impacts on the integrated water resource system in Singapore. In addition, among the many alternatives to augment water supply, decision makers need to know which ones are the more sustainable plans to pursue. This essay proposes an integrated decision support approach that incorporates System Dynamics and a multi-criteria decision support tool called Analytic Hierarchy Process. Our research results reveal that, based on the initial construction costs, the proposed underground reservoir is not a cost-effective development plan, compared to other similar plans such as building more seawater desalination plants, NEWater plants, and local water catchments. It proposes that the decision makers could build upon the integrated decision support structure so as to achieve a more holistic analysis of the long-term benefits and costs of the underground reservoirs.

Introduction
“Now even Singapore has floods!” a tourist on Orchard Road exclaimed in 2010. It seems unbelievable that Singapore, a highly developed and affluent city-state, also begins to suffer from flash floods, which are usually associated with the developing countries. Since the early 2010s, a huge challenge for Singapore’s water resource management has been the increasingly intense floods in Bukit Timah residential area and Orchard Road shopping district (AsiaOne 2011a; Channel NewsAsia 2011). People were exposed to higher risks of water-borne diseases and the economy was adversely affected (Lur 2011). Then, the critical question is could Singapore move beyond the constraints of the natural water cycle, “[collect] every drop of rain” (PUB 2011a), and alleviate the problem of urban flooding?

Professor Lui Pao Chuen, the nation’s former Chief Defence Scientist and current Advisor to both National Research Foundation (NRF 2007) and Underground Master Plan Task Force (NUS 2012), proposed a solution to this challenge in
early 2012. He suggested that the country should build underground water reservoirs, similar to Jurong Rock Caverns that will store 1.47 million cubic meters of oil in 2014 (Teo 2011). As there are already similar rock cavern projects completed in Singapore and around the world (Nordmark 2002; Parker 2004), building more rock caverns for flood alleviation and storm-water storage seems to be a technically feasible project for Singapore.

However, our research results reveal that, based on the initial construction costs, the proposed underground reservoir is not a cost-effective development plan, compared to other similar plans such as building more seawater desalination plants, NEWater plants, and local water catchments. This essay aims to 1) propose an integrated decision support approach to help Singapore achieve sustainable water resource management; 2) present some preliminary research results related to the proposed underground reservoirs; 3) convince decision makers that this integrated decision support approach could be further enhanced to test out various ways to make the underground reservoirs more cost-effective.

**An integrated decision support approach**

This essay proposes an integrated decision support approach that incorporates System Dynamics (SD) and a multi-criteria decision support tool called Analytic Hierarchy Process (AHP). It demonstrates the usefulness of this innovative approach in helping to achieve sustainable water resource management and to assess the cost-effectiveness of various development plans in Singapore’s water sector. Figure 1 summarizes the proposed approach. First, a SD model takes in credible real-world datasets and simulates the consequences of different alternative 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. Through this approach, more informed decisions could then be made.

![Figure 1: Schematic overview of the integrated SD-AHP decision support approach](image-url)
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 behavior of the entire system. Past modeling studies of water resource mainly focus on the irrigation system of the agricultural industries. For example, SD has been used to study water resource in Canada (Simonovic 2002a; Simonovic 2002b; Simonovic and Rajasekaram 2004), Yellow River in China (Xu et al. 2002), water for irrigation in Spain (Fernandez and Selma 2003), and water balance in Mono Lake, California (Vorster 1985). To date, there are no published studies utilizing SD as a decision support tool to analyze Singapore’s integrated water resource system. This study aims to fill in this research gap.

In order to capture the essence of Singapore’s water sector, the author has developed a system dynamics model called SingaporeWater. As the second water agreement with Malaysia will expire in 2061 and the proposed hydrological infrastructures have long lifespans, the model runs from year 2000 to 2100, so as to reveal the long-term impacts of proposed plans. It is developed with Vensim Personal Learning Edition, a free software package with a visual graphical user interface that helps conceptualize, build, and test system dynamics models.

The 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, the Four National Taps provide water for both domestic and non-domestic consumptions. A Causal Loop Diagram in Figure 2 captures these key factors. To a highly modern and developed city-state such as Singapore, the quality of water supply has been carefully monitored, and thus, is not a great concern in sustainable water management. For this reason, quality index is not captured in 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 three key indices (Equation 1 to 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 neighboring countries. It should be equal or greater than one in order for Singapore to claim self-sufficiency in water. Economic sustainability in water sector is captured by the cost index. It gives a sense of how much investments have gone into the water sector in order to have a particular level of water supply for Singapore. Generally, the higher the index, the less cost-effective the investment plans are.

\[
\text{Adequacy Index}(t) = \frac{\text{Total Water Supply}(t)}{\text{Total Water Demand}(t)} 
\]

\[
\text{Self-sufficiency Index}(t) = \frac{\text{Total Water Supply}(t) - \text{Imported Water}(t)}{\text{Total Water Demand}(t)} 
\]

\[
\text{Cost Index}(t) = \frac{\text{Annual Investments}(t)}{\text{Total Water Supply}(t)} 
\]

The key stocks and flows in the model are shown in Figure 3. The model also includes the proposed underground reservoirs. 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. The complete stock and flow diagram is in Appendix A. Comparing the diagram and the system description by Public Utilities Board (PUB) leads to the conclusion that the SD model indeed captures the key elements of Singapore’s integrated water resource 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 rock caverns, water reclamation plants, and local water catchments are estimated from those of similar projects in Singapore. Key figures about these water-related projects are tabulated in Table B.1 in Appendix B.
Because of the availability of imported water and the addition of desalinated water and NEWater, Singapore will continue to enjoy high self-sufficiency in water until the early 2040s. More specifically, the model demonstrates that Singapore has achieved full self-sufficiency in water in 2010 and will continue to be self-sufficient till 2040 (Figure 4b). 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). However, due to the termination of imported water and closing down of the existing water plants, self-sufficiency in water drop drastically from the 2030s onwards (Figure 4b).

If Singapore invests one to three percent of its GDP in underground reservoirs from 2040 onwards, then it needs to continuously pump up the water stored underground. The water supply from this source reaches about 280 million cubic meters in 2100 (Figure 4a). Clearly, underground water alone is not sufficient to meet Singapore’s increased water demand. The self-sufficiency index stagnates at about 0.5 to 0.8 after 2040 (Figure 4b). Due to space constraint, the simulation results for other development plans are not featured in this essay.

Figure 3: Key stocks and flows in SingaporeWater system dynamics model
Figure 4: Long-term impacts of investments in underground reservoirs
Analytic hierarchy process for decision support

Because of the inevitable trade-offs among decision criteria, it is usually difficult to make decisions based on SD simulation results alone. The Analytic Hierarchy Process (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.

This section presents the basic decision hierarchy with the overall goal of achieving sustainability in water resource management. As shown in Figure 5, the three key criteria of 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 one to three percent of the nation’s GDP solely into one of the Four National Taps.

![Figure 5: Basic decision hierarchy for sustainable water resource management in Singapore](image)

The SingaporeWater SD model has simulated long-term impacts of various development plans under different population scenarios. In this essay, the focus is on the scenario of population growth from five million in 2012 to six million at the end of the 21st century. Under this population scenario, Singapore should pursue development plans in the following order of priorities: 1) seawater desalination; 2) NEWater; 3) local water catchments; 4) underground reservoirs; 5) status quo (Figure 6). It is worth to note that the relative weight of investing in underground reservoirs is almost equal to that of the status quo. This implies that, under the
assumptions made in *SingaporeWater*, investing in underground is rather inconsequential in the pursuit of self-sufficiency in water.

![Performance Sensitivity for nodes below: Goal: Sustainability](image)

**Figure 6**: Performance sensitivity of the five development plans with respect to each decision criterion

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 red arrow in Figure 7. Decision makers could start with the least cost alternative, and then decide if investing more resources to reach the next best alternative is worthwhile.

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 (Figure 7). This is consistent with the AHP results, which demonstrates that the proposed underground water reservoir is of a much lower priority compared to other plans.
Figure 7: The efficient frontier when Singapore’s population grows from five million to six million

As the results have shown, the proposed underground reservoir is not a cost-effective development plan, compared to other development plans that could help Singapore achieve higher self-sufficiency in water with lower costs. The big price tag makes the underground reservoir the least cost-effective development plan among the five plans analyzed. The results are consistent with PUB’s statement in 1997: the underground reservoirs “would cost as much as 20 times more than surface reservoirs of similar size”, and thus, were dismissed as “an expensive proposition” (Chua 2012).

Discussion and conclusion
Driven by credible 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 integrated SD-AHP decision support approach has provided new insights for sustainable water resource management.

Although the preliminary results argue against the “expensive proposition”, the author fully appreciates the merits of the proposed underground reservoirs. They could store extra rainfall, alleviate the risk of flooding, and diversify sources of water supply. As Professor Chan Eng Soon put it, the idea of an underground reservoir is “really refreshing, especially we’re not just looking at flood issues, but also at various other grand challenges related to energy and space utilization”.

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Clearly, one of the main concerns would be the formidable cost. Unlike Jurong Rock Caverns, an underground reservoir is probably going to be a public infrastructure financed by taxpayers' money. The general public must be convinced of the cost-effectiveness of the proposed project. Prof Lui mentioned two ways to offset the cost. One is to sell the rocks that are dug out; the other is to sell the hydroelectricity generated from pumping water from ground level into the caverns (Chua 2012). These are probably feasible solutions. However, the next question is how much of the total cost is going to be offset by the sales of rocks or the sales of hydroelectricity?

In response to Prof Lui’s ideas, the author proposes that the decision makers could build upon the integrated decision support structure, as presented in this essay, and incorporate the energy consumptions of the Four National Taps, the opportunity costs of expanding surface reservoirs, and many other relevant factors. The improved decision support system allows decision makers to conduct many relevant “what-if” analyses. For example, it could simulate how the underground reservoirs could help if there were a prolonged period of severe drought in Singapore. In this way, a more holistic analysis of the long-term benefits and costs of the underground reservoirs could be made possible. Through this approach, we might be even able to prove that the underground reservoirs are cost-effective, after all.
Appendix A

Figure A.1 Full stock and flow diagram in *SingaporeWater*


## Appendix B

### Table B.1 Key input data based on related water projects in Singapore

<table>
<thead>
<tr>
<th>Projects</th>
<th>Construction time</th>
<th>Construction cost (S$)</th>
<th>Capacity (m³/year)</th>
<th>Capacity increase per dollar invested</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Seawater desalination</strong></td>
<td></td>
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<tr>
<td>SingSpring Desalination Plant at Tuas (Hyflux 2002)</td>
<td>1.75 years (2004 to 2005)</td>
<td>250 million</td>
<td>49.8 million</td>
<td>0.20</td>
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<tr>
<td></td>
<td>20 years (2005 to 2025)</td>
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<td></td>
</tr>
<tr>
<td>Tuaspring Desalination Plant at Tuas (Peng 2012)</td>
<td>2~3 years (2011-2013)</td>
<td>1.05 billion</td>
<td>116.25 million</td>
<td>0.11</td>
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<tr>
<td></td>
<td>25 years (2013 to 2038)</td>
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<tr>
<td><strong>NEWater</strong></td>
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<tr>
<td>Bedok NEWater Plant (Hyflux 2001)</td>
<td>1~2 years (2001 to 2002)</td>
<td>16.1 million</td>
<td>14.6 million</td>
<td>0.91</td>
</tr>
<tr>
<td>Kranji NEWater Plant Phase 1 (PUB 2005)</td>
<td>1~2 years (2001 to 2002)</td>
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<tr>
<td></td>
<td>N.A.</td>
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<tr>
<td>Kranji NEWater Plant Phase 2 (PUB 2005)</td>
<td>0.5 years (2005 to 2006)</td>
<td>7.4 million</td>
<td>4.15 million</td>
<td>0.56</td>
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<tr>
<td></td>
<td>N.A.</td>
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<tr>
<td>Seletar NEWater Plant (Hyflux 2003)</td>
<td>0.5~1 years (2003 to 2004)</td>
<td>Decommissioned in May 2009</td>
<td>27.8 million</td>
<td>14.6 million</td>
</tr>
<tr>
<td>Ulu Pandan NEWater Plant (Keppel 2010)</td>
<td>2 years (2005 to 2006)</td>
<td>90~100 million</td>
<td>54 million</td>
<td>0.54~0.6</td>
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<td></td>
<td>20 years (2007 to 2027)</td>
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<tr>
<td>Changi NEWater Plant (Channel NewsAsia 2008)</td>
<td>2 years (2008 to 2010)</td>
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<td></td>
<td>25 years (2010 to 2035)</td>
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<tr>
<td><strong>Local water catchments</strong></td>
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<tr>
<td>Marina Reservoir (PUB 2011b)</td>
<td>2 years (2009 to 2011)</td>
<td>226 million</td>
<td>60 million</td>
<td>0.265</td>
</tr>
<tr>
<td>Punggol-Serangoon Reservoir (AsiaOne 2011b)</td>
<td>5 years (2006 to 2011)</td>
<td>300 million</td>
<td>30 million</td>
<td>0.10</td>
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<tr>
<td><strong>Underground rock caverns</strong></td>
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<tr>
<td>Jurong Rock Caverns Phase 1 (Teo 2011)</td>
<td>5~6 years (2007 to 2013)</td>
<td>890 million</td>
<td>1.47 million</td>
<td>0.00165</td>
</tr>
</tbody>
</table>
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Biography

Xi Xi is a final year student in Industrial and Systems Engineering and University Scholars Programme, National University of Singapore (NUS). In the past three years, she has worked as a research fellow at Singapore-MIT Alliance and represented NUS in various international exchange programs, conferences, and workshops in India, U.S., and Italy. While serving as the president of Institution of Engineers Singapore-NUS Student Branch, she witnessed how professional engineers make a positive impact to the society by applying their knowledge and skills. She hopes that she could also contribute to the Singapore society through this system dynamics study. Associate Professor Poh Kim Leng mentors the research project presented in this essay.