Flexible Design: An Innovative Approach for Planning Water Infrastructure Systems Under Uncertainty

by

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B.S. Civil and Environmental Engineering
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Submitted to the Engineering Systems Division in partial fulfillment of the requirements for the degree of

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Abstract

This thesis develops a framework for a flexible design approach to support decision-making in water supply infrastructure planning. It contrasts with a conventional, deterministic planning approach that uses past data or forecasts to anticipate future needs. This thesis surveys current approaches that attempt to consider uncertainty, including scenario planning, decision analysis, sensitivity analysis, real options, dynamic strategic planning, and adaptive management. A flexible design approach builds on current approaches and explores flexibility through infrastructure size and function. The approach intends to be applicable across various water infrastructure systems. This thesis describes real world and theoretical applications of flexible design, including climate change adaptation planning for water utilities, flexible planning for water infrastructure investments, and flexibility in urban drainage systems.

The proposed flexible design approach employs probabilistic and simulation methods to anticipate a range of future circumstances and identify top-performing strategies. The engine of the framework is a time-series stochastic analysis that uses simulation in a discounted cash flow Excel model. First, it identifies key inputs and performance metrics, characterizes uncertainty distributions, and defines strategies of varying flexibility. Next, it employs Monte Carlo simulation and compares strategy performance through target curves and multiple criteria analyses. Singapore's water resources system inspires the characteristics of the model. The best-performing flexible approach introduces a cost savings of 15% over a 50-year timespan.

To successfully implement a flexible design approach, leaders in the profession must guide the shift to planning methods that explicitly recognize the role of uncertainty in the planning process. While some implementation barriers present difficulties, the proposed flexible design approach enables substantial cost savings and fosters a deeper understanding of a water resources system in the face of future uncertainty.

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Title: Professor of Engineering Systems and of Civil and Environmental Engineering

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Contents

Figures and Tables

Abbreviations and Acronyms

ASCE	American Society of Civil Engineers
AWWA	American Water Works Association
CERP	Comprehensive Everglades Restoration Plan
COFAS	Comparing the Flexibility of Alternative Solutions
DCS	Distributed Control System
DSPM	Decision Support Planning Method
GDP	gross domestic product
ICLEI	International Council for Local Environmental Initiatives
IRP	Integrated Resource Plan
IWA	International Water Association
LILP	Lincoln Institute of Land Policy
$\mathbf{m^3}$	cubic meter
MBDA	Murray-Darling Basin Authority
MCDA	Multi-criteria decision analysis
MCM	million cubic meters
MCS	Monte Carlo simulation
MIT	Massachusetts Institute of Technology
NPV	net present value
PUB	Public Utilities Board (Singapore)
S$	Singapore Dollar
SDL	sustainable diversion limit
UN	United Nations
UNESCO-IHE	United Nations Educational, Scientific, and Cultural Organization, International Institute for Infrastructural, Hydraulic, and Environmental Engineering
USACE	United States Army Corps of Engineers
USF	University of South Florida
WSAA	Water Services Association of Australia
WUCA	Water Utility Climate Alliance

1 Introduction

Do not boast about tomorrow,
for you do not know what a day may bring.

– Proverbs 27:1

The future is uncertain. Technologies, needs, policies, economies, and environments change every day. Some of these changes are quantifiable and we attempt to make best estimates to what will happen, but we will always encounter game changing events and new technologies that we could not have anticipated before.

When decision makers consider needs for future water infrastructure, they can use a conventional, deterministic approach that assumes current conditions will not change or that we can safely rely on a forecast of long-term requirements. Figure 1 depicts such an approach, where we assume little future change or forecast a single future scenario:

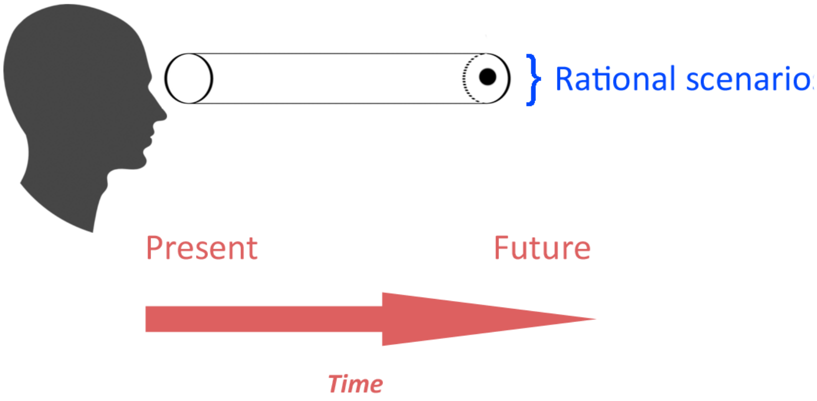

Figure 1: Conventional planning assumes little future change (adapted from Galloway, 2013)

However, conditions change over time and forecasts are rarely accurate. Thus, we need an approach that acknowledges uncertainty and attempts to learn from future conditions by adjusting our decisions over time. This is what a flexible design approach aims to do. It acknowledges that the future contains many possibilities with risks and opportunities. It aims to protect investments from downside losses, such as financial vulnerability to shrinking water demand. A flexible design approach also allows decision makers to take advantage of upside opportunities, such as installing a more efficient or cheaper technology (de Neufville & Scholtes, 2011). Figure 2 depicts a flexible design approach that considers a range of future scenarios.

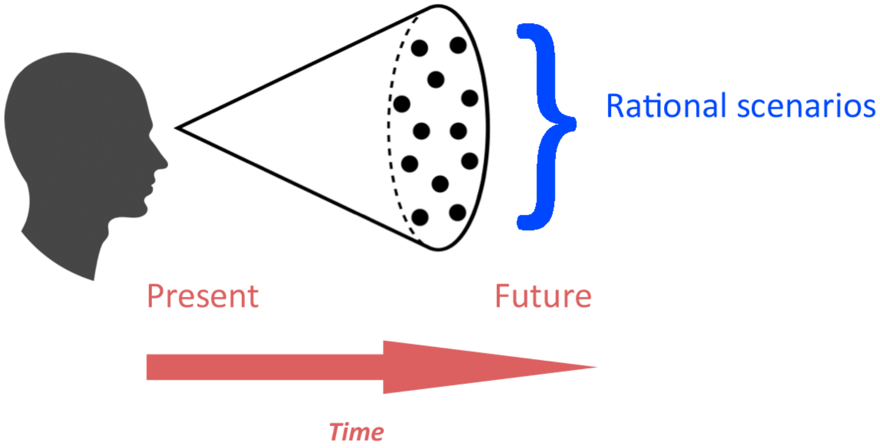

Figure 2: Flexible design considers a range of future rational scenarios (adapted from Galloway, 2013)

1.1 Sources of Future Uncertainty in Water Infrastructure Systems

To plan for future water infrastructure systems, decision makers in water resources planning and management consider the factors that affect water supply, population, demand, and the costs to supply water. They spend considerable effort in aligning their decisions with the best available scientific knowledge of these factors. However, there are varying sources of uncertainty including the lack of data, inability to predict future supply and demand, and uncertainty about natural and physical processes of the water cycle in the face of changing environmental, economic, and technological settings (Coates et al., 2012). Negative consequences are especially magnified due to uncertain effects from climate change, where shifting precipitation levels, variable temperatures, and sea level rise could be detrimental. There is also social uncertainty of how individuals and institutions will react to the market and new technical innovations. Finally, conflicting water demands have different levels of political will, financial resources, and institutional practices (Tropp & Joyce, 2012).

1.1.1 Water Supply and Environment

Changes in land use, groundwater levels, and urbanization drive variability in a water resources system. As the demand for water resources and the vulnerability of aging infrastructure increases, the effects of natural disasters may become more disruptive

(Islam & Susskind, 2013). Climate change can affect water supply and human health through variability in the mean temperature and more extreme events, like floods and droughts. Table 1 describes the potential effects of climate change through changes in precipitation, temperature, and sea level rise (Loftus et al., 2011).

Climate hazard	**Impact**	**Effect**
Decreased precipitation	Water scarcity	• Reduced biodiversity and ecosystem services • Increased rates of malnutrition and waterborne diseases • Reduced availability of irrigation water (decreased crop yield) • Decreased ability of thermal power plant cooling processes
	Reduced streamflow	• Reduced sediment and nutrients • Negatively impacted coastal fisheries
Increased precipitation	Flooding	• Damage to transportation infrastructure • Decreased storage capacity • Contaminated water bodies due to overflows
Higher temperatures	Increase in water's bacterial and fungal count	• Higher treatment requirements to remove odor and taste • Reduced water quality due to algal blooms
Sea level rise	Saltwater intrusion into coastal aquifers	• Salinization of groundwater and abandonment of source
	Storm surges and flooding	• Damage to coastal infrastructure

Table 1: Potential climate change effects in an urban environment (Loftus et al., 2011)

1.1.2 Demand and Economy

The population and the water needs of the domestic, commercial, and industrial sectors directly affect the anticipated water demand. Furthermore, unpredictable population growth rates can have significant impacts on forecasts.

For example, population forecasts for Delhi have changed dramatically in the past decade. In 2007, the United Nations (UN) forecasted that Delhi would have 22.5 million people by 2025. In 2011, Delhi's population surpassed this forecast with 22.7 million people and the UN adjusted their forecast for 2025 to 32.9 million people, 46% higher than the 2025 forecast made just four years before. Figure 3 shows projected and actual population values in Delhi according to UN data.

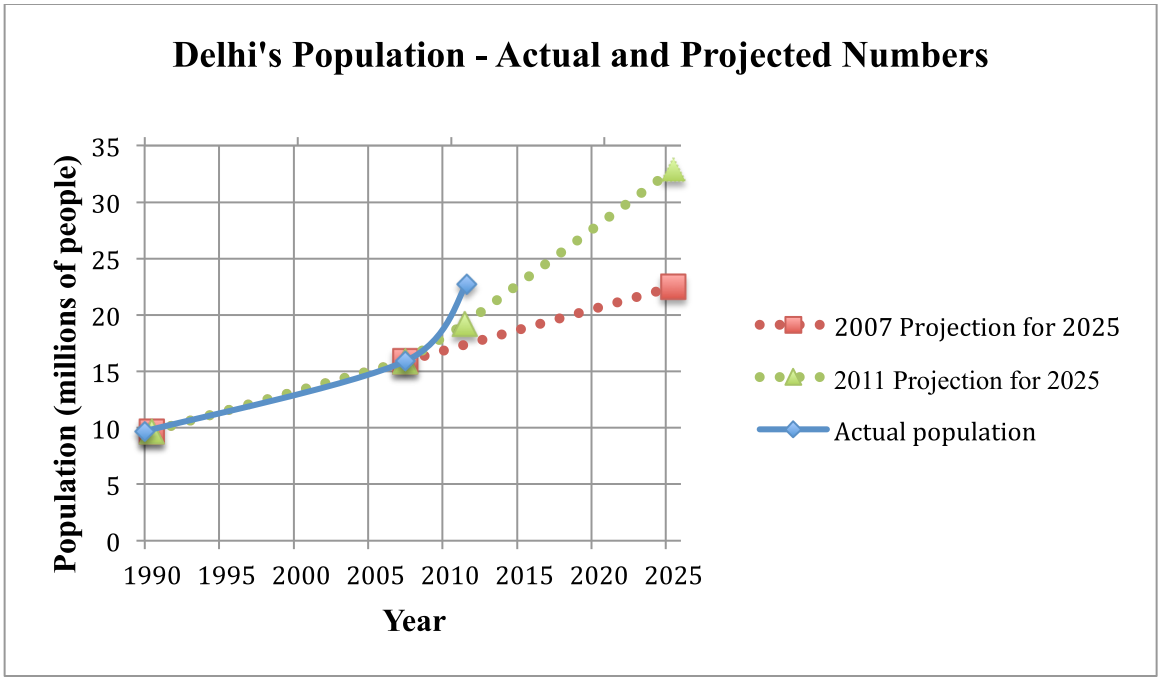

Figure 3: Projected and actual population values in Delhi (United Nations, 2007, 2011)

Despite best efforts to estimate future growth rates, there is still great uncertainty in population forecasts. In particular, forecasts from linear extrapolation are consistently inaccurate and "inherently treacherous" (Toffler, 1985). Relying on forecasts can lead to dangerous situations, including underbuilding future infrastructure.

Conversely, if we overestimate the future population, we may build infrastructure that will be underutilized. One example is in East Germany: in the early 1990s after the fall of the Iron Curtain, many East German cities set up new urban drainage master plans in anticipation of high growth rates. However, the actual population growth was lower than anticipated. The oversized drainage systems and water treatment plants led to very high water prices in the form of wastewater treatment tariffs (Peters et al., 2011).

1.1.3 Water Treatment Technology and Costs

Water equipment technology has greatly improved over time, particularly in industrial and municipal settings where we can now achieve water quality levels that were uncommon a decade ago. Water treatment systems are becoming more energy efficient and safer, while reducing their environmental impact (Milgiore, 2010).

One notable example is the cost of reverse osmosis technology for seawater desalination. In 1995, the price was approximately \$0.80/m^3 (Malek et al., 1996). Ten years later, press releases published a price of \$0.39/m^3 (S\$0.49/m^3) at Singapore's Tuas Seawater Desalination plant, one of the most energy efficient seawater reverse osmosis plants in the world (Black and Veatch, 2006). The management and operation structure of water supply is also changing as many cities are privatizing water treatment operations to reduce costs and improve technical efficiency (Plappally & Lienhard, 2013).

1.2 Thesis Structure and Organization

The objective of this thesis is both methodological and analytical. **Chapter 1 (Introduction)** and **Chapter 2 (Current Approaches)** identify future uncertainty in factors like the environment, water supply, economy, water demand, and technology costs. These uncertainties fuel the need for a flexible approach that can adjust in response to future changes in these factors. These chapters describe current approaches that attempt to consider future uncertainty, but result in strategies that are unresponsive to future change.

Chapter 3 (Flexible Design Approach) describes how flexible design amplifies and adds to existing approaches, and how flexibility can be achieved through size and function. This chapter illustrates efforts to implement flexibility in climate change adaptation frameworks for U.S. water utilities and theoretical analyses of flexible design in academic and professional literature.

Chapter 4 (Case Study) demonstrates an analytical framework of a flexible design approach inspired by Singapore's water resources. The engine is a time-series stochastic analysis in a discounted cash flow Excel model. The chapter identifies key inputs and performance metrics, characterizes uncertainty distributions, and defines strategies with different levels of flexibility. Monte Carlo simulation is used to compare strategy performance through target curves and multiple criteria analyses. This analysis found that the best-performing flexible strategy was 15% cheaper than its inflexible counterpart over a 50-year time span.

Chapter 5 (Implementation) describes leadership efforts from professional organizations and institutions, and addresses implementation barriers regarding institutional resources, flawed perceptions, and data complexity. **Chapter 6 (Conclusions)** synthesizes insight from current approaches, real-world and theoretical analyses, and the analytical case study. It concludes with a discussion of the path moving forward.

2 Current Approaches

A conventional, deterministic planning approach is relatively passive, predicated upon a specific set of assumed possibilities. Generally, these approaches do not systematically consider uncertainty and often rely on forecasts derived from historical or extrapolated data, resulting in a "predict-and-plan" approach (Quay, 2010).

2.1 Conventional Approaches that Neglect Uncertainty

Water resources engineering textbooks (Mays, 1996; Prakash, 2004) largely focus on standardized engineering practices derived from historical rainfall and flow data, while water resources planning handbooks place a significant focus on water demand forecasting. A demand forecast requires a variety of historical data sources including consumption, daily and monthly production, weather, demographics, conservation history, rate structure and pricing, and water loss sources (AWWA, 2007). However, these supply and demand forecasts are frequently wrong, as there is great uncertainty about these values in a constantly changing environment. Conventional methods assume that an area's future hydrology will be similar to past hydrology (Milly et al., 2008) and that the statistical characteristics of hydrological processes will remain stationary (Coates et al., 2012).

Water resources planning textbooks largely ignore variability and uncertainty. Water supply planning projects conventionally describe system performance in terms of a "safe" or "firm" yield, yet droughts have shown that such dependable levels do not exist. Master plans typically project water demand needs for the next 5 to 20 years (Grayman, 2005), but they generally do not state the degree of uncertainty or the implications of imprecise predictions. In addition, practitioners typically use the "most likely parameter value" and ignore parameter uncertainty in distribution systems. While conventional methods may have been adequate when our population and surroundings were more predictable, this may not be the case today.

2.2 Current Approaches that Consider Uncertainty

Examining uncertainty in water distribution systems creates a particularly challenging situation due to the (Grayman, 2005):

- Complexity of the spatial and temporal aspects of the data
- High degree of model uncertainty in system performance factors
- Difficulty in defining an aggregate measure of water distribution system performance that accounts for temporal and spatial factors, as well as hydraulic and quality indicators

The approaches in this section are an improvement to the conventional approach, however they can still lead to strategies that are unresponsive to external change.

2.2.1 Scenario Planning

The scenario planning approach was developed in post-World War II military planning, when the U.S. Air Force attempted to predict their opponents' actions and prepare their reactions (Means et al., 2005). The approach identifies critical uncertainties and driving forces, and then develops a range of potential conditions. It helps to coordinate decision-making with concrete actions. However, one limitation of scenario planning is that the decision maker must pre-determine the scenarios or futures (Means et al., 2005).

In the 1970s, Royal Dutch Shell used the approach to identify potential scenarios that would influence the price of oil including an oil price crisis. This preparation helped to guide the company's decisions within the next decade and facilitated knowledgeable management responses (Means et al., 2005).

2.2.2 Decision Analysis

This approach has been used for many years in water resources (Means et al., 2010), transportation, and sewer planning (Quay, 2010). Decision analysis seeks an optimal strategy over a multi-stage analysis and often uses a decision tree or influence diagram (Barsugli et al., 2012). Although computer software can complete most of the calculations, substantial development effort is still required to determine possible plans, future outcomes, and outcome probabilities.

System optimization is a common approach within decision analysis and aims to maximize the performance from a set of assets or productive sources using methods like linear, non-linear, dynamic, and quadratic programming. Practitioners often use optimization in water resources planning. However, the technique is limited as it assumes that the system's conditions and constraints are well known. Optimization attempts to maximize the benefits from a project or minimize costs, but it does not optimize the system flexibility itself (de Neufville, 2000).

2.2.3 Sensitivity Analysis

Sensitivity analysis methods investigate the relationship between changes in the input data and performance. However, one main disadvantage is it generally involves varying one input parameter while keeping the remaining parameters fixed; it does not measure the combined effects of multiple changes. Another disadvantage is that the sensitivity analysis is usually conducted at the completion stage to check ranking order against parameter estimates. The sensitivity analysis does not resolve the inherent uncertainties in a conventional decision analysis (Hyde et al., 2004).

2.3 Characterizing Uncertainty

2.3.1 Fuzzy Set Methods

In a deterministic approach, the estimated parameters of a groundwater system are treated as true values; we neglect all uncertainty. In contrast, a stochastic approach is non-deterministic and accounts for parameter variance based on the mean values of the parameters (Jones, 1992). Fuzzy set methods express uncertain components of risk and cost as fuzzy numbers. Fuzzy numbers are numerical values where the range of parameter uncertainty is described by the strength or degree of acceptance of possible values.

These methods are particularly useful when there are insufficient data to characterize the uncertainty in detail. Stansbury et al. (1999) argues that fuzzy set methods are advantageous to probabilistic methods such as MCS because:

- Dependencies between parameters must be evaluated in a sensitivity analysis
- There is often insufficient data to characterize the probability distributions of the input parameters, yet there is often enough information to characterize the parameter bounds

2.3.2 Monte Carlo Simulation

The Monte Carlo simulation (MCS) approach uses the concept of random numbers as part of a simulation process. The approach involves building a deterministic model of the process and assigning model parameter values through probability distributions. Then, the model undergoes multiple iterations. The proper application of Monte Carlo simulation requires (Grayman, 2005):

- Identifying sources of uncertainty
- Determining the most important variables within the probabilistic analysis
- Assigning probability distributions to the variables

The ability to meet these requirements depends on each problem and assigning probability distributions is not usually a simple task. Also, the discipline of working through a problem is valuable to the practitioner because it requires an explicit examination and characterization of the uncertainties, and it forces a deeper understanding of the problem (Grayman, 2005).

Multi-criteria decision analysis (MCDA) is an approach commonly used in water resources decision-making that considers multiple criteria and system interactions. Hyde et al. (2004) used an MCDA stochastic approach for two water resources case studies by defining uncertainty in the input values through probability distributions, performing a reliability analysis through MCS, and running a significance analysis using the Spearman rank correlation coefficient. This improved MCDA approach with MCS integrates uncertainty into the input parameters and allows decision makers to investigate the sensitivity of concurrent changes (Hyde et al., 2004). This approach enables the user to compare feasible alternatives by selecting criteria, defining alternatives, weighing the criteria, assessing performance through performance values, conducting sensitivity analyses, and choosing the best alternative.

2.4 Comparison of Approaches in Literature

Generally, conventional methods involve substantial effort in finding the best information available on demand, flows, and costs, and do not typically consider uncertainty or flexibility. In a review of several water resources engineering, planning, and management, “uncertainty” and “risk” rarely appear in the earlier textbooks or are only referenced in the context of supply risk and rainfall data, structural failure risk, or environmental risk assessment. Water resources engineering textbooks tend to focus on structural risk and limit their perception of uncertainty to water supply, thus neglecting uncertainty in water demand. Over time, these approaches have moved toward formally considering uncertainty through more rigorous approaches like scenario planning and decision analysis. However, there are still additional opportunities for improvement. Table 2 shows how different areas of study perceive uncertainty, document approaches, and address flexibility in water resources.

Area of study	**Title, author, and date**	**Considers uncertainty in**		**Provides support for**		
		Water supply	**Water demand**	**Scenario planning**	**Decision analysis**	**Valuation techniques to evaluate flexibility**
Water resources engineering	Water Resources Engineering Handbook (Mays, 1996)	X	X		X	
	Water Resources Engineering: Handbook of Essential Methods and Design (Prakash, 2004)	X				
Water resources planning and management	Water Resources Planning and Development (Petersen, 1984)	X				
	Water Resources Management (Stephenson, 2003)	X	X			
	Water Resources Systems Planning and Management (Loucks & van Beek, 2005)	X	X		X	
	Water Resources Planning Manual of Water Supply Practices (AWWA, 2007)	X		X		
Flexible design approach	Flexibility in Engineering Design (de Neufville & Scholtes, 2011)	X	X	X	X	X

Table 2: Textbook literature in water resources engineering, planning, and management

2.5 Adaptive Management

Adaptive management is a related, though distinctly different concept than flexible design. It aims to help decision makers reduce uncertainty and enable management strategies that can respond to unanticipated events (National Research Council, 2004) and is often used for environmental management projects. Adaptive management focuses on learning from a project or policy's effect and continuously improving future decisions (Medema et al., 2008). There are several classifications that differentiate adaptive management approaches as passive or active: passive approaches reduce uncertainty by using a single design or plan and adjusting hypotheses over time, while active approaches use multiple designs or criteria to test competing hypotheses (Walters & Holling, 1990; National Research Council, 2004; RECOVER, 2010).

2.5.1 U.S. Army Corps of Engineers

The foundations of adaptive management in the United States began as a natural resources management approach from the 1970s (Walters & Hilborn, 1978). The approach entered ecology planning in the 1980s and later gained traction in the U.S. Army Corps of Engineers (USACE) in the 1990s. Since then, the USACE has primarily used the approach for restoring natural systems that are affected by development or new habitat development (Galloway, 2006).

The USACE has also proposed using adaptive management to improve navigation on the Upper Mississippi River, which would modify the construction schedule for locks based on observable demand changes (Galloway, 2006). There are also ongoing adaptive management efforts at various stages at Kissimmee River (Florida), the Everglades Restoration Project (Florida), Assateague Island (Maryland), and Poplar Island (Maryland) (RECOVER, 2010). Recent USACE efforts towards adaptive management include prioritizing the need for further demonstration projects (USACE, 2009).

Adaptive management emphasizes a "learning and adjusting" approach through its development of alternative system models and taking note of observable triggers. While these qualities are similar to that of a flexible design approach, current USACE efforts do not place a strong emphasis on systematically exploring uncertainty drivers and their implications in the planning process.

2.5.2 Murray-Darling Basin in Australia

The Murray-Darling Basin Authority (MDBA) announced their plans to incorporate adaptive management into their decision-making and planning processes for their 2011 Draft Basin Plan. The MBDA is responsible for the water resources management of the Murray-Darling Basin, a region in southeastern Australia with a strong agricultural industry. The Draft Plan aimed to balance the environmental health of the basin through sustainable diversion limits (SDLs) to conserve stream flow (Murray-Darling Basin Authority, 2011).

Their Monitoring and Evaluation Program measures progress towards restoring the environmental health of the basin and uses these results to feed into future Basin Plan improvements. The proposed SDLs will be reviewed over time and adjusted as needed. The MDBA also uses adaptive management on a localized level, which includes actions like releasing floodwater to a forested area to relieve regional flooding (Murray-Darling Basin Authority, 2011).

2.5.3 Focus on the Operational Phase

A flexible design approach systematically compares how different strategies perform under uncertainty in the planning phase. Adaptive management is similar to flexible design because it recognizes that future circumstances change and monitors performance over time. However, when compared to flexible design, adaptive management focuses more on monitoring and adjusting (i.e. coping strategies) in the operational phase. This contrasts with a flexible approach that strongly focuses on maximizing system value through flexibility created in the planning phase and carried out in the operational phase. However, we can still learn from the adaptive policies within these management cases, though they can be better improved with more active management elements. Such cases would benefit from a more detailed characterization of flexibility described in **Chapter 3 (Flexible Design Approach)** and a rigorous multiple uncertainty analysis in the planning phase as demonstrated in **Chapter 4 (Case Study)**.

3 Flexible Design Approach

The proposed flexible design approach builds on approaches from **Chapter 2 (Current Approaches)** and amplifies additional approaches that respond to future change, including real options and dynamic strategic planning. This chapter describes how flexibility can be achieved through size and function, and why decision makers should explore the concepts of learning rates, economies of scale, and the time value of money. Finally, this chapter describes real-world and theoretical analyses of flexibility in planning.

3.1 Approaches that Respond to Future Change

Real options and dynamic strategic planning are approaches that explicitly consider uncertainty and result in strategies that are responsive to future change. They strongly influence the development of a flexible design approach. For resource planning and development, real options and dynamic strategic planning are relatively new concepts.

3.1.1 Real Options

In financial markets, real options is a technique designed to protect investments from the negative effects of market events through options such as project abandonment and growth opportunities in response to current conditions (Trigeorgis, 1996; Saleh et al., 2001). Urban water utilities often use discounted cash flow analyses to evaluate the risk and viability of an investment. The development of real options has recently entered investment valuation techniques under uncertainty. Real options analysis encourages decision makers to evaluate a variety of options with different future profiles. The approach is appropriate in situations where (Borison & Hamm, 2008):

- The comparable project benefits are uncertain
- We can make better decisions over time with future information
- There is flexibility in a project or portfolio component
- There are adjustment costs to reverse the project or project components

A real options approach is especially beneficial for large water infrastructure where the process of determining prices requires committing to capital expenditure plans that have uncertainty in needs, timing, or costs. In some analytical applications of water resources infrastructure strategy (Borison & Hamm, 2008), “real options” is synonymous with “flexible design.” However, the limitation of real options for infrastructure planning is that decision makers in the field are not familiar with the approach. In order to make real options accessible to this group, we need to develop tools that address options valuation in a clear way (Geltner & de Neufville, 2012).

3.1.2 Dynamic Strategic Planning

Dynamic strategic planning combines elements of decision analysis with real options by explicitly recognizing risk and uncertainties, building flexibility into a plan, and adjusting the plan over time. This approach seeks long-term benefits and develops a process to achieve the best results given a range of circumstances (de Neufville, 2000). It is dynamic in that it considers time-dependent changes in a system, whereas a static model calculates a system in equilibrium (Olsen et al., 2000). The dynamic strategic planning approach has been investigated in various industries such as airport planning (de Neufville & Odoni, 2003). The dynamic aspect and focus on performance maximization over a range of future circumstances are integral to the flexible design approach.

3.2 Flexible Design Builds on Current Approaches

A flexible design approach encourages learning from the information we gain over time and sets us up to be strategic with our next move. The future set of rational scenarios is not limited to the initially established conditions and can be characterized by a continuous range of events. By integrating flexible design into the decision-making process, practitioners can respond actively to future change by (de Neufville & Scholtes, 2011):

- Anticipating a range of future circumstances
- Building in insurance against future losses
- Enabling the possibility to respond to desirable situations

For water infrastructure planning, a flexible design approach directly addresses the issue of knowing what to build and when to build it. This approach includes ways to physically adapt water infrastructure to changing conditions. Consider a city's water resources system that must be expanded over time to meet increasing water demand. Unlike a fixed design that locks into an infrastructure or expansion plan that is unable to respond to future circumstances, a flexible plan allows but does not necessitate expansion. A flexible design for a water treatment plant may involve an initial plant with lower capacity that has the ability to expand if needed. This might require the owner to procure the rights for adjacent land or to have the structural capability to build additional water treatment units. We may learn that the population is rapidly growing, so we need more capacity, or that a new treatment technology is now much cheaper than anticipated, so we can alter the expanded plant design for cost efficiency. The flexible design approach is applicable at different spatial scales (national, state, regional, local) and across different decision-making capacities (planning, design, and management).

3.3 Conventional Approach vs. Flexible Design Approach

Figures 4 and 5 highlight the difference between the conventional “predict-and-plan” technique with a flexible design approach using theoretical values. In Figure 4, the forecast of water customers (blue line) represents an estimate made at Year 0: 140,000 water customers by Year 20. However, the actual number of customers (red line) accelerates more quickly than anticipated. If decision makers still rely on their original plan, they may not be financially or institutionally prepared to build additional infrastructure by 2020 to serve the increasing demand.

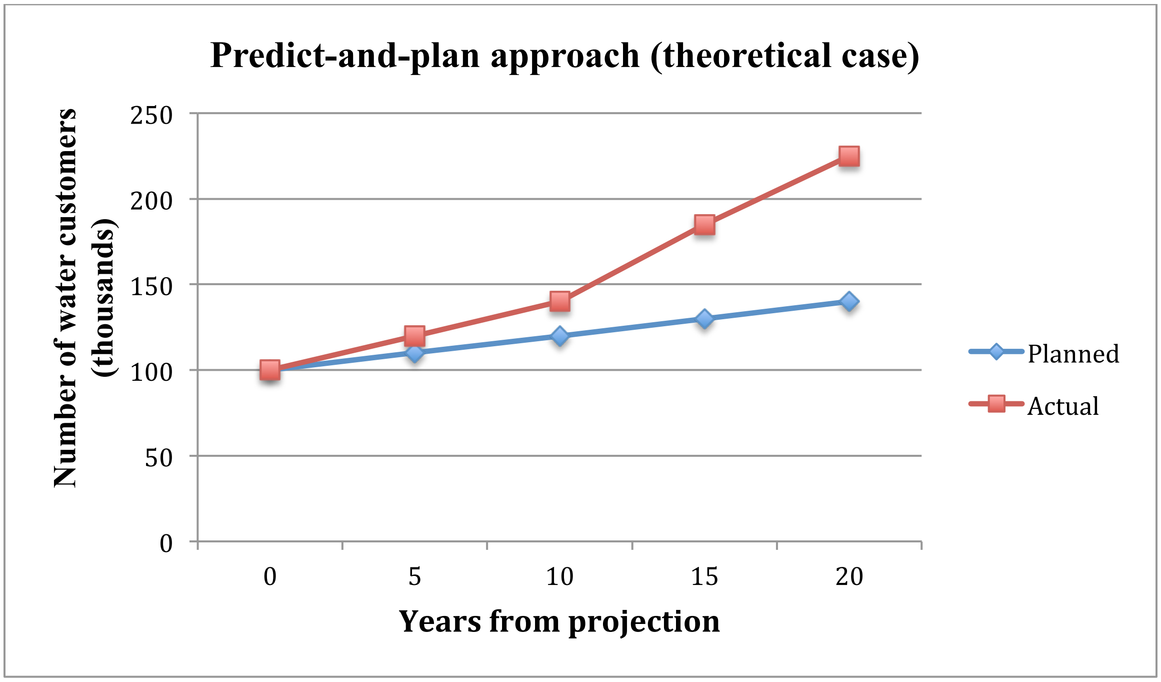

Figure 4: Conventional predict-and-plan approach over a 20-year period

In Figure 5, decision makers evaluate the current population every five years and adjust their water infrastructure construction plan accordingly. This changes the nature of the blue line, which is now no longer a severely underestimated forecast, but a moving line that more closely follows the actual water needs.

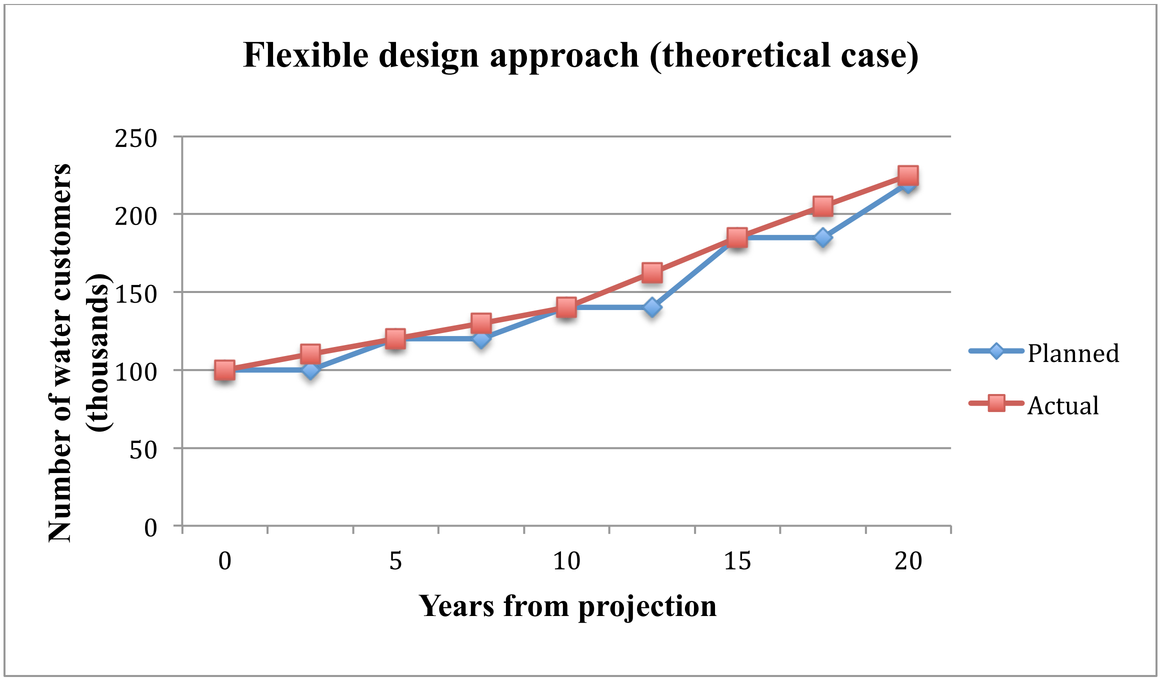

Figure 5: Flexible design approach over a 20-year period

The flexible design concept builds on existing approaches previously described in this chapter and **Chapter 2 (Current Approaches)**. Figure 6 shows how the flexible design approach can amplify and add to these approaches.

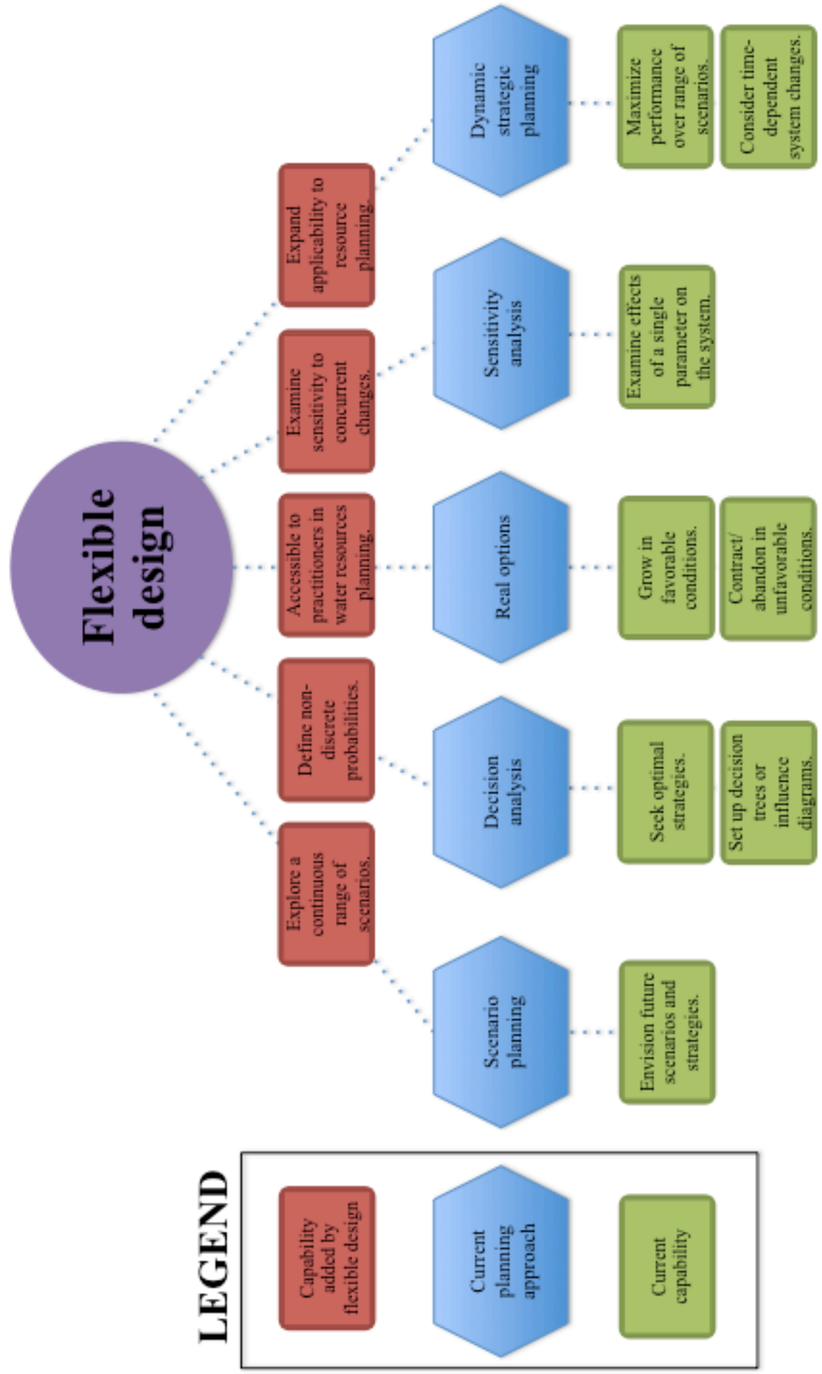

Figure 6: Flexible design approach amplifies and adds to current approaches' capabilities

3.4 Flexibility in Size

Flexibility in infrastructure size facilitates adding capacity when demand increases. An expandable design contains the built-in capacity to increase in size, such as bridges that are built with additional strength that could support a second deck if the demand arises (de Neufville & Scholtes, 2011).

Desalination plants often facilitate size changes through modularity. One example is in ENERCON's seawater desalination plants, which use 20-foot containers that each contains a separate part of the plant. Figure 7 showcases the modular container design, which facilitates transport and setup, protects the plant from the outer climate, and facilitates removal and replacement of the modules (ENERCON GmbH, 2005).

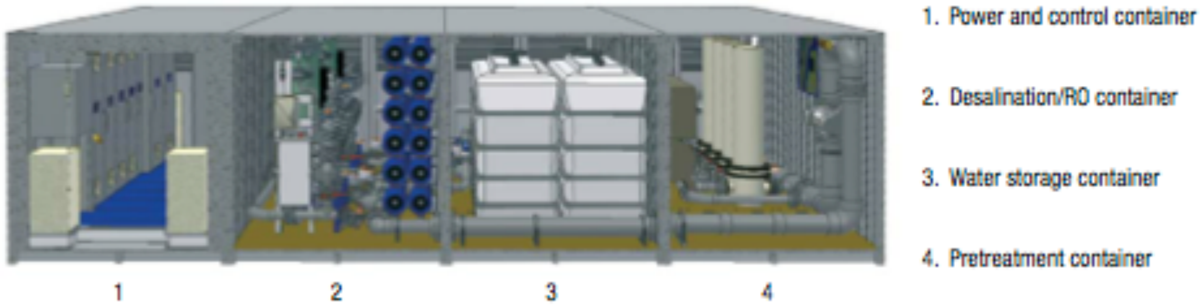

Figure 7: ENERCON's modular seawater desalination plant design (ENERCON GmbH, 2005)

Another example of flexibility in size is the operation of seawater desalination plants by Hyflux Ltd. based in Singapore. In the Tuaspring Seawater Desalination plant, the desalination plants are modular. This modularity is compatible with their Distributed Control System (DCS), which uses continuous information and data management to perform automation, operational control, and plant data monitoring. The DCS is also an interface for their flexible instrumentation and control concepts, and allows future expansion by adding equipment as needed (Hurn & Hagedorn, 2012). Figures 8 and 9 show aerial and interior views of the Tuaspring Desalination Plant in Singapore.

Figure 8: Aerial view of Hyflux's Tuaspring Desalination Plant (Hurn & Hagedorn, 2012)

Figure 9: Interior view of Hyflux's Tuaspring Desalination Plant (Hurn & Hagedorn, 2012)

3.4.1 Learning Rates

Learning rates refer to the common observation that as we produce more items, the cost to build subsequent items becomes cheaper. Thus, unit costs decrease with increasing experience. Current literature also describes these patterns as learning curves, progress curves, experience curves, and learning by doing. The most common rate formulation is that the unit cost decreases by a fixed percentage (the learning rate) each time the experience doubles. This is because companies become more efficient over time, alter design elements, introduce new technologies, or find ways to eliminate waste in the construction process (de Neufville & Scholtes, 2011). Recent efforts have quantified these learning rates based on experience accumulation and cost reduction data for energy technologies, which are particularly useful for applications in long-term energy studies (McDonald & Schrattenholzer, 2001).

3.4.2 Economies of Scale

Economies of scale describe how it is cheaper per unit to build facilities in larger sizes. This concept is prevalent in many types of infrastructure and drives decision makers to build larger facilities. It is important to note that the economies of scale concept often overstates the case for building large infrastructure upfront because it assumes that we will use all of the installed capacity immediately. The reality is that some of this capacity will remain unused until it is needed, so the actual economies of scale are often less than their calculated potential. This reality counteracts some of the economies of scale effect (de Neufville & Scholtes, 2011).

3.4.3 The Time Value of Money

The present value of a deferred cost is lower than the immediate value of that cost; we would rather pay later, assuming the price remains the same. This leads us to value a phased design instead of building all of the capacity upfront. A phased design allows decision makers to expand capacity in smaller units, which is advantageous in deferring construction costs. Phased construction also allows further cost reductions in future infrastructure as we learn how to build units more effectively. The cost reductions from a phased design counteract the advantages of economies of scale (de Neufville & Scholtes, 2011).

However, a phased design may disrupt an earlier phase's operations and require companies to increase their design and implementation efforts. Also, high transaction costs can make it more economical to reduce the number of purchases. Finally, an inflation rate that is higher than the discount rate would lead us to value a design that builds the capacity upfront (de Neufville & Scholtes, 2011).

3.5 Flexibility in Function

Flexibility in the system's function may allow operators to remove, add, or adjust the function. One example is in ENERCON's desalination plants that are flexible at the production level. A plant's water production can range between 12.5% and 100% of the nominal capacity by adjusting the piston speed. This flexibility allows operations to continue running with a fluctuating energy demand. Also, operators can adjust the output depending on water demand without shutting down the plant (ENERCON, GmBH, 2005). Figure 10 shows the flexible operation range versus a conventional plant's fixed operation point.

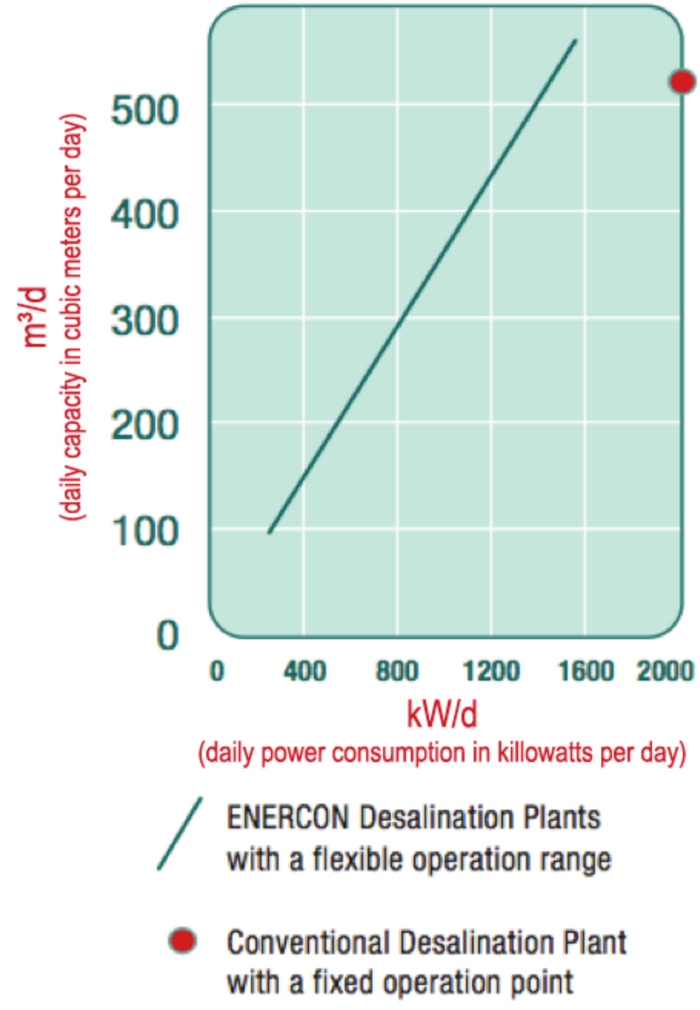

Figure 10: ENERCON's flexible operation range, daily power consumption vs. daily capacity (adapted from ENERCON GmbH, 2005)

3.6 Climate Change Adaptation in Water Utility Planning

Water utilities in Denver and Phoenix are currently using scenario planning and elements of a flexible design approach in the context of climate change adaptation. Their efforts involve systematically considering structural flexibility and uncertainty analysis in the initial planning process. Both utilities consider a range of possible futures to guide current decisions and explore how uncertainty affects decision-making. Though their approaches are not identical to the proposed flexible design approach, we can gain valuable insight from their efforts.

3.6.1 Denver Water

Denver has historically faced water resources issues including severe droughts and water shortages from the Colorado River. Denver Water is the region's public utility that serves over 1.3 million people across 335 square miles. In 2007, Denver Water conducted a vulnerability assessment to examine challenges in response to two simplified scenarios with projected temperature increases. The utility used a hydrologic model created by the Colorado River Basin Forecast Center (Denver Water, 2009). The assessment concluded that keeping precipitation constant, two anticipated temperature increases would affect streamflow and water supply as shown in Table 3.

Temperature increase (°F)	**Streamflow reduction (%)**	**Water supply reduction (%)**
2	7	7
5	19	14

Table 3: Denver Water's vulnerability assessment on temperature effects (Denver Water, 2009)

In 2008, Denver Water created an Integrated Resource Plan (IRP) that combined a traditional scenario planning approach with prioritized factors that would contribute to future uncertainty (Quay, 2010). They chose to use scenario planning because it allowed them to identify and rank critical uncertainties, and facilitated "out-of-the-box" thinking in defining a spectrum of impacts (Denver Water, 2009). Stakeholder participation included discussing scenarios and priorities with the Denver Water board, customers, and regional water providers. Denver Water grouped factors into five possible scenarios, then conducted future analyses that explored the range of potential climate change impacts. Finally, they identified signposts that would alert planners when a certain scenario is likely to occur, such as reservoirs reaching certain levels, indicating that water demand will likely exceed available supplies. Denver Water is currently developing a decision framework that includes a detailed short-term plan and options for the long-term (Quay, 2010). Since 2010, there has been limited documentation regarding their scenario planning and adaptive management efforts, partially due to board delays in finalizing the IRP (Denver Water, 2012).

3.6.2 Phoenix Water Services Department

Phoenix Water Services Department examined the impacts of global climate change on normal and drought conditions. Phoenix has historically experienced highly unpredictable wet and dry periods, ranging from 10 to 100 years long (Quay, 2010). Tree ring research shows that 20-30 year droughts were not uncommon in the region over the past 1,000 years (City of Phoenix, 2012).

The city currently uses reservoirs to store excess flow from wet periods and supply water during dry periods. In the previous 2005 plan, they defined ranges of future possibilities for three factors: delivery of surface water supplies, regional growth and development, and consumers' water use behavior. Combined with a range of drought conditions, spatial growth patterns, and levels of consumer use, the Department generated 144 scenarios of supply, demand, and the resulting water budgets (Quay, 2010).

Since they adopted the 2005 plan, have monitored trends, growth, and demand. They have also adjusted their trigger points with new information. For example, the recent economic recession resulted in the slowing growth of new consumers, so this moved some trigger points into the future (Quay, 2010).

In 2010, their updated plan involved downscaling global climate model output to replace the climate scenarios from the 2005 plan. Stakeholder involvement included regional water suppliers, various interest groups, and the city council. Through their analyses, they identified a portfolio of robust strategies that would work in the short-term, as well as a worst-case infrastructure timeline that portrayed the timing and magnitude of water shortages for the next 25 years over a 30-year dry period. They estimated trigger points where they would need to deploy mandatory demand reductions or provide more water supplies (Quay, 2010).

3.7 Theoretical Analyses of the Flexible Design Approach

Several theoretical analyses of flexible design highlight the applicability of the flexible design approach across a variety of complex systems.

3.7.1 Water Infrastructure Investments in Sydney

Urban regions in Australia have historically experienced very variable annual rainfall. An analysis contracted by the Water Services Association of Australia (WSAA) investigated flexibility in water resources planning. This study examined investment flexibility, described as the ability to learn about uncertainties over time and respond appropriately while learning (Borison & Hamm, 2008).

The analysis used risk-adjusted decision trees and planned decisions in stages at five-year intervals. It tested two fixed strategies and one flexible strategy. The fixed strategies committed to building desalination plants and importing water, respectively. The flexible strategy had a "wait/recycle" alternative that reflected the possibility that recycling may be a more feasible alternative. The flexible strategy divided the desalination cost uncertainty into three periods, which reflected the learning that may result from building additional plants. This hypothetical analysis found that a flexible strategy resulted in $400 million or 20% more value than the best fixed strategy. The flexible strategy also reduced risk by $500 million, measured by standard deviation (Borison & Hamm, 2008).

3.7.2 Urban Drainage Systems in Hamburg

Research efforts at the University of South Florida (USF) examined flexible strategies in urban drainage system designs. Since drainage systems have an operation life span of 40 to 80 years, predictions for future drainage needs can be difficult to make. The USF research group conducted a hypothetical case study using the new residential quarters of the Dorfanger-Boberg area in Hamburg, Germany. The model of this system is applicable to sustainable urban drainage areas in a new development site (Eckart, 2012).

First, the group identified the required flexibility by describing future scenarios. Second, they generated alternative solutions with inflexibility and flexibility. Next, they filtered the most promising alternative solutions through two significance cases: a chi-square test and F-test (Eckart, et al., 2010). Out of the 22 alternatives with varying levels of flexibility in modular platform design, decentralized structure, real time control, and scalability, they chose eight alternatives for future study and identified the most optimal alternative (Eckart, 2012). Then, they measured flexibility by modeling the life-cycle costs of the alternative solutions in a time-series model with different trigger levels at which flexibility was considered. Finally, they selected the optimal alternative solution that maximized flexibility by minimizing the performance regret, "effort of change" regret, and "range of change" regret (Eckart et al., 2010).

3.7.3 Deep-water Oil Fields

Another analysis case of flexible design was in resource management of deep-water oil fields. The application of flexible design for a major deep-water oil field demonstrated a 78% increase in the project's expected value and a 20% reduction in the initial capital expenditures. This analysis consisted of a three-step process, including a Monte Carlo simulation to determine the distribution of possible outcomes, a multidimensional analysis of the costs and benefits, and the validation of a strategic choice by considering investment timings and sensitivities (Lin et al., 2009; de Neufville & Scholtes, 2011).

3.7.4 Regional Water Allocations in India

There can also be flexibility in water allocation policies. In India, cities and industries are rapidly growing in water scarce areas. The increasing demand for waste management and reliable water supply strains existing water resources. Agriculture is shifting from low-value grains to high-value crops, which increases drip irrigation (Briscoe & Malik, 2006). With limited water supplies and changing demands, national and regional decision makers are currently unable to optimize their water management policies in a shifting society. To explore different strategies that would allow water allocations to change alongside current needs, they could consider flexibility in their distribution policies.

In the Tamil Nadu region, a major drought in the 1990s forced major chemical and fertilizer plants outside of Chennai to close for six months. A study of the Tamil Nadu region compared the water use and economic performance of the existing rigid allocation methods with that of a flexible system, where the flexible system allows changes in water allocations for agriculture, domestic, and industry sectors. The flexible allocation scenario resulted in a 21% larger economy in 2020 and 15% lower water use than the fixed allocation scenario. In the flexible scenario, the water allocations changed as the economic value of water transformed across each sector over time (Bhatia et al., 2005).

3.8 Learning from the Past

We can gain valuable insight from examining real-world and theoretical analyses that investigate flexibility. Water utilities in Denver and Phoenix are analyzing scenarios to anticipate a range of different futures and using observable signposts to trigger their actions. Their incremental approach minimizes their initial investment so they can delay further decisions until they gain better data and knowledge. **Chapter 4 (Case Study)** develops a complementary flexible design framework that intends to be generally applicable to water resources systems.

It is important to note that Denver and Phoenix face several obstacles moving forward. First, is often unclear how climate indicators, such as atmospheric CO_2, can project long-term global climate change patterns at a regional level (Quay, 2010). This is a technical barrier that regional planners may face in future work, especially regarding climate change where models are typically based on a larger scale. Second, institutions including water utilities face various barriers to implement a flexible approach, which are discussed in detail in **Chapter 5 (Implementation).**

4 Case Study

This chapter describes an example framework of a flexible design approach. It acknowledges that with limited knowledge about the future, engineers and planners must decide what technology to invest in, how to size facilities, and when to build infrastructure. This framework intends to be universally applicable across various water resources systems.

The framework's model addresses future uncertainties including the annual population growth rate, per capita water use, and the operating cost of desalination plants. It also considers financial benefits from economies of scale and learning effects. The methodology includes setting up the resource model, identifying system performance metrics, identifying key inputs and uncertainties, and choosing development paths. Then, the model uses in a discounted cash flow Excel model to define optimal development strategies that are flexible and responsive to future changes. Singapore's water resources system inspires the model.

4.1 Introduction

Singapore is an island nation that is highly constrained in land and natural rainfall storage (Tortajada, 2006). Future uncertainties in Singapore's water system lie in factors such as population, water demand, energy prices, and improvements in water treatment technology.

The Public Utilities Board (PUB) is Singapore's national water agency that is responsible for managing the investment, construction, maintenance, operation, and pricing structure of Singapore's water infrastructure. Singapore's four water supply sources, also known as taps, include:

- Imported water from Malaysia
- Reservoirs (catchment areas)
- NEWater (high-grade reclaimed wastewater purified with dual-membrane and ultraviolet technologies)
- Desalinated water (seawater through a reverse osmosis desalination process)

The model assumes that the four sources feed into Singapore's water supply in the proportions shown in Figure 11, which are based on PUB's annual reports (PUB, 2010) and additional assumptions outlined in the Appendix.

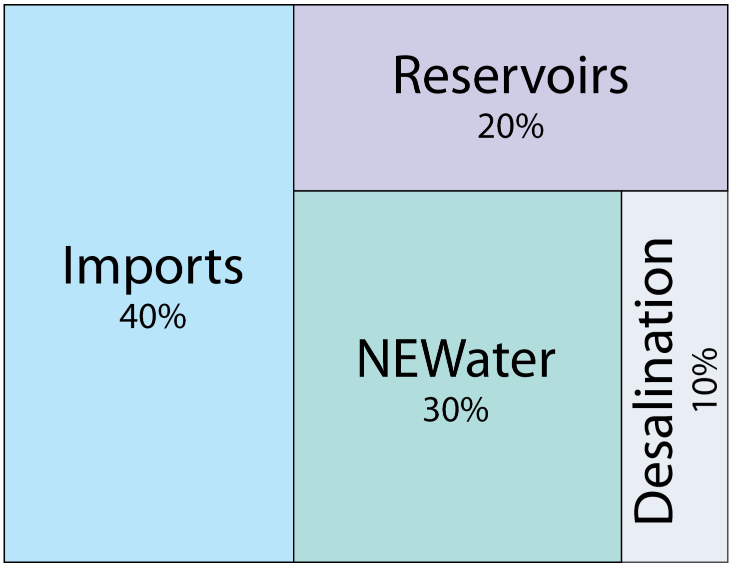

Figure 11: Assumed current loads: demand fulfillment rates for four taps (based on PUB, 2010)

The deterministic and inflexible strategies in this analysis assume that future water infrastructure will be built according to 2060 infrastructure goals. Figure 12 shows the projected infrastructure portfolio for the total water demand in 2060, which is based on annual reports (PUB, 2010) and additional assumptions discussed in the Appendix.

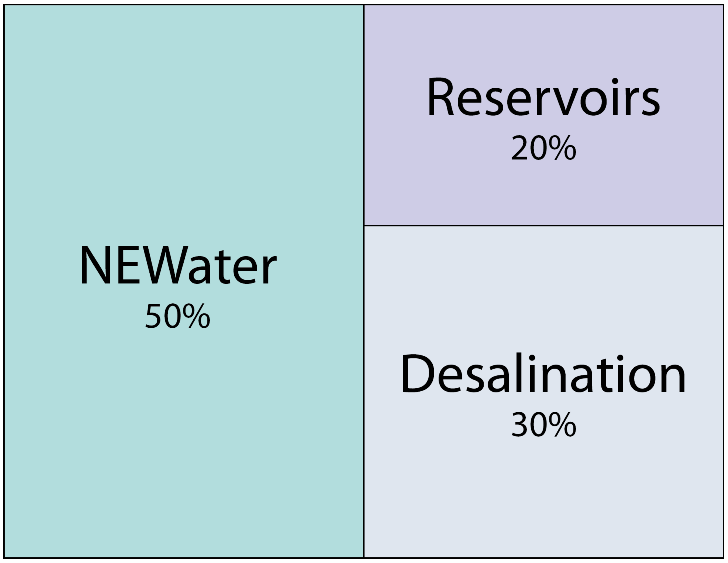

Figure 12: Assumed 2060 goal loads: demand fulfillment rates for four taps (based on PUB, 2010)

4.2 Model Setup

4.2.1 Methodology Overview

The following steps outline the methodology of the analysis.

1. ***Set up an Excel model with demand and supply parameters.*** The example analysis used a simplified screening model that accounted for water demand, supply, and costs from 2010 to 2060.

2. ***Identify system performance metrics that will facilitate strategy comparison.*** The example used the NPV (net present value) of the cost to build and operate the water infrastructure over the 50-year timespan. The discount rate was 10%.

3. ***Identify key inputs, uncertainty distributions, and development strategies or paths.*** The demand parameters included the annual population growth rate, per capita water usage, and a ratio of domestic/commercial water demand. The supply parameters included the land availability, fixed costs, and operating costs of each water supply source. The model characterized uncertainty distributions on the annual population growth rate, the per capita water usage in 2060, and the operating cost for desalination plants in 2060. There were eight total development paths (deterministic, inflexible, and flexible).

4. ***Simulate performance through a Monte Carlo simulation.*** The model used Excel's @RISK add-on to perform a simulation with 5000 iterations.

5. ***Measure performance through target curves and multiple criteria analyses.*** The analyses measured performance through cost target curves (NPV vs. cumulative probability) and multiple criteria analyses based on mean, P5, and P95 values.

4.3 System Assumptions

4.3.1 Fixed and Operating Costs

Since this study focuses on the framework development, the model incorporated limited information from press releases, historical data, and current literature. Table 4 shows the assumed fixed (new construction) and operating costs for the four water sources.

Tap	Cost, S$ per cubic meter	
	Fixed	Operating, O_B
Imported water	-	0.003
Reservoir	1,329	0.25
NEWater plant	1,351	0.30
Desalination plant	1,818	0.49

Table 4: Current fixed and operating costs

Imported water, reservoirs, NEWater plants, and desalination plants fulfill the current daily water demand, previously shown in Figure 11. The model assumed that the present facilities would continue to fulfill the current daily demand of 1.7 million cubic meters (MCM) and that there would be a 0% draw of imported water by 2060. The decreasing dependence on imported water occurred linearly in the model. See the Appendix for further discussion on fixed costs, operating costs, and the 0% draw assumption.

4.3.2 Learning Rates and Economies of Scale Factors

As described in detail in Section 3.4, learning rates describe how unit costs decrease with increasing experience. Learning rates are often modeled by reducing costs by a certain percentage after total capacity doubles. *Equation 1* defines the slope B of the learning rate, L (de Neufville & Scholtes, 2011).

$$B = \frac{\ln(100\% - L\%)}{\ln(2)} \tag{1}$$

Equation 2 describes the functional form, where $\mathrm{U_i}$ is the production cost per cubic meter of the ith unit, $\mathrm{U_1}$ is the fixed cost per cubic meter, and B is the slope of the learning rate (de Neufville & Scholtes, 2011):

$$U_i = U_1 i^B \tag{2}$$

To evolve the operating costs over time, the model applied the assumed learning rate as a function of the base operating cost, learning rate, and cumulative infrastructure capacity. *Equation 3,* derived from *Equations 1 and 2*, describes how the operating cost, O_T, evolves over time in relation to the base operating cost from Table 4, O_B:

$$O_T = O_B i^{\frac{\ln(100\% - L\%)}{\ln(2)}} \tag{3}$$

The assumed learning rates in this analysis consider the nascent nature of each technology. Desalination has the highest cost per unit out of the supply technologies in consideration. Due to its high potential to become more efficient through further research and development, it was assigned the highest learning rate.

Economies of scale describe how it is cheaper per unit to build facilities in larger sizes. For each facility type, the model assigned an economies of scale factor, A, based on the realistic range of 0.6 to 0.7 (de Neufville & Scholtes, 2011) and the relative nascent nature of each technology. The model assigned the most significant (i.e. the smallest) factor A to reservoirs. It then determined the coefficient, K, for each facility from historical cost data from Table 5.

Equation 4 details the economies of scale calculation (de Neufville & Scholtes, 2011):

$$Average\ cost\ of\ capacity = K(capacity)^{A-1} \tag{4}$$

To evolve the fixed costs for new infrastructure over the timespan, the model applied the economies of scale factors and learning rates. Table 5 shows the assumed learning rates and economies of scale factors. K is calculated from the cost and capacity data in the Appendix.

Tap	**Learning rates**		**Economies of scale**	
	Learning rate, L (%)	**Slope, B**	**Economies of scale factor, A**	**Coefficient, K (10^3)**
Reservoir	5	-0.074	0.60	164
NEWater plant	10	-0.152	0.65	87
Desalination plant	20	-0.322	0.70	59

Table 5: Economies of scale, learning rates, and associated coefficients

4.3.3 Facility Sizes

To examine the value of building different facility sizes, the model assumed that the building strategy would build either "small" or "large" infrastructure with certain daily capacities. It based "small" capacities on current daily capacities. "Large" capacities were double the current daily capacities. Table 6 describes the current fulfillment rates of each facility type and future sizes for future construction. For more details on assumptions for "small" capacities, see the Appendix.

Tap	**Daily Capacity (10^3 cubic meters)**		
	Current total	**Small**	**Large**
Imported water	680	-	-
Reservoir	510	148	296
NEWater plant	340	110	220
Desalination plant	170	170	340
Total	1,700	-	-

Table 6: Current fulfillment rates and assumed facility sizes

4.4 Path Development With a Static Forecast

4.4.1 Deterministic Path Development

Deterministic paths reflect conventional planning methods that do not consider uncertainty. These paths assumed the following assumptions for 2060, which were projected linearly throughout the timespan:

- Singapore's daily water demand will double from 1.7 MCM (current) to 3.4 MCM
- The operating cost for desalination will be S$0.40 per cubic meter

The model used these assumptions to determine how much additional supply capacity needed to be built. It used the 2060 goal loads in Figure 12 to choose what type of infrastructure to build. The model calculated the number of facilities needed by dividing the additional capacity required by the "small" or "large" capacity sizes for each technology. Table 7 describes these facility choices.

Tap	**Load of total water supply (%)**		**Facilities requested for**	
	Current	**2060 goals**	**“Build small”**	**“Build large”**
Imported water	40	0	0	0
Reservoir	20	20	3	2
NEWater plant	30	50	8	5
Desalination plant	10	30	7	4
Total	100	100	18	11

Table 7: Facility choices for deterministic path development

The model determined the build schedule and spread out the timing and type of built facilities. Construction began in 2015 and continued in 5-year increments until 2060. The model built up to three facilities in each time period. The build schedule ensured that the total water demand fulfilled was equal to or higher than the projected water demand for each time increment. The model calculated the performance of the deterministic paths through the net present value calculation with a discount rate of 10%.

4.5 Path Development Under Uncertainty

4.5.1 Characterizing Uncertainty

The remaining paths – inflexible and flexible – considered uncertainty in the following factors:

- The annual population growth rate
- Per capita water demand in 2060
- The operating cost of desalination plants in 2060

Figures 13, 14, and 15 show the assumed probability density functions.

Annual population growth rate: A normal distribution with a mean value of 2% and standard deviation of 0.5%. The mean value was based on historical UN population growth data (UN Data, 2011). Figure 13 depicts the growth rate's distribution.

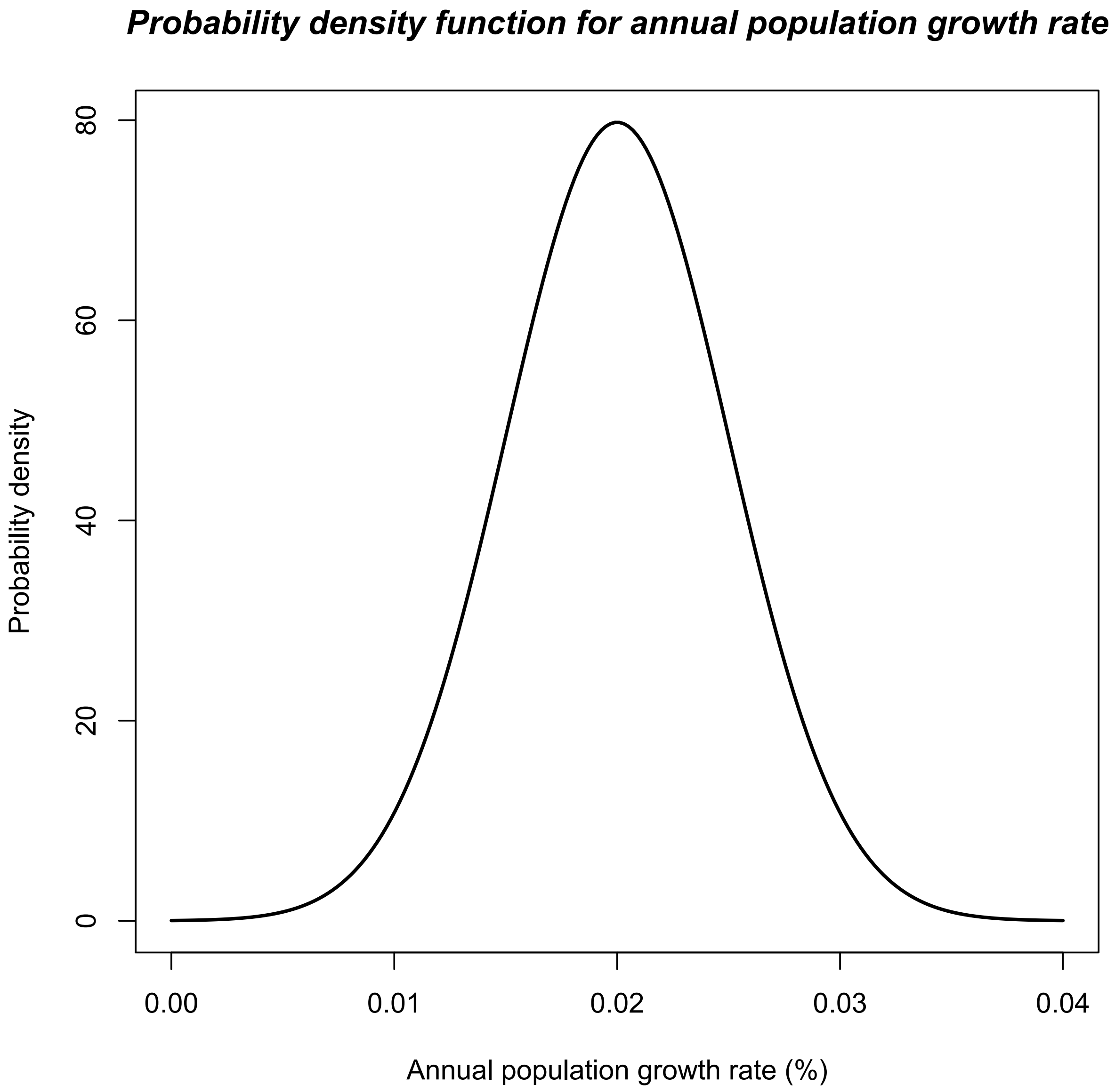

Figure 13: Probability density function for annual population growth rate

Daily per capita water demand: A normal distribution with a mean of 0.30 cubic meters per day and standard deviation of 0.04 cubic meters per day. Figure 14 depicts the per capita water demand distribution.

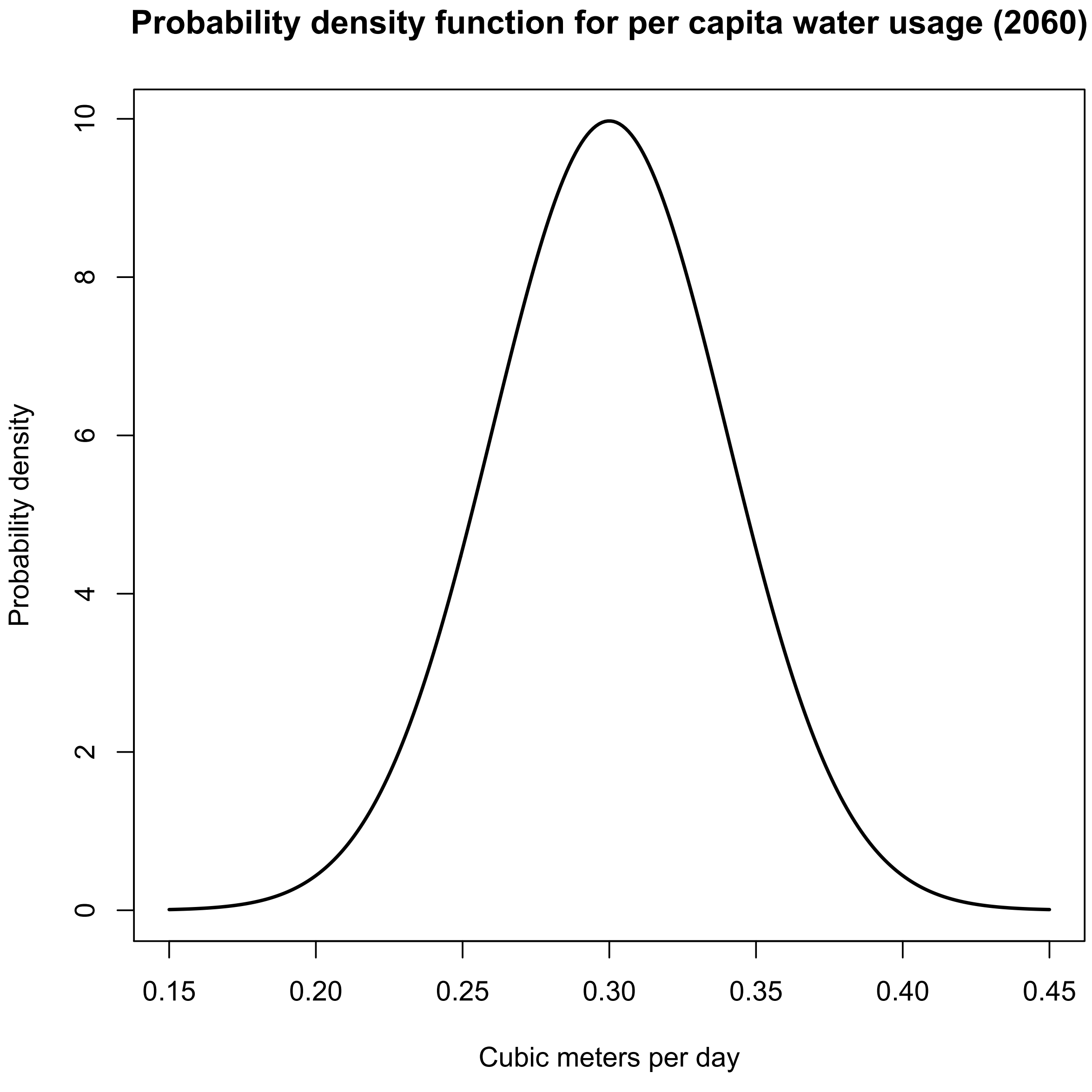

Figure 14: Probability density function for per capita water usage (2060)

Operating cost of desalination in 2060: A Weibull distribution with a shape of S$2.00, scale of S$0.20, and shift of S$0.10. A Weibull distribution was chosen because it could characterize skew towards lower values, reflecting the assumption that the price will likely decrease due to research and development efforts in desalination technology. Figure 15 depicts the desalination operating cost distribution.

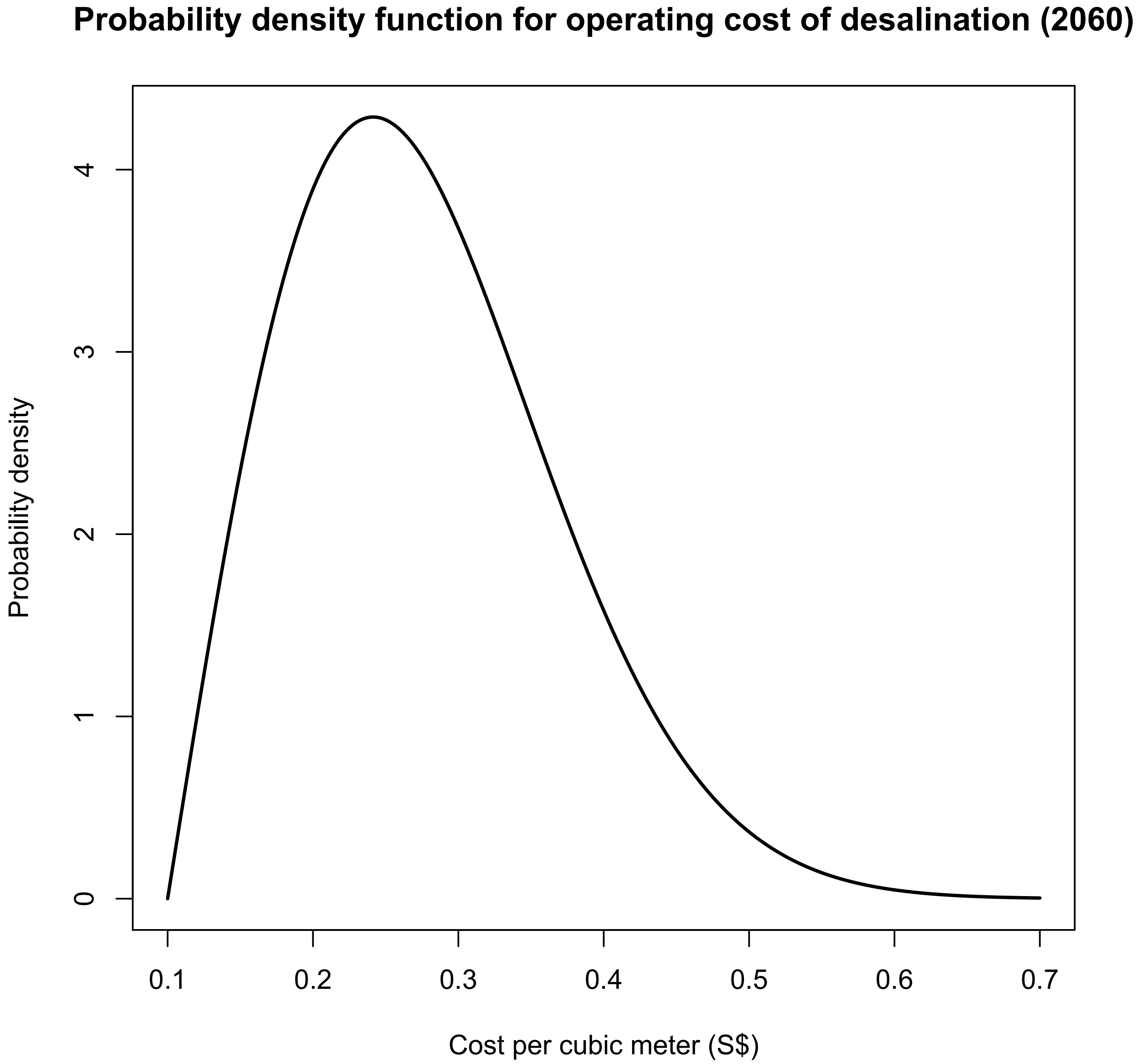

Figure 15: Probability density function for operating cost of desalination (2060)

4.5.2 Inflexible and Flexible Path Development

The two inflexible development paths act within a fixed resource allocation under uncertainty. The planning decisions followed the same number and type of new infrastructure as the deterministic scenarios from Table 7, however the build schedule was automated in Excel. The model spread the capacity load among the technologies according to the 2060 goal loads from Figure 12.

The four flexible development paths made decisions based on a flexible resource allocation plan under uncertainty and did not rely on goal loads when choosing the facility types. Instead, the model fulfilled the additional amount of water demand by minimizing the anticipated capital and operating costs.

Two of the flexible scenarios forced one desalination plant to be built every ten years. If the facility choice driver requested a desalination plant during the same time period of a forced desalination plant, then two desalination plants were built. By investigating the effect of "forcing" the construction of desalination plants, the model provided insight into the long-term benefits of investing in desalination technology. Table 8 describes the six inflexible and flexible development paths.

Development path	**Path #**	**Facility size**
Inflexible	1	Small
	2	Large
Flexible	3	Small
	4	Large
Flexible with forced desalination	5	Small
	6	Large

Table 8: Description of inflexible and flexible development paths

4.5.3 Model Diagram

Figure 16 is a schematic diagram of the model's elements and interactions. The uncertain factors in the red boxes describe the distributions from Figures 13, 14, and 15.

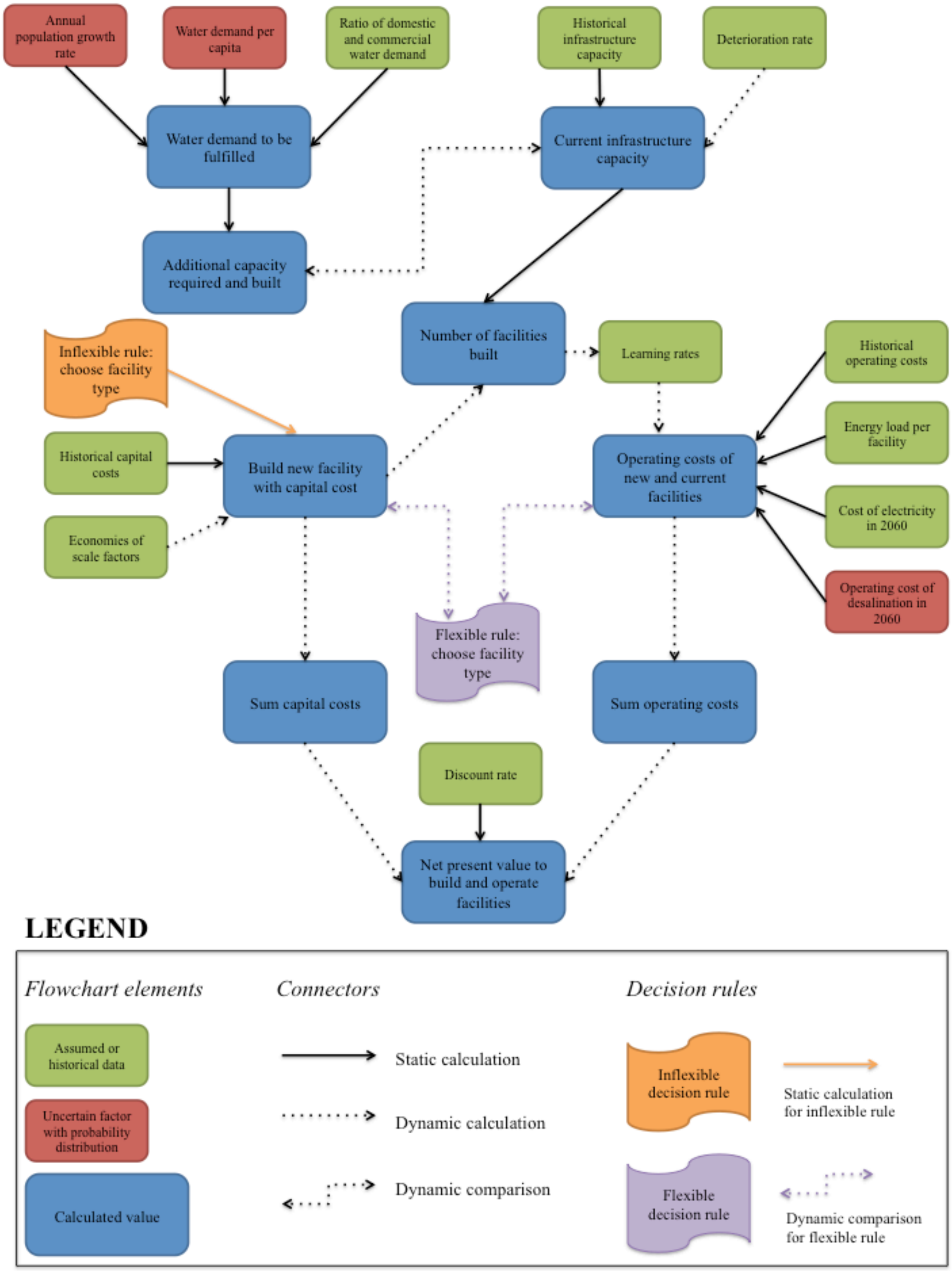

Figure 16: Schematic diagram of the model

4.6 Simulation and Results

4.6.1 Monte Carlo Simulation

Monte Carlo simulation is valuable because it allows the model to consider a range of future scenarios over multiple iterations, as previously described in Section 2.3. Using the @RISK software add-on, the model ran a Monte Carlo simulation of 5000 iterations on the deterministic, inflexible, and flexible development paths. The simulation results consisted of NPV performance values for each path's iteration.

4.6.2 Multiple Criteria Analysis

Table 9 shows the mean, P5, and P95 NPV values for the inflexible and flexible development paths. The values of flexibility were calculated by comparing the mean values of the flexible paths to the corresponding inflexible paths.

Development path	**Path #**	**Facility size**	**Value (billions of S$)**			
			Mean cost	**P5 cost**	**P95 cost**	**Mean value of flexibility**
Inflexible	1	Small	6.03	3.96	9.16	-
	2	Large	5.54	3.68	8.33	-
Flexible	3	Small	5.52	3.60	8.41	0.51
	4	Large	4.69	3.07	7.14	0.85
Flexible with forced desalination	5	Small	5.70	3.76	8.70	0.33
	6	Large	4.84	3.20	6.54	0.70
Dominant scenario?			4	4	4	4

Table 9: Multiple criteria analysis with mean, P5, P95, and mean value of flexibility

From the multiple criteria analysis, the flexible "large" development path had the lowest cost when measured by mean value, P5 value, and P95 value. It also had the highest mean value of flexibility. The flexible scenarios add S$330 to S$850 million in present value terms to the system when compared to their inflexible counterparts. The most dominant path had a 15% cost savings from its corresponding inflexible path that used deterministic planning. See the Appendix for a detailed calculation.

4.6.3 Target Curves

Deterministic vs. Inflexible

Target curves present the distribution of possible values associated with each development path. Figure 17 compares the performance of the deterministic paths with their corresponding inflexible paths. The x-axis contains the NPV and the y-axis contains the probability that the realized performance will be lower than the target NPV.

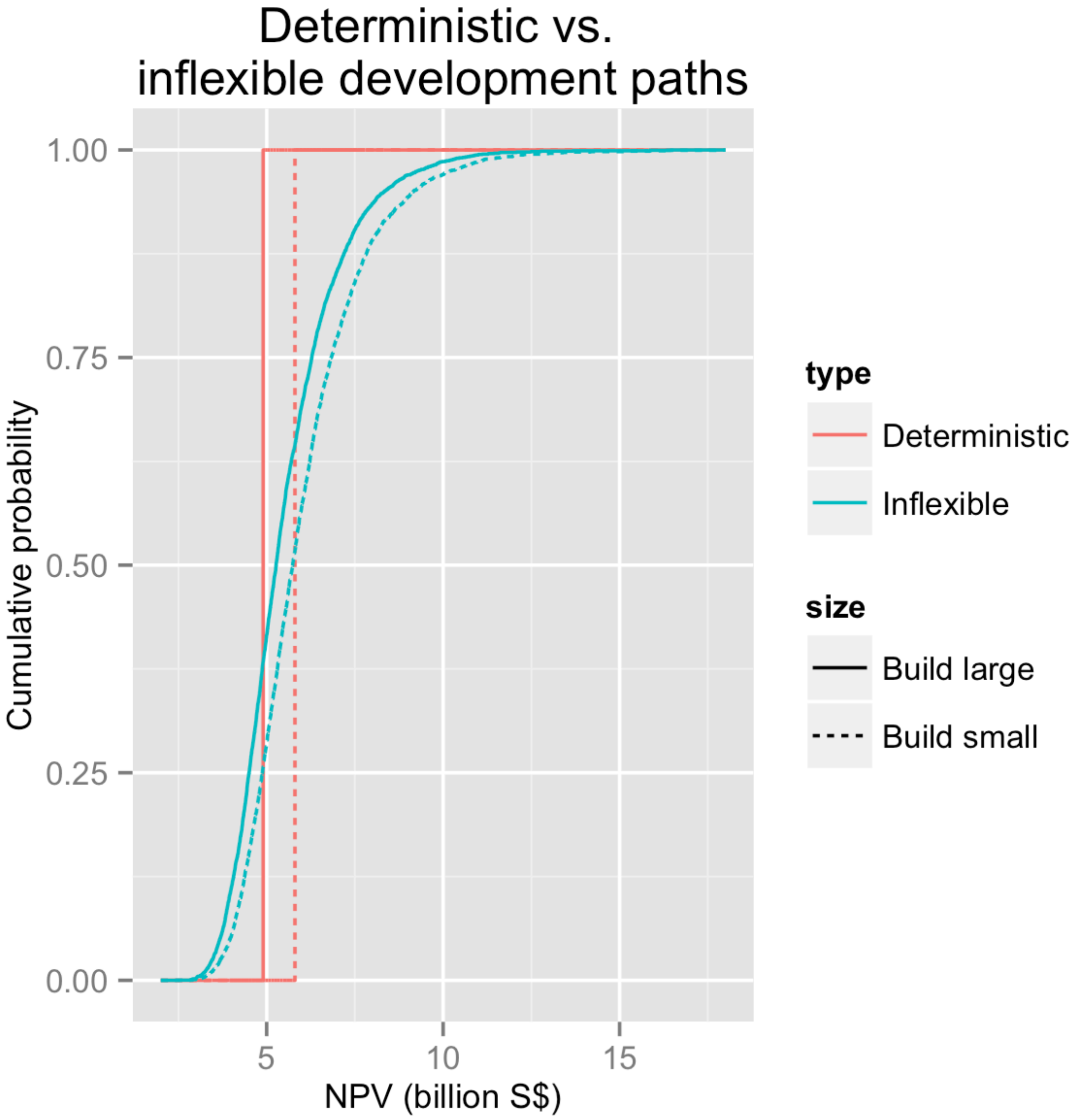

Figure 17: Cost target curves for deterministic and inflexible development paths

Figure 17 compares the deterministic paths that do not consider uncertainty ranges with inflexible pathways that do consider these uncertainty ranges under simulation. For the small facility paths, the deterministic line (dashed red) and inflexible path (dashed blue) do intersect near the inflexible path's (dashed blue) P50 value. However, the large facility paths noted by the deterministic line (solid red) and inflexible path (solid blue) intersect near the inflexible path's P38 value. This reveals that the static deterministic cost does not consistently match the corresponding average (P50) present cost of the simulated performance under uncertainty.

Thus, a single fixed design on the most probable or "average" situation does not necessarily correspond with the realistic average cost in a future that is full of uncertainty. Planning with a deterministic mindset can blind decision makers from the effects of uncertainties outside of their set of fixed assumptions. If a decision maker is convinced that a set of infrastructure decisions would cost a certain value, they may neglect to build in insurance against potential losses and may not be prepared to take advantage of good situations (de Neufville & Scholtes, 2011).

Inflexible vs. Flexible

The six target curves in Figure 18 show the range of the inflexible and flexible paths' NPV performance value. Since the analysis seeks to minimize the costs, the analysis prefers strategies that are consistently to the left of the other curves.

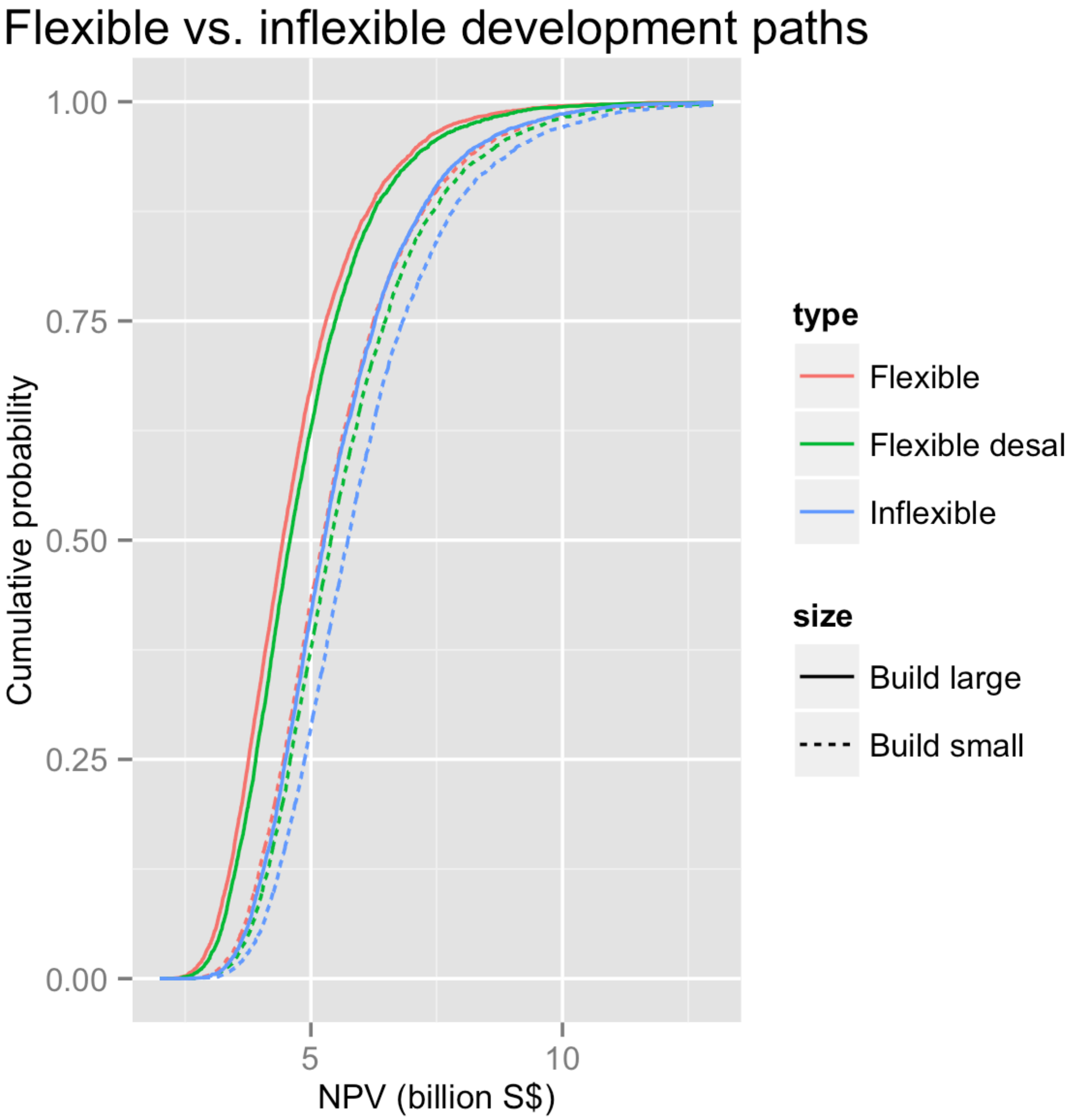

Figure 18: Cost target curves for inflexible and flexible development paths

From the simulated results, the flexible "build large" development path consistently produced the lowest cost and showed stochastic dominance. The second most stochastically dominant development path was the flexible "build large" path with forced desalination.

4.7 Discussion and Insight

This analysis suggests that a decision maker could gain substantial system understanding through Monte Carlo simulation, target curve analysis, and multiple criteria analysis. In particular, this analysis found that the flexible "build large" development path was the most cost-effective. For desalination plants, the cost benefits from the economies of scale outweighed the benefits from learning rates in the NPV comparison.

More generally, this example analysis provides valuable insight to how a flexible design approach can help decision makers understand the value of flexibility in their infrastructure planning process. Although agencies and firms may currently practice similar approaches, this example methodology presents a systematic way of considering and evaluating flexibility. In addition, decision makers and other stakeholders can participate in the model development process by adjusting the assumptions, inputs, and decision rules to better understand how they affect the system.

4.7.1 Future Work for Additional Analyses

Alternatives for deterministic path development: In this analysis, the deterministic approach was based on 2060 goal loads and assumed that the plan to fulfill these goals was fixed throughout the timespan. This definition is a somewhat extreme version of a deterministic approach. Further analyses could investigate more moderate interpretations of deterministic planning.

Consideration of water tariffs: The model assumed that the per capita water demand was exogenous. Future research can investigate how changing water tariffs can be an additional feedback to water demand. There is strong empirical evidence that price-based approaches are cost-effective and advantageous in terms of monitoring and enforcement, however most utilities are reluctant to use dynamic prices because of coordination, communication, and public perception issues. In the United States, the price elasticity of demand of residential water is typically between -0.3 and -0.4. This means that a 10% percent increase in the marginal price of water diminishes demand by about 3% to 4% (Olmstead & Stavins, 2006). Further analyses could investigate how consumers' behavior would change in response to dynamic water prices and incentives.

Further study into the discount rate: Additional studies could consider recent efforts (Weitzman, 2007; Simpson, 2008) to investigate the optimal discount rate in a present value analysis for urban infrastructure systems. Some economists use the cost of capital (6% to 8%). Other economists suggest using a smaller discount rate such as 1.4%, which accounts for the negative externalities of greenhouse gas producing projects (Simpson, 2008).

***Additional system complexity and uncertain factors*:** Further studies could increase system complexity to consider factors such as network and piping costs, construction constraints, technological obsolescence, and facility deterioration.

Game-changer events: Changes to national policies or new water technologies can have drastic changes on the reliability and cost to fulfill water demand. Additional analyses could incorporate events with a certain probability occurrence.

Systems dynamics approach: A systems dynamics approach is useful for considering how a complex resource system performs over time. It uses feedback loops, stocks, and flows to model the feedback. Karen Noiva's master's thesis is an excellent example of a systems dynamics model of Singapore's water resources system (Welling, 2011).

5 Implementation

The real problem of humanity is the following: we have Paleolithic emotions, medieval institutions, and god-like technology.

– E.O. Wilson, Harvard biologist and Pulitzer Prize winning author

Decision makers and engineers typically prefer a clear set of choices based on a single measure of performance, which most conventional planning approaches and analyses provide (Grayman, 2005). In addition, practitioners may believe that there is less risk of criticism if they use established procedures (Coates et al., 2012) that may not change quickly or easily. Flexible approaches can be hard to implement until there is an objective assessment that demonstrates that a risk-based flexible design approach is an improvement over current procedures (Lee, 1999).

Before the flexible design approach can become the new operating procedure, decision makers must first change their perception of risk and uncertainty. This paradigm shift must start with leaders in the water and infrastructure planning professions. These leaders must acknowledge that it is their professional responsibility to recognize the role of uncertainty in the planning process. It is only after this that we can overcome additional implementation barriers.

5.1 Leadership from Professional Organizations and Institutions

The "logic of collective action" describes how a concentrated private cost and an uncertain diffused public benefit results in the lack of an individual incentive to take action (Olson, 1982). Decision makers in water resources may not be adequately incentivized to deviate from their institutions' standard, conventional procedures. In general, industry and water institutions have not reached a consensus on the validity and acceptance of a flexible design approach. However, several organizations are playing an important role in legitimizing the need for progressive approaches that explicitly consider uncertainty. These organizations provide supporting materials for implementing approaches such as adaptive management, scenario planning, and flexible design. Their efforts include hosting workshops, publishing materials, and providing technical guidance, which are described in this chapter.

5.1.1 Water Utility Climate Alliance

The Water Utility Climate Alliance (WUCA) was created in 2007 to support climate research that reflects the needs of the water sector. Member agencies include ten U.S. water providers: Central Arizona Project, Denver Water, Metropolitan Water District of Southern California, New York City Department of Environmental Protection, Portland Water Bureau, San Diego County Water Authority, San Francisco Public Utilities Commission, Seattle Public Utilities, Southern Nevada Water Authority, and Tampa Bay Water (WUCA, 2013). In the past, WUCA advised the federal climate change research program to meet the needs of the water utilities and their members have testified on legislation towards funding federal climate research (Barsugli et al., 2009).

In 2010, WUCA published "*Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning*," a white paper that aims to help utilities learn and use new decision support planning methods (DSPMs). These methods consider multiple future scenarios and explicitly incorporate uncertainties into the planning process (Means et al., 2010). While this document is useful for high-level understanding of DSPMs, it could be improved with additional focus on how to present results to decision makers.

5.1.2 Survey Describing Needs and Barriers

Founded in 1990, the International Council for Local Environmental Initiatives (ICLEI) is an international association of cities and local governments dedicated to sustainable development. In a 2012 survey, ICLEI found that the top two anticipated issues for negative impacts of climate change were related to water infrastructure. Respondents reported that "increased storm water runoff" is the most anticipated issue in the short term with 65% agreement of the respondents. "Changes in demand for storm water management" ranked close behind with 61% agreement. The top three reported challenges for member cities were:

- Securing funding for adaptive planning
- Communicating the need for adaptation to elected officials and local departments
- Gaining commitment and generating appreciation from national government for the realities of local adaptation challenges

In addition, 85% of the cities reported that "securing funding for adaptation work" is a major challenge, while 60% of the cities are not receiving any financial support for their adaptation activities. These results suggest that issues related to water infrastructure are of strong importance to city planners and that it is difficult for cities to enter the implementation phase due to the lack of commitment and support from their government leaders (Carmin et al., 2012). The continued efforts of ICLEI include a series of campaigns and programs that aim to help local governments generate awareness of key sustainability issues and establish action plans (ICLEI, 2012).

5.1.3 Tools for Scenario Planning

In 2012, the Lincoln Institute of Land Policy (LILP) published "*Opening Access to Scenario Planning Tools*" as part of series to bridge the gap between the theory and practice of scenario planning. Intended for the general planning community, this report aims to be a knowledge base for scenario planning. The report contains examples of successful implementation of scenario planning and compares different tools by scale, accessibility, capability, and costs. These tools include CommunityViz, Envision Tomorrow, INDEX, ad I-PLACE^{3}S. The report also describes other tools that are in development, including Urban Vision, Decision Commons, Rapid Fire, and Urban Footprint (Holway et al., 2012).

This report seems valuable to the planning community and is a well-informed knowledge base for scenario planning tools. However, it lacks rigorous analytical detail of the various scenario planning case studies. Second, while the report mentions flexibility as a valuable aspect of the planning process, it does not discuss how to valuate flexibility.

The online companion to LILP's report is at *www.scenarioplanningtools.org*, which aims to foster ongoing collaboration of the development and use of scenario planning tools. The website contains active updates of scenario planning applied in different contexts, ways to engage in the scenario planning community, and resource publications (Scenario Planning Tools, 2013).

5.1.4 Tools for Adaptation and Flexibility in Urban Water Systems

The International Water Association (IWA), a professional water association spanning 130 countries and over 10,000 members, has a specialist program called "Cities of the Future." This program aims to establish IWA as an international authority and reference base in the water sector to help organizations understand how to create "robust and resilient responses" to future change. It has also been featured in international conferences such as Stockholm World Water Week and Singapore International Water Week (IWA, 2013a).

Through the IWA's "Climate Change and Adaptation" specialist group, they aim to help governments and utilities incorporate adaptive planning by identifying climate-related impacts and risks, and increasing impact awareness. The specialist group also connects different communities in water planning, including utilities, management institutions, and climate change scientists (IWA, 2013b).

In 2010, the IWA, ICLEI, and UNESCO-IHE (a Netherlands-based leading water education institution) authored a handbook titled "*Adapting Urban Water Systems to Climate Change: A handbook for decision makers at the local level.*" The handbook examines key areas of climate change vulnerability in the context of urban water systems and proposes techniques to implement adaptation. It aims to be a useful resource for governments and utilities that seek to implement adaptation into their water planning strategies. Its key messages include the following (Loftus et al., 2010):

- Adaptation is not new and can happen at different scales
- The urban water system is highly vulnerable to climate change
- Climate change will not always happen gradually or linearly
- The urban water cycle cannot be adapted in isolation

The handbook describes flexible system responses to changing conditions in water supply, wastewater management, and storm water management. The handbook provides details of adaptation efforts in cities including Barcelona, Berlin, Genoa, Istanbul, Lisbon, Oslo, Melbourne, and Seattle. It discusses the use of the Comparing the Flexibility of Alternative Solutions (COFAS) tool, a water management decision-support tool that visualizes the ability of a solution to respond flexibly.

The handbook also features various references and training materials available through SWITCH, which was a major research partnership funded by the European Commission from 2006 to 2011. SWITCH materials include detailed resources on past adaptation cases and decision-support software tools to model water supply and storm water (SWITCH, 2013). These materials are available online at *www.switchtraining.eu* and *www.switchurbanwater.eu.*

5.2 Observation and Assessment

One prominent trend of recent leadership efforts is that organizations are working together. IWA, ICLEI, UNESCO-IHE, and SWITCH have formally partnered to provide materials for adaptive and flexible planning. This is beneficial because it combines the resources and expertise of practitioners across a variety of disciplines. Second, websites are becoming dynamic resources for practitioners. This is valuable because it can remain up to date and also provides opportunities for user collaboration.

However, there is room for improvement. The existing handbooks are helpful, but they could benefit from more rigorous examples of a flexible approach, similar to the framework previously outlined in **Chapter 4 (Case Study)**. Ideally, these efforts would outline a more detailed methodology and provide example metrics and visuals for valuating flexibility, which are especially useful as practitioners attempt to move forward with implementation.

5.3 Implementation Barriers

In addition to gaining support from leaders of professional organizations and institutions, practitioners must still overcome implementation barriers. Some of these barriers involve issues with institutional resources, flawed perceptions of upfront costs, and complexity in data and uncertainty characterization.

Flexible design approaches increase human resource demands: Flexibility poses new time and resource demands for system monitoring, data collection, and process evaluation. A flexible approach may require more effort in the initial planning stage and monitoring process. For water resources utilities that are often financed by the federal, state, and regional sources, a flexible design approach may be difficult or impossible due to budget constraints. The implementation ability is also dependent on the prosperity of the region, especially for large projects. For example, the Netherlands and Bangladesh both face recurrent flood risks, but the Netherlands can more easily afford heavy investment in infrastructure development for flood protection (Tropp & Joyce, 2012).

Decision makers may perceive that flexibility means higher upfront costs: The perception that flexibility means higher upfront capital costs is misguided. Flexibility provides for the immediate future and reduces the obligation to lock into infrastructure plans for anticipated future needs. It deters and potentially avoids unnecessary costs.

Quantifying uncertainty can be difficult: Decision makers can find it difficult to quantify future uncertainty, which can discourage cooperation and stakeholder participation. Also, it can be difficult to build the model and quantify the links among input variables and decision-making parameters. Practitioners can overcome this barrier with better data, knowledge, and training.

Flexibility and multiple performance measures add complexity: Monte Carlo simulation and other techniques allow users to characterize uncertainty through probability distributions instead of single point estimates. Decision makers can derive metrics from these results, such as mean and standard deviation. These techniques can add additional complexity to existing operating procedures and they may be outside of a practitioner's skill set. In addition, practitioners may have to consider potential tradeoffs when they decide on a performance metric, such as the tradeoff between capital expenditures and system reliability (Grayman, 2005). Though a flexible approach introduces complexity, working through the approach is beneficial as practitioners can gain a deeper understanding of the system and may make more knowledgeable decisions.

6 Conclusions

Uncertainty is the only certainty there is
and knowing how to live with insecurity is the only security.

– John Allen Paulos, Professor of Mathematics at Temple University

This thesis developed a framework for a flexible design approach that intends to be applicable across various water infrastructure systems. It surveyed current approaches that attempt to consider uncertainty and described different applications of flexible design. The analytical case study used probabilistic and simulation methods to compare flexible and inflexible strategies, and identified the best-performing strategy with a cost savings of 15%. The thesis outlined leadership efforts towards incorporating adaptability and described implementation barriers.

6.1 Value of the Flexible Design Approach

Theoretical analyses in **Chapter 3 (Flexible Design Approach)** and the example analysis in **Chapter 4 (Case Study)** showed that flexibility can help maximize system value and minimize costs. While flexibility may not be financially valuable for every system, it is always valuable in improving the decision maker's understanding of the system. A flexible design approach creates a learning platform where decision makers can characterize the risks associated with key parameters and gain insight into how different types of strategies perform under a range of future circumstances. Flexible design can replace or serve as a complementary approach to existing methods. A deterministic approach may still be useful at the early stages of the decision-making process, as it can help narrow down a long list of potential alternatives.

6.1.1 Next Best Alternatives

Considering the barriers described in **Chapter 5 (Implementation)**, it is likely that implementing a flexible design approach will present difficulties. The next best alternative to the flexible design approach is partial implementation of a risk-focused flexible design approach, such as scenario planning or adaptive management as described in **Chapter 2 (Current Approaches)**. This alternative may appeal to those who are not necessarily in favor of the status quo, but want to avoid the complexity and contention in legal and technical changes (Lee, 1999) associated with a full-scale implementation of flexible design.

Maintaining the status quo and continuing with a deterministic approach that ignores uncertainty is another option. This alternative will satisfy organizations with highly constrained financial and human resources that cannot afford to devote resources a more intensive approach. However, great uncertainty in the future, including potential climate change impacts, may prohibit some regions from sustainably maintaining the status quo (Lee, 1999). A deterministic approach is not suitable for a changing environment. Quantifying the risks associated with investment and management decisions is an essential step forward (Lee, 1999).

6.2 Moving Forward

A flexible design approach requires the following (Sewilam & Alaerts, 2012):

- Decision makers should have adequate information on the current problems, sources of risk, and desired direction of change
- Decision makers should be aware of different ways they can implement flexibility
- Organizations should provide the ability to learn, challenge established methods, and react to unexpected internal and external changes
- There should be freedom to change policies in light of new information

A flexible approach challenges conventional planning methods and defies the assumption of non-variability in future conditions. Though there are implementation barriers to a flexible approach, there is an increasing need for flexible design as a risk management tool, especially in regions where there are major uncertainties or when the public costs and benefits at stake are large (McCray et al., 2010). Examples of these regions are high-density regions on the coast and regions with supply issues that make them particularly vulnerable to the effects of climate change and sea level rise.

Success will require more radical and strategic changes in the water management and planning process. There is no doubt that it will be challenging from both technical and coordination standpoints. These difficulties are compounded by the high uncertainty of cost savings over the long run.

However, early adopters are realizing the value of flexibility and are using more advanced approaches to reduce costs and increase their preparedness for future changes. Practitioners in water resources are starting to undergo a paradigm shift in how they perceive uncertainty in the planning process. Though there are obstacles, the path to flexible infrastructure planning is worth the hard work.

Appendix: Additional Discussion for Case Study

The focus of **Chapter 4 (Case Study)** is on the methodology and framework; it does not intend to be a critical examination of Singapore's water resources management. Details regarding the assumptions, @RISK modeling software, and internal calculations are located in this Appendix.

Assumptions regarding current proportions of water supply

Imported water accounts for a sizable portion of the island's water supply. Though the exact proportion of the total supply is unclear, press releases (PMO, 2009; CNN World, 2011) have noted a 40% figure. Considering the published figures (PUB, 2010) of 10% for desalinated water and 30% for NEWater, this leaves 20% of the current supply from reservoirs.

Assumptions regarding 2060 water supply goals

The Malaysia-Singapore agreement for imported water is scheduled to expire in 2061 (Water Technology Net, 2008). The model assumes that long-term goals aim to ensure self-sufficient water security, so the PUB should be able to provide 100% of its domestic supply by the agreement expiration. This assumption is in line with PUB's new formulation and implementation of water policies, high investment in desalination, and similar actions (Tortajada, 2006).

The model assumes that there will be no reliance on imported water by the end of the model's time period in 2061. The "Supply in 2060" projections from PUB's 2009/2010 Annual Report state 30% of water supplied by desalinated water and 50% by NEWater (PUB, 2010). With the assumption of no imported water, this leaves the remaining 20% supply from reservoirs.

More information on @RISK Excel add-on

The @RISK (pronounced "at risk") add-on facilitates risk analysis with Monte Carlo simulation. Alternatively, a user can run a simple Monte Carlo simulation in Excel without any add-ons using Excel's distribution function language (such as NORMDIST for a normal probability distribution) and random sampling (using the RAND() function). The advantage of using @RISK (and similarly, Crystal Ball) is its built-in uncertainty characterization and simulation interfaces. It is especially useful for running analyses for complex systems with a high number of iterations. For more information about the software, visit *www.palisade.com/risk*.

Calculations: Fixed and Operating Costs

Imported water: Following the assumption that Singapore will continuously decrease their supply of imported water, the model assumed no additional fixed costs for imports. The operating cost for imported water was reported as "less than 1 cent per 1000 gallons" (Tortajada, 2006). With a conversion of approximately 220 imperial gallons to 1 cubic meter, this makes the operating cost approximately S$0.0022 per cubic meter, which was then rounded up to S$0.003 per cubic meter.

Reservoirs: Singapore is severely land constrained and approximately 2/3 of the island serves as reservoir catchment area (PUB, 2010). The Marina Barrage Reservoir was recently built on reclaimed land. Considering the land constraints, the model assumed that future reservoirs would also be completed on reclaimed land. The model based future reservoir costs on that of the Marina Barrage at $226 million (CNN World, 2011). According to the PUB, Marina Barrage is able to meet 10% of Singapore's current water demand (PUB, 2013), so it estimated that the capacity of the Marina Barrage was 170,000 cubic meters (based on the daily 1.7 MCM demand). The model estimated the operating cost for reservoirs by considering the relative costs of NEWater plants and desalination plants.

NEWater plants: The model assumed the fixed cost for NEWater plants from the recently built Ulu Pandan NEWater plant, which was a S$200 million plant (Keppel Corporation, 2004) with a daily capacity of 148,000 cubic meters (Keppel Corporation, 2010).

Desalination plants: The model based the fixed cost for desalination plants on the recently built Tuas desalination plant, which was a S$200 million contract with a daily capacity of 110,000 cubic meters (Water Technology Net, 2006). The operating cost of S$0.49 was from a 2006 press release (Black and Veatch, 2006).

Cost savings calculation for dominant flexible path (#4)

Where values are in billions of S$, flexibility introduces a cost savings of approximately 15%:

$$\frac{5.54 - 4.69}{5.54} = 0.153 \approx 15\%$$

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