

A real options approach to the design and architecture of water supply systems using innovative water technologies under uncertainty

Stephen X. Zhang and Vladan Babovic

ABSTRACT

Water supply has become a priority for developed and developing nations of the world. Conventional water resources alone cannot meet the growing demand for water in urban cities. Management of the problem is amplified by uncertainty associated with different development strategies. Singapore has limited conventional water resources and progressively architects its water supply system through acquiring and sustaining multiple (alternative) water resources through innovative technologies. The full rationale and merits of such a policy cannot be properly understood based on traditional project valuation methods alone. This paper provides decision support using a real options approach by evaluating innovative water technologies from multiple perspectives under uncertainty.

This paper demonstrates that incorporating innovative water technologies into water supply systems can concurrently improve water supply from the financial, political and socioeconomic perspectives. The development of innovative water technologies provides flexibility to the water supply system, and is a fundamental and effective means of risk management. The evaluation of innovative water technologies is based on an integrated real options approach, which provides decision support for architecting water supply systems under uncertainty. The approach gives specific tangible values for the water technologies and complements the general prescriptive Integrated Water Resources Management (IWRM) framework.

Key words | flexibility, innovative technologies, multiple objectives, planning, risk management

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INTRODUCTION

Rapid urbanization is a global phenomenon. Many large cities are on the coast, and their hinterlands are acting as catchments for conventional water resources. The hinterland is increasingly industrialized and urbanized, which leads to water-stressed catchments. Population growth, increased population density, industrial expansion and the spatial distribution of urban and industrial water use result in an expanding and dynamic water footprint. This produces a disparity between supply, demand and distribution, as the legacy water supply system and conventional water resource management respond to urbanization. Driven by the need for water security, most cities are seeking alternative solutions (often through innovative water technologies) to

recalibrate their water resource management strategies against a growing water footprint.

Over the past decades, development in innovative water technologies has made it possible to capture and use alternative water resources, such as seawater, brackish and used water (Thomas & Durham 2003; Boutkan & Stikker 2004). Consequently, the proper evaluation and decision-making methods of such alternative resources have become an imperative for the security and the sustainable development of water supply systems. The management and development of water resources should take account of, and integrate, social, economic, environmental and technical dimensions (World Bank 2009) and have regard for the political

dimensions of water, due to the growing reality that water resources can be politically contested (Chikozho 2008).

However, the decision support for the management of alternative water resources from multiple perspectives, as proposed in Integrated Water Resource Management (IWRM), is a complex challenge (Thomas & Durham 2003). Such a challenge is made even more difficult in the face of uncertainty. Decisions regarding the exploitation of innovative water technologies and the need for a guiding architecture to integrate innovative water technologies into existing water supply systems have to be made now; yet economic–technical–political uncertainties surrounding water resource systems will unfold over decades and ultimately shape the efficacy of water supply systems.

A REAL OPTIONS APPROACH

Traditional water resources planning and analysis methods are based on requirements that are unrealistically fixed (Medellin-Azuara *et al.* 2007). The conventional approach of discounted cash flow (DCF) is not appropriate because it cannot capture managerial flexibility (Feinstein & Lander 2002). Managerial flexibility refers to decisions that managers can take to, for instance, start, increase or decrease the use of a particular resource, based on information that is available at that time.

In order to take into account managerial flexibility, we can borrow methods from options theory – which has revolutionized how we use flexibility to deal with uncertainty in the financial world (Myers 1977). Options can be purely contractual in monetary terms, which forms the basis of financial options that confer rights to buy or sell financial assets, or physical, in which case they are known as real options (Trigeorgis 1996). They may also include more abstract assets, such as knowledge-based resources incorporated in systems or projects.

Both financial options and real options are defined as rights but not obligations to take certain actions at some point in time. Whereas the exercise price and expiration date for a financial option are specified contractually, those for a real option are generally not explicitly specified and depend on both the property and the context of the real option. For detailed developments and explanations of

real options, there are a range of texts at various levels, for example, Dixit & Pindyck (1994); Trigeorgis (1996); Copeland & Antikarov (2001), Mun (2006).

Having real options would always be advantageous – if they were free. However, having real options, i.e., flexibility, always involves costs, because it may involve developing additional capabilities that would not otherwise be in play within the strategic decision-making landscape, because it may involve making smaller-stage investments and losing the economies of scale available in larger investments, or because it may cause delays or dilute potential benefits. The key questions are therefore: what is the value of each of the different forms of flexibility that might be added to the system? And which ones justify their costs? Estimating the values of different forms of flexibility is the task of ‘real options analysis’.

The real option analysis that calculates the value of real options for system planning and design commonly consists of a set of procedures (De Neufville 2003; Cardin *et al.* 2007; Zhang & Babovic 2010). One such procedure is outlined in Figure 1. A flexible system design process starts with the definition of the system objectives and the identifications of risk drivers, followed by the formulation of project states and real options. An exercising plan of the real options is then set, based on which options are exercised to change the system to adapt to uncertain futures.

The value of options can be defined as the difference of the value of the project with real options and the value of the project without real options (Copeland & Antikarov 2001) and is commonly illustrated as follows (Trigeorgis 2001):

$$\begin{aligned} \text{Value of options} &= \text{NPV (with real options)} \\ &\quad - \text{static NPV of expected cash flows} \end{aligned} \quad (1)$$

The determination of the value of flexibilities under uncertainty permits system designers and managers to decide which flexible design elements that allow their systems to evolve effectively over time are worth their costs. Still, one concern is that the values of real options to systems or projects may not only be monetary but multifaceted and need to be measured by multiple objectives deemed appropriate – such is the case for water supply systems. To meet the need for evaluating real options from multiple

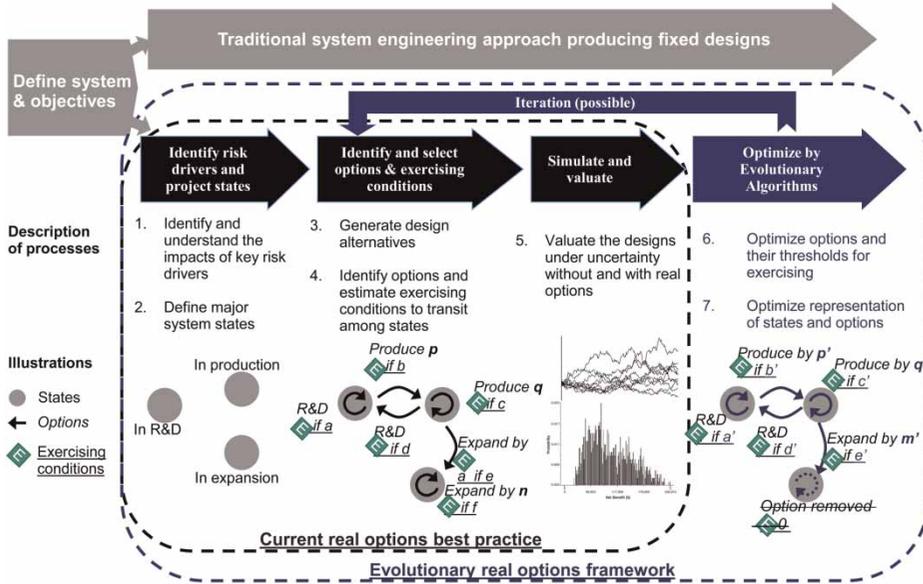


Figure 1 | A real options methodology for designing flexible systems optimally with real options – adapted from Zhang & Babovic (2010).

perspectives, this paper extends the conventional real options approach. In generic terms, the value of real options can be stated as

$$\begin{aligned} \text{Value of options} &= \text{Expected system objective measures} \\ &\quad (\text{with real options}) \\ &\quad - \text{Expected system objective measures} \\ &\quad (\text{without real options}) \end{aligned} \quad (2)$$

The computation of the expected value of options usually involves Monte Carlo simulations (Broadie & Detemple 2004). For example, if the calculation of an objective measure of a flexible project or system is represented as

$$O = E * [h(V_{t_0}, V_{t_1}, \dots, V_{t_m}, X_1, \dots, X_p)] \quad (3)$$

where O denotes the objective measure, h denotes the payoff that depends on the paths of uncertainties $V_{t_0}, V_{t_1}, \dots, V_{t_m}$, and the exercising conditions X_1, \dots, X_p of options $(1, \dots, p)$. A path of uncertainty refers to some data points at successive times for an uncertain variable. The exercising condition of an option refers to the condition that the option should be exercised so that the owner of the option gets benefits. Monte Carlo methods approach the problem by generating n random realizations of the paths of the uncertainties, checking whether the real options are exercised along each path and computing their corresponding

n number of payoffs, which are then averaged to estimate the expected payoff.

For an extensive treatment on the use of Monte Carlo methods in option pricing, see Glasserman (2004). A key issue in the pricing of real options is that they are usually American-type options. American-type options may be exercised at any time prior to the contracted expiry dates. As a result, the exercising conditions X_1, \dots, X_p of these options $(1, \dots, p)$ are generally hard to set optimally (Brydon & Gemino 2008). One of the most popular methods to determine the optimal exercising conditions is the regression-based approach (Longstaff & Schwartz 2001).

In the application domain, the real options approach has recently been used to design flexible engineering systems – for example, a parking garage in Zhao & Tseng (2003), a communications satellite system in De Weck *et al.* (2004), a terrorism protection system in Buurman *et al.* (2009) and an irrigation system in Michailidis *et al.* (2009). In engineering systems, innovative solutions are constantly developed and provide managerial flexibilities to change the systems, yet such flexibilities cannot be evaluated sufficiently by ‘intuitive synthesis’ and ‘gut feel’ in industries increasingly characterized by complexity, uncertainty and rapid change (Khatri & Ng 2000).

In the planning of water supply systems, the real options approach is particularly relevant because it is able to

dynamically evaluate the managerial decisions to use innovative water technologies to transform the water supply system under uncertainty.

WATER SUPPLY SYSTEM OF SINGAPORE

Singapore is a highly urbanized city state with the second highest population density in the world. Singapore's water demand for water can only be met by an area several times its size; if conventional water resources alone are used. Singapore imports raw water from its neighbor Malaysia under the 1961 and 1962 water agreements, which will expire in 2011 and 2061, respectively. Increasing water demand in Malaysia has triggered question marks over its water supply to Singapore (Kog 2001). Moreover, the asymmetrical water supply to Singapore has been supposedly used as leverage by the Malaysian government to influence the government of Singapore (Leifer 2000).

In order to become less dependent on imported water, Singapore has been progressively developing innovative water technologies, for example introducing desalinated and recycled water to the water supply system.

The water catchment area in Singapore is predicted to increase to two-thirds of the island's surface area by 2011, when two new reservoirs, Marina Reservoir and Punggol/Serangoon Reservoir, are completed. This is technically very challenging considering that the catchment areas cover highly urbanized lands.

Desalination is another important resource for augmenting water availability. In 2005, the first municipal-scale seawater desalination plant based on Reverse Osmosis (RO) started producing water at Singapore dollar S\$0.78/m³ (Lee 2005). At the time of writing, 1 US dollar was about 1.35 Singapore dollars.

Lastly, reverse-osmosis-based recycled water (called NEWater in Singapore), a milestone in the development of water reuse (World Bank 2006), is expected to contribute about one-third of the total water supply in Singapore by 2011.

Tortajada (2006) provided a summary of the remarkable and exemplary achievements in the water management of Singapore. The four aforementioned resources in Singapore

(imported water, catchment water, desalination water and NEWater) are collectively labeled as the 4-tap system of water supply.

Meanwhile, Singapore pays close attention to the development and application of emerging water technologies. An example of this is desalination by freezing using LNG (Liquefied Natural Gas) regasification as a heat sink (Salim *et al.* 2006).

Natural gas, considered to be a clean and efficient energy, can be liquefied and transported on LNG carriers. Before it can be used, LNG must be regasified using an external heat source from various types of vaporizers – seawater being the most common medium. A research project was set up to explore the prospect of desalinating seawater by cooling it below freezing point to produce an ice and salt solution mixture and separating them to obtain salt-free water (Salim *et al.* 2006).

The project also carried out an indicative economic analysis using conventional valuation methods. Without taking uncertainty into account, the cost of producing a cubic meter of water through desalination-by-regasification is around S\$0.50–0.60 – higher than the cost of NEWater. A rational decision-maker will always choose NEWater over desalination-by-regasification in case an expansion is needed, and as a consequence developing desalination-by-regasification would not yield any benefits. However, we believe a real options approach may reveal different findings and we apply the approach to this case to exemplify the potential impacts of innovative water technologies on water supply systems under uncertainty based on multiple objectives.

APPLICATION OF THE REAL OPTIONS APPROACH

Objective measures

Managing uncertainty using flexibility introduces new objectives for integrated water management (Pahl-Wostl 2007). In addition, the objectives for each water supply system are, to some degree, unique, due to their physical, social, institutional and economic conditions (Shah *et al.* 2005). These factors establish a context for defining and measuring the objectives of a water supply system. In the case of Singapore,

three objectives are identified below together with methods to evaluate them.

- **Financial cost:** The expected total cost of supplying water, valued using discounted cash flow with a discount rate of 6%, which is the same as that used in the water supply modeling by Voivontas *et al.* (2003) and comparable to the 7% discount rate suggested by the guidelines on Federal programs in the United States (White House 1992) and 5% used for civil design criteria by Energy Market Authority (2006) of Singapore. The financial cost also includes a cost for the emergency provision of barging water to meet shortage, should it happen.
- **Socioeconomic risk:** The risk of the cost of water reaching a level sufficiently high to have significant effects on the cost of living and doing business in Singapore – an undesirable socioeconomic situation. Though the cost of water to consumers (the unit selling price) may be different from the unit cost of producing water, owing to tariffs or subsidies, at the national level the cost of water production affects the socioeconomic well-being of a country. Thus a high unit cost of supplying water can be translated into socioeconomic risk. The risk is measured by the duration (as a percentage of the study period) during which the unit cost of water supply is higher than a threshold level. The level is S\$1 in the simulations and results of this paper and is customizable in the model.
- **Political risk:** The risk stems from the vulnerabilities of Singapore in the asymmetrically dependent relationship with Malaysia, the perceived weakened position in bilateral negotiations on other issues and the reduction of national sovereignty (Kog 2001). The risk is measured by the duration (as a percentage of the study period) during which Singapore is expected to fail to be self-sufficient in water supply if the supply of imported water is interrupted.

Obviously, there is a trade-off between aiming to minimize the political risk by being self-sufficient in water supply and aiming to minimize the financial cost by using inexpensive resources, as imported water is the least expensive source at the moment. Desalinated and recycled water cannot be compared with imported water from a financial perspective alone, since domestic water resources moderate the potential issues arising from

importing water. The financial cost of imported water cannot represent the full 'cost' Singapore pays in view of water import dependence. It is therefore essential to consider a premium to be paid for importing water to justify the political concerns (Lee 2005).

If the premium on self-sufficiency is ' x ' dollars, then the sum of the premium ' x ' and the momentary price of water (say ' y ') would be the price ($y + x$) of water that Singapore is willing to pay for self-sufficiency. The premium depends on the reliance of Singapore on the volume of imported water. If the reliance is considerable and hardly replaceable, the party that supplies the water will have strong leverage and the premium of self-sufficiency increases. At one extreme end, if ' x ' is infinite, it would imply that Singapore deems the risk of importing water is insurmountable and will search for a plan to produce all its water domestically. At the other end, if ' x ' is 0, it would imply that Singapore deems there is no added risk in imported water and will use whichever is cheaper monetarily – without discriminating between an imported water supply and domestic water supply. Most likely, the premium is somewhere in-between those two extreme positions.

Uncertainties

The water supply system and its related water resources (conventional and alternative water resources) require large substantial investments *ex ante* yet face a highly uncertain environment in the decades to come. The present study period of the water supply system of Singapore spans 30 years from 2007 to 2037. With such a long planning horizon, the environment of the water supply system will inevitably change in ways that cannot yet be foreseen. Each water resource in Singapore's water supply system has its own peculiar uncertainties. For example, international negotiations on water agreements have been unproductive and subsequently stalled (Lee 2005); the cost of desalination has been falling over a period of decades (Zhou & Tol 2005); to what extent that trend will continue is unknown. Desalination and NEWater are based on an energy-intensive reverse osmosis (RO) process and therefore subject to highly volatile energy prices. Last, but not least, the demand for water in Singapore over the study period of 30 years remains an open question.

The uncertainties are therefore twofold in the water supply system of Singapore:

1. uncertainties associated with the capacity of water supply; and
2. uncertainties associated with the cost of water supply.

The capacity required to be built in each of the resources in the water supply system is uncertain for two major reasons: (a) the amount of imported water, which contributed almost 50% of the total water supply at the time of the study, is subject to political uncertainty and (b) the required capacity depends on the uncertain future water demand (both domestic and industrial). The demand is calculated as below:

$$D_Y = (Pop_Y^r + Pop_Y^{nr}) * WCPC_Y / (1 - r_Y) \quad (4)$$

where D_Y denotes the total water demand in year Y , Pop_Y^r and Pop_Y^{nr} respectively the residential and non-residential population in year Y , $WCPC_Y$ the average water consumption per capita and r_Y the ratio between industrial and total water consumption in year Y .

The cost of supplying water is also uncertain. This is partly due to the fact that many water resources are dependent on fluctuating energy prices and partly due to the changes in operational cost, where the pace of innovation and advancement in the operational process of each water resource remains uncertain.

Fuel costs represent a major part of the cost for water generated based on RO processes. The Desalination Economic Evaluation Program (DEEP-3), a tool made freely available by the International Atomic Energy Agency for the performance and cost evaluation of desalination and water transport solutions, was used to study the dependence of RO plants on energy costs. The results indicate that energy costs contribute directly to about half of the total cost – the number is on par with the studies done by Zhou & Tol (2005) and Methnani (2007). In this light, we model separately the energy costs and the (other) operational costs of the desalination by RO and NEWater:

$$C_{desal_ro} = C_{desal_ro}^{oper} + C_{desal_ro}^{energy} \quad (5)$$

$$C_{newater} = C_{newater}^{oper} + C_{newater}^{energy} \quad (6)$$

where C_{desal_ro} and $C_{newater}$ denote the costs of water by desalination from RO plants and NEWater plants, respectively. $C_{desal_ro}^{energy}$ and $C_{newater}^{energy}$ are their associated energy costs, which are perfectly correlated, because they are proportional to the energy price C^{energy} . $C_{desal_ro}^{oper}$ and $C_{newater}^{oper}$ denote the operational costs, which are highly correlated due to the employment of the same underlying RO mechanism. Therefore the operational costs of NEWater and desalination by RO are modeled by two Brownian processes, correlated with a covariance of 70%:

$$\text{Cov}(C_{desal_ro}^{oper}, C_{newater}^{oper}) = p_{dn} \quad (7)$$

where p_{dn} denotes the covariance.

Desalination by regasification of LNG, deriving cold energy from the liquefied natural gas, employs a different mechanism. Therefore the cost of desalination-by-regasification $C_{desal_regas}^{oper}$ is assumed to be an uncertain variable independent of the aforementioned costs.

All the uncertainties that are related to the costs of markets or operations (Table 1) are modeled using a Geometric Brownian Motion (GBM) model (Dixit & Pindyck 1994). A variable V that follows a GBM at time t is

$$dV = aVdt + sVdz \quad (8)$$

where $dz = \text{Wiener increment} = e^{dt^{1/2}}$ (where e denotes the standard normal distribution), a denotes the drift and s denotes the volatility of V .

In this study, the drifts and the volatilities are estimated, as insufficient (public) data are available to determine these variables exactly. The drifts may be negative, as in the case of operational costs which are projected to reduce over time, or positive, as in the case of population which is projected to grow.

Following Pindyck (1993) and Chen & Funke (2005), the uncertainties in this study are modeled by two different processes. For politics and policy-related risk, a jump process based on scenarios is used (Fuss *et al.* 2008). 'Political risk' encompasses rare events, including, for instance, political instability and arbitrary government decisions reflected in political violence, taxes, asset destruction or expropriation,

Table 1 | List of uncertainties modelled by GBM in the water supply system of Singapore

Methods of modeling	Uncertainty V	Relative standard deviation s	Drift a (%)	Note
GBM	Fuel cost for RO process: C^{energy}	20% (log)	0	
GBM	Operational cost of desalination by RO: $C^{oper}_{desal_ro}$	10%	-7.5	
GBM	Operational cost of NEWater: $C^{oper}_{newater}$	10%	-7.5	
GBM	Cost of desalination-by-regasification: $C^{oper}_{desal_regas}$	20%	-7.5	
GBM	Non-resident population: Pop_Y^{nr}	10%	3.27	
GBM	Resident population: Pop_Y^r	5%	0.60	
GBM	Average water consumption per capita: $WCPC_Y$	2.13%	0	
GBM	Ratio between industry and total water consumption: r_Y	2.20%	0	1

Note 1. Instead of simulating the industrial water demand directly, this study models is based on the domestic water supply and the ratio of industrial water to domestic water supply.

refusal to respect or enforce contracts, nationalizations, currency fluctuations and inconvertibility, strikes, riots, sabotage, terrorism and wars (Clark & Tunaru 2004). Such events arrive intermittently at discrete intervals and can be represented by a conditional Poisson jump process (Clark 1997):

$$dV = aVdt + (k - 1)Vdq \quad (9)$$

where dq equals 0 with probability $(1 - \lambda dt)$ and a jump size of $(k - 1)$ with a probability of λdt .

Table 2 | List of uncertainties modeled by scenarios in the water supply system of Singapore

Methods of modeling	Source of uncertainty	Realization of the scenario	Probability	Note
Scenario	1961 International Water Agreement	Lapse	80%	
		Renewed	20%	
Scenario	1962 International Water Agreement	Following the agreement	98%	
		Quantity halved	1%	1
		Cancelled	1%	1

Note 1. The 1% is the cumulative probability of the scenario in 30 years, and in each year the probability of the mutually exclusive scenario is (1/30)%.

The scenarios of events are formulated and alongside their associated probabilities of occurrences are estimated (Table 2). The scenarios in this application are mutually exclusive (e.g. the imported water cannot be simultaneously cut and halved) and non-repetitive (e.g. the imported water cannot be cut twice).

In reality, the list of uncertainties mentioned is by all means a great simplification of all the uncertainties that may affect the system. Furthermore, the quantification of uncertainties is inexact due to the lack of relevant information. The vulnerability is susceptible to increase as economic, political, social and technological trends are projected into the remote future. Nevertheless, systems and models based on predictions of a range for an uncertain parameter stand better chances than those based on predictions of a single 'hit-or-miss' value of a parameter. This advantage of the approach adopted here is particularly true for systems designed for a long lifetime and facing greater degrees of uncertainty. In addition, the reality is that the variables and the expected value of a system are invariably distributions of possibilities rather than deterministic values.

Real options

Ample real options are available for water supply systems. In the Singapore context, an alternative water resource provides decision-makers with 'a right but not an obligation' to use that resource to transform the water supply system and therefore represents a real option. For instance, one can incorporate or expand the capacity of desalination-by-regasification if future developments favor that over the others. Figure 2 illustrates several real options present in the development and operation of a new water technology/resource.

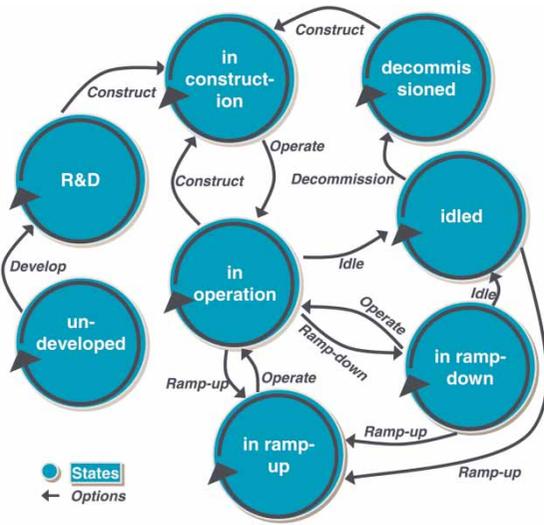


Figure 2 | Real options in the development and production of a water technology represented in an influence diagram.

The circles represent the (steady) state of a particular innovative water technology and the arrows represent the real options, which change the state of the water technology from one to another (e.g. from ‘undeveloped’ to ‘R&D’). There is also a circular arrow inside each of the states, indicating the option to continue within that state (e.g. the circle arrow in the ‘undeveloped’ state represents the option to let the technology remain undeveloped, or the *option to wait*). Another popular real option illustrated in the graph is the ‘operational flexibility’ – option to ramp-up or ramp-down. The option to ramp-up or ramp-down enables decision-makers to alter the levels of water supply based on actual requirements.

Exercising the real options alters the system from one state to another. The conditions to exercise the real options depend on a myriad of factors – not only the attributes of those very real options themselves, but the attributes associated with other water resources and exogenous factors related to the overall water supply system. For example, the exercising conditions to develop a particular innovative water technology will be lowered if the demand on the overall system increases or if the production costs of other water resources increase.

In this study, we evaluate two real options to use alternative water resources through two innovative water technologies (NEWater and desalination-by-regasification)

in the context of the water supply system of Singapore. One of them, the option to use NEWater, has been exercised in Singapore, which has altered the water supply system from the previous 3-tap system to the current 4-tap system. The 4-tap system and the previous 3-tap system are compared in this study to examine the effects of the option of NEWater on the overall water supply system.

This study also compares the so-called 4.5-tap system (referring to the 4 taps plus desalination-by-regasification) and the 4-tap system in order to study the effect of the option of desalination-by-regasification. Desalination-by-regasification is at the phase of development now and may or may not yield a viable option.

However, in order to generate the real options of innovative water solutions, the costs of the real options must be paid *ex ante*. The real option to incorporate or expand the capacity of a particular water solution does not come naturally but requires prior preparatory undertakings, such as developing certain technologies and capabilities, which are known as the costs of the option. In this case, the estimated costs of options related to the development of NEWater and desalination-by-regasification are S\$14 million (based on communication with PUB, whose demonstration-scale NEWater plant costs about S\$14 million over two years (including cost for operation, comprehensive water analysis, manpower, etc.)) and S\$1 million (based on communication with Dr Salim, who studied desalination-by-freezing through the regasification of LNG (Salim *et al.* 2006)), respectively. A consequent question is whether the option costs are outweighed by the potential benefits of the options. This paper quantitatively models the costs and benefits of the options to determine whether they are worth pursuing.

The two real options discussed in this paper only represent a small subset of all the possible real options for a water supply system in practice. Nevertheless, in principle, the approach used in this research can be extended to include more elements – real options, uncertainties, objectives, etc. More comprehensive models will improve the accuracy and reliability of the approach. However, the principal objective of this paper is to demonstrate the real options approach. Hence the paper reduces discussions associated with the technicalities as much as possible while maintaining the elementary level of functionality in presenting the real options methodology – new to the area of water management.

Modeling of the water supply system without and with the real options

The model developed in the present study is based on a set of data (including population data, water consumption per capita, the ratio of industrial/domestic consumption, and the breakdown of the cost and capacity of each tap) in year Y (Figure 3). The initial conditions for the dataset are drawn from the historical records for year 2006.

Based on the set of data in year Y , the expected water demand in year $Y+t$ is projected. If the projected demand is too large or too small compared with the built capacity in year Y , an adjustment of the capacity is needed between year Y and year $Y+t$.

At the same time, between year Y and year $Y+t$, the water demand may evolve differently than projected. To simulate the evolution of uncertain parameters, Monte Carlo simulations are used to randomly generate thousands of inputs (10,000 in this study) based on specified probability distributions as a sample set of data for year $Y+t$. The simulated data consists of water demands, simulated costs for every water supply tap, simulated future scenarios about the international water agreements, etc. Comparisons of the simulated water demands against the planned capacities will inform us how well the water supply system performs in year $Y+t$ based on the three objective

measures of the water supply system. Finally the individual objective measures from each run of the simulations are aggregated as the indicators of the performance of the system under uncertainty.

When the overall capacity of the water supply system needs to be adjusted, we also need to determine which tap is to be expanded or reduced. It is assumed in this study that neither imported water nor water from catchments can be increased from their current levels. That leaves desalination by RO as the only resource for expansion in a 3-tap system, while in case of a capacity reduction, both desalination by RO and imported water can be reduced. Figure 4 explains the flowchart to determine which tap to adjust in a 3-tap system.

In a 4-tap system, in case of an expansion, NEWater is generally preferred over desalination by RO, because their operational costs are highly correlated due to the same underlying RO process whereas NEWater consumes less energy. The flowchart is illustrated in Figure 5.

In 4-tap and 4.5-tap systems, for simplicity, the study only considers desalination by RO and imported water in the case of a capacity reduction. In doing so, the differences between the 4.5-tap and the 4-tap are well controlled: the only difference between the two systems is that the option to expand desalination-by-regasification is added in the 4.5-tap (Figure 6).

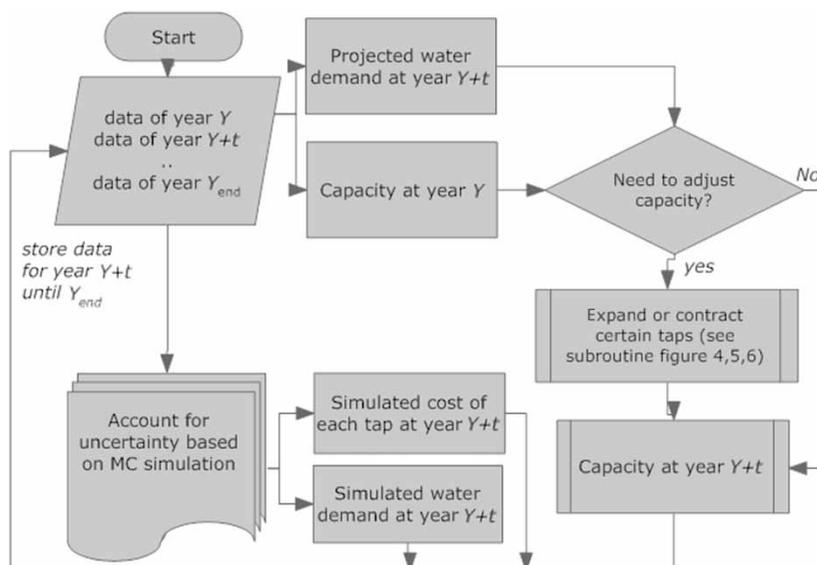


Figure 3 | The evolution of the water supply system according to the evolution of uncertainties.

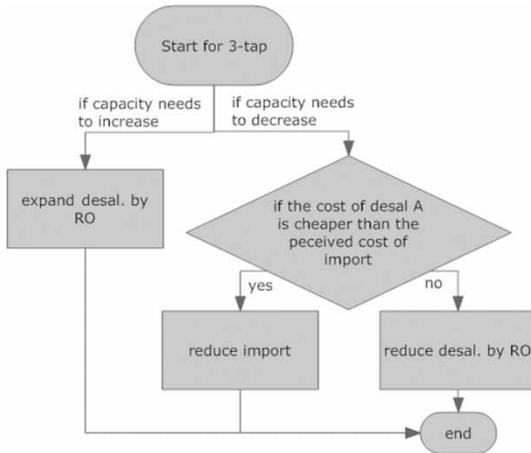


Figure 4 | The flowchart to determine which tap to adjust in a 3-tap system.

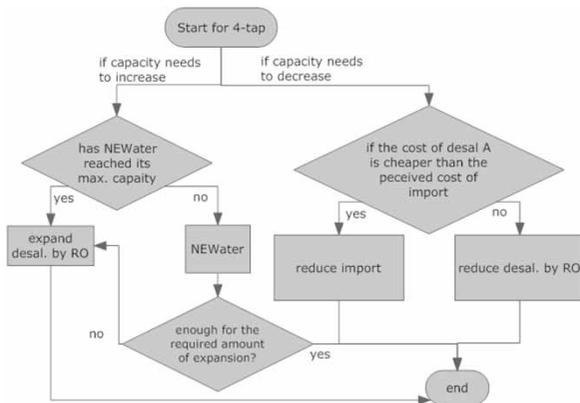


Figure 5 | The flowchart to determine which tap to adjust in a 4-tap system.

The optimization and selection of option exercising conditions

In the case of an expansion in the 4.5-tap system, we need to establish under which conditions one should introduce desalination-by-regasification over NEWater and desalination by RO. The exercising conditions associated with the real options of desalination-by-regasification are set by approximation by a linear set of functions (Longstaff & Schwartz 2001; Tsitsiklis & Van Roy 2001).

While the approximation approaches by Longstaff & Schwartz (2001) and Tsitsiklis & Van Roy (2001) both deal with a single stochastic process, in the present case there are several stochastic processes (the paths of the costs of desalination-by-regasification, desalination by RO and

NEWater), all of which may affect the exercising conditions of desalination-by-regasification. This study uses all of them as variables to approximate the exercising conditions. Desalination-by-regasification will be used if the following relationship is met:

$$C_{desal_regas} < \beta_0 + \beta_1 * C_{NEWater} + \beta_2 * (C_{NEWater})^2 + \beta_3 * C_{desal_RO} + \beta_4 * (C_{desal_RO})^2 + \beta_5 * C_{NEWater} * C_{desal_RO} \tag{10}$$

where C_{desal_regas} denotes the unit cost of desalination-by-regasification and β_i are parameters to be set in ways that optimize the exercising conditions based on the system objectives. Here, genetic algorithms are used to find the optimal β_i .

Model assumptions

Before the results are presented, all the key assumptions in constructing the model and generating the results are listed as below:

- The exchange rate between the Singaporean and Malaysian currencies is not modeled as a variable and is assumed to stay constant at 2.2. In reality, this rate is relevant as the Malaysian currency is used in the international water agreements.
- The renewal of the 1962 agreement, which expires in 2061 and consequently is outside the lifespan of this study, is not considered.
- The sunk costs, such as the reservoir construction costs in Singapore and Malaysia, are deemed to be irrelevant.
- Despite climate change, the rainfall in tropical Singapore is assumed to be sufficient to fill the reservoirs.
- The maximum capacity of each tap is assumed as follows:
 - (a) imported water: the maximum capacity is the contracted capacity according to international agreements;
 - (b) water from desalination: the maximum capacity is assumed to be limitless, as seawater is practically inexhaustible;
 - (c) recycled water/NEWater: Public Utility Board (PUB) of Singapore is targeting to meet 30% of Singapore’s water needs by NEWater, and this study assumes that number can reach up to 50% as its possible maximum, as the majority of water in Singapore

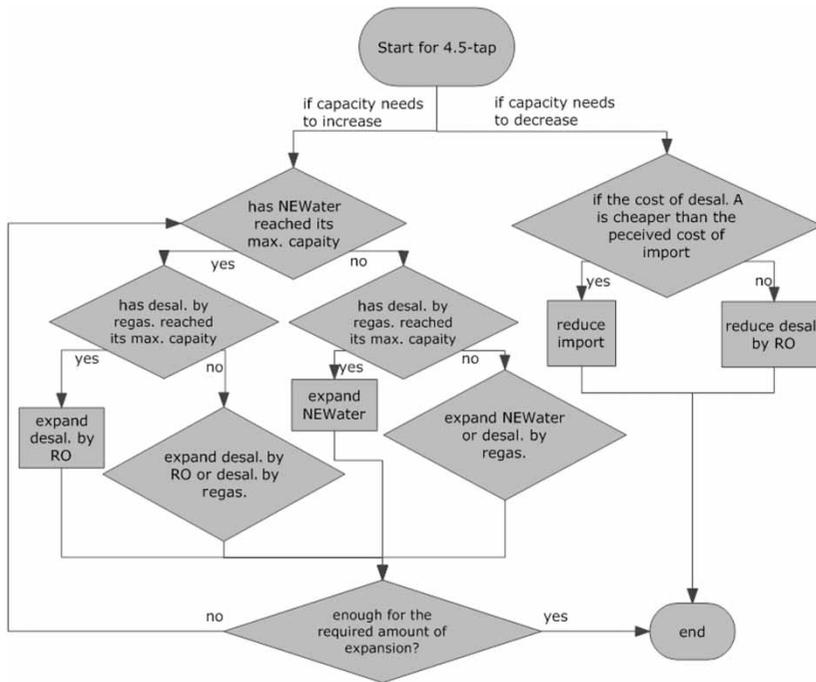


Figure 6 | The flowchart to determine which tap to adjust in a 4.5-tap system.

is discharged into sewage (Tay *et al.* 1994), giving rise to a large potential for water reclamation and re-use;

(d) catchment water: the maximum capacity is as large as it is at present. Currently 0.68 million cubic meters of water can be harvested on average per day from the largely urban water catchments, which are challenging to further increase in land-scarce Singapore;

(e) water from desalination by regasification of LNG: the initial capacity is 41 thousand cubic meters per day as in Salim *et al.* (2006) and the capacity could be doubled every decade.

- The model does not account for the possible revenue that could be generated through the knowledge gained in the process of acquiring and managing the innovative water solutions which, in reality, is valuable and presents the knowledge possessors' 'growth options' – opportunities to be exploited worldwide.

SIMULATION RESULTS

The model, developed in Excel[®], runs reasonably fast. The typical computational time GA takes to find a satisfying

solution is 2–3 h for 10,000 samples in Monte Carlo simulations. It in average takes GA with a population size of 60 about 40 generations to find a satisfying solution. One solution is listed in Table 3. It shows the impacts the options of NEWater and desalination-by-regasification have made to the overall water supply system on financial cost, socioeconomic risk and political risk.

The simulation results show that the 4-tap (with NEWater) system clearly outperforms the 3-tap system (without NEWater) in all three aspects. Not only is the financial cost to supply water reduced, but also both the risk of bearing a high water cost (socioeconomic risk) and the risk of running short of water (political risk) are reduced. Having the option to use and expand NEWater can reduce the duration of bearing a high water cost by 0.1% (i.e. 126 d in 30 years) and the duration of water shortage in the case of an interruption to imported water by 0.3% (239 d in 30 years). The improvements from the three measurements are all very significant and altogether they make up the overall benefits that NEWater has brought to Singapore's water supply system. The benefits have to be compared with the costs of the real options. Since the options to develop NEWater and desalination-by-regasification are estimated to cost S\$14

Table 3 | Value of real options from improving the water supply system of Singapore

		Financial cost (mill S\$)	Socioeconomic risk (%)	Political risk (%)
System evaluation	3-tap system (A)	2,379.2	1.17	2.61
	4-tap system (B)	2,267.6	1.15	2.18
	4.5-tap system (C)	2,262.8	1.15	2.18
Value of real option	NEWater (A–B)	112	0.10	0.30
	Desalination using LNG regasification (B–C)	4.9	0.00	0.00

million and S\$1 million, respectively, the incorporation of NEWater to build the 4-tap system is clearly a dominating choice compared with the 3-tap system from all objective measures. The 4.5-tap (with desalination-by-regasification) system is also a dominating solution over the 4-tap system, but its improvement is smaller comparatively.

The smaller improvements of desalination-by-regasification can be attributed to its relatively limited maximum capacity. Desalination-by-regasification is also different compared to NEWater with regard to their current status. The NEWater option was already exercised and incorporated in Singapore's water supply system – such an option which can bring benefits should they be exercised now is referred to as an 'option in the money'. In contrast, desalination-by-regasification is under R&D. It is 'out of money' – it is not worthwhile to exercise it now. As discussed previously, a conventional valuation based on static projections (without uncertainties) reveals that desalination-by-regasification should not be used and thus has a payoff of zero when uncertainties are not considered. The value of desalination-by-regasification is purely derived from its option value under certain realizations of paths of uncertainties – uncertainties involved with both the technologies and the contexts. Therefore, a proper and complete evaluation of an innovative water technology must take a real options approach.

Sensitivity analysis

Political parameters, due to their sensitive and intractable nature, are the most difficult to estimate. A sensitivity study is carried out to examine the results based on different estimates of political parameters (Figure 7). In this exercise, the probability of the 1961 agreement to lapse has been varied between 0.6 and 1.0. The probability of interrupting

the 1962 agreement (cut off completely or quantity halved) has been varied from 0 to 0.02. The premium on imported water has been varied from S\$0 upwards to S\$0.4 to estimate different positions Singapore can take in view of importing water and self-sufficiency in water.

By and large, the results from the sensitivity study show that both NEWater and desalination-by-regasification retain their expected benefits when the political parameters vary in reasonable ranges. The minimum financial values of NEWater and desalination-by-regasification remain significantly higher than their respective option costs. This type of sensitivity/what-if analysis can be easily supported in the real options approach to test the robustness of the decisions on real options by different sets of assumed values/distributions.

Exercising conditions of desalination by LNG regasification

Exercising conditions by educated guesses

The exercising conditions of desalination-by-regasification are critical to its value. Reasonable guesses have been made to estimate suitable exercising conditions, such as to exercise the option if the unit cost of desalination-by-regasification is less than a certain pre-defined amount (Table 4). However, under any of those circumstances, the option value obtained is smaller than the cost of the option (S\$1M).

Exercising conditions formulated through genetic algorithms

In this study, we also use GA to find the exercising conditions. The exercising conditions are formulated based on (1) the cost of desalination-by-regasification, (2) the cost of

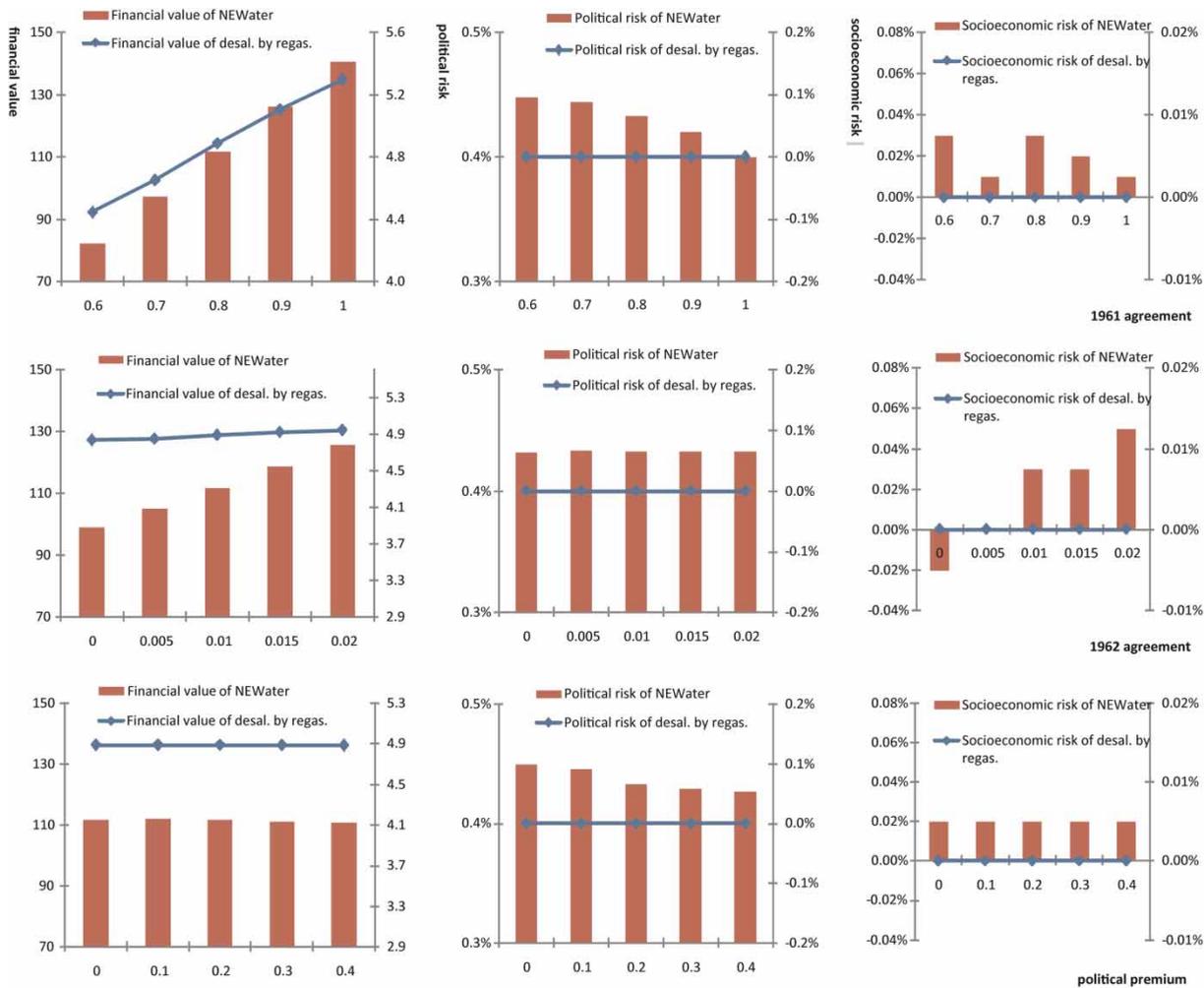


Figure 7 | The sensitivity of the expected benefits of NEWater and desalination-by-regasification towards political parameters. The value of the NEWater is marked on the left vertical axes in each of the nine graphs, while the value of the desalination-by-regasification is marked on the right vertical axes in each of the nine graphs. In row 1, the horizontal axis represents the probability of the 1961 agreement lapsing. In row 2, the horizontal axis represents the probability of the 1962 agreement being cancelled or halved in capacity. In row 3, the horizontal axis presents the premium of importing water.

NEWater, (3) the cost of desalination by RO and (4) the design variables β_i in Equation (10). GA searches the optimal design variables that will minimize the three objective measures of the system. The near-optimal sets of β_i found by GA to exercise desalination-by-regasification over NEWater and desalination by RO are listed respectively in Table 5.

The optimal cost below which desalination-by-regasification is preferred over NEWater in an expansion could be plotted (Figure 8(a)). The figure shows that the optimal cost of exercising desalination-by-regasification over NEWater increases as the cost of NEWater increases and as the cost of desalination by RO increases.

Similarly, Figure 8(b) depicts the optimal exercising cost below which desalination-by-regasification is preferred over desalination by RO in the case of an expansion. As this only happens when the tap of NEWater has reached its maximum capacity and cannot be further expanded, we have fewer choices and in this case the optimal exercising cost of desalination-by-regasification is lower than that in Figure 8(a).

Such exercising conditions as functions involving multi-fold and complex relationships of multiple uncertain parameters are difficult for humans to define optimally without the aid of an effective search technique. An evolutionary algorithm, as demonstrated here, is able to optimize the exercising conditions of real options beyond conventional means.

Table 4 | The expected option value of desalination-by-regasification when it is exercised should its cost be lower than a predefined monetary threshold

Monetary threshold (\$S)	4.5-tap system (C)			Option of desal. by regas. (B-C)		
	Financial Cost (mill \$S)	Socioeconomic risk (%)	Political risk (%)	Financial value (mill \$S)	Socioeconomic risk (%)	Political risk (%)
0.05	2,268.1	1.15	2.18	-0.5	0.00	0.00
0.10	2,268.5	1.15	2.18	-0.8	0.00	0.00
0.15	2,268.8	1.15	2.18	-1.1	0.00	0.00
0.20	2,269.5	1.15	2.18	-1.9	0.00	0.00
0.25	2,270.5	1.15	2.18	-2.8	0.00	0.00
0.30	2,271.5	1.15	2.18	-3.8	0.00	0.00
0.35	2,272.7	1.15	2.18	-5.0	0.00	0.00
0.40	2,273.7	1.15	2.18	-6.1	0.00	0.00
0.45	2,274.8	1.15	2.18	-7.2	0.00	0.00
0.50	2,275.8	1.15	2.18	-8.1	0.00	0.00
0.55	2,276.7	1.15	2.18	-9.1	0.00	0.00
0.60	2,277.5	1.15	2.18	-9.9	0.00	0.00

Table 5 | Parameters found by GA in a set of functions that define the exercising conditions of desalination-by-regasification over NEWater and over desalination by RO, respectively

Parameters	NEWater	Desalination by RO
β_0	-0.85337	-0.71848
β_1	0.98436	0.91202
β_2	0.78495	0.8827
β_3	0.41935	0.18084
β_4	0.42913	0.28446
β_5	-0.35484	0.82796

DISCUSSION

Innovative water solutions are considered as real options, and such real options are evaluated in the context of the water supply system of Singapore based on multiple objectives.

The results have demonstrated the valuation and design with real options in systems is a fundamental and effective means to deal with uncertainties. Unlike financial institutions, which seek to ascertain the absolute values of options to

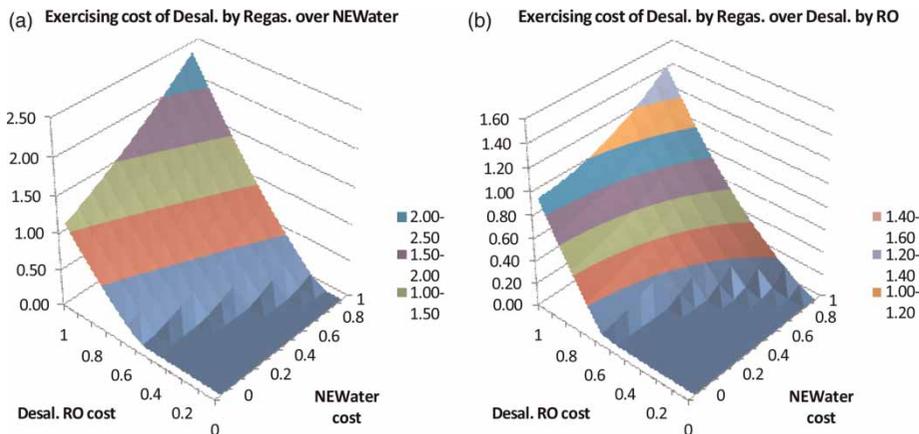


Figure 8 | The optimal exercising cost of desalination-by-regasification, below which desalination-by-regasification is preferred over NEWater (a). The optimal exercising cost of desalination-by-regasification, below which desalination-by-regasification is preferred over desalination by RO (b).

generate profit from financial arbitrage, the issue of importance for real options in system design is not to resolve a number but to take options into account and make better design choices. Insights, not numbers, are the overall aim of the decision analysis (Howard 1980). The insights that designs involving real options, such as innovative (even immature) water technologies can be the dominant design solutions, is more critical than the absolute accurate values of real options. The real options approach can fundamentally change the design decisions with respect to innovative technologies as well as the overall system design.

The results echo the recognition that water reuse is a good management option to conventional water resources (Medellin-Azuara *et al.* 2007). Also, the results are in line with the strategic policy Singapore has been implementing in acquiring and maintaining portfolios of multiple water resources. Singapore has expressed the view that, should it become self-sufficient, it would still continue to purchase water under fair terms from Malaysia or any other country willing to be its long-term supplier (Long 2001). Such a strategic policy, as shown in this study, can only be appreciated when (1) decision-making on incorporating an alternative water resource is made in the context of the local water supply system (UNEP 2002; Boutkan & Stikker 2004) and (2) the model of the water supply system is embedded and integrated within the local context including socioeconomic, financial, technical, political and operational aspects, as proposed by Thomas & Durham (2003).

In addition, in order to match the multi-objective characteristics of water resources management, this study departs from the conventional real options analysis, which only looks at the financial value of real options, and introduces two additional objectives (socioeconomic and political). This multi-objective approach can be further extended to encompass more objectives deemed appropriate, for example, water quality, environmental impacts and carbon footprint. Based on multiple objectives, the evaluation of innovative water technologies through a real options approach gives specific tangible values. Such specific tangible values are needed to complement and substantiate the general prescriptive IWRM framework. This real options approach of evaluating innovative water technologies can be used as part of the comprehensive IWRM in conjunction with other specific programs on water

quality, environment and sustainability to provide well-informed recommendations in local contexts, thus mitigating the vagueness and generality of IWRM – a point lamented by Biswas (2004).

Adopting the multi-objective real options approach as well as the integrative IWRM framework in a systematic manner has been made conducive in Singapore by the unified national water institution of PUB (Tortajada 2006; Nazerali 2007). Institutionally, PUB manages the entire water cycle – the protection and expansion of water sources, sewerage and drainage, stormwater management, catchment management, desalination, demand management, electricity and gas, etc. Such a unified institution can aid holistic architecting and planning and reduce the administrative challenges in evaluating and incepting innovative water solutions for its water supply system. However, the approach for evaluating innovative water solutions is not only useful in countries with single water institutions, but also equally useful in countries where several institutions take charge and need such an explicit evaluation approach to discuss innovative water solutions between them.

As a water-scarce city state, Singapore's experience is somewhat unique. Nevertheless, many of the measures it has taken to achieve its remarkable progress in water management do offer useful lessons even for large countries (World Bank 2006). Similarly, the context of the water supply system in Singapore is somewhat epitomized due to its particular context, yet the approach to evaluate innovative water technologies in the context of water supply systems presented in this study is general, and it is possible to have this approach adapted to other problems.

CONCLUSIONS

Using innovative water solutions to transform the overall water resource system is a salient and strategic issue. The development of such innovative water solutions is assessed in this paper using a real options analysis based on multiple objectives. It is found that innovative water technologies cannot be evaluated from a static perspective nor can they be evaluated in isolation. Incorporating innovative water solutions can add flexibility to the water supply system and

thereby can improve the system from multiple perspectives. The value of an alternative water solution is integrally associated with the fluctuations of many uncertainties. The uncertainties are not always to be avoided, but could also present valuable opportunities. Thus uncertainties and the flexibilities offered by the innovative solutions to the design of the overall water resource systems need to be studied integrally.

The method of real options analysis can help through the determination of the value of flexibility, which in turn supports decisions-making about whether a specific water technology is worthy of pursuit. In addition to this, a real options approach is able to fundamentally provide decision-makers with a proactive stance towards risk in the planning and architecturing of projects and systems.

While real options and financial options connote conceptual similarity, real options applications lack the standardization of financial options. The model of real options has to accommodate the complexity and peculiarity of application domains, and as a consequence the real options models lack the elegance of their counterparts of financial models. Adapting real options methods to water resources problems requires us to challenge our often implicit and deterministic decision-making process and formulate and model it explicitly and nondeterministically.

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