DECISION SUPPORT PLANNING METHODS: INCORPORATING CLIMATE CHANGE UNCERTAINTIES INTO WATER PLANNING

WUCA

Water Utility Climate Alliance

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Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning

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Preface

The Water Utility Climate Alliance (WUCA) developed this white paper to present multiple-outcome planning techniques to water utilities interested in incorporating climate change into their planning. Integrating climate change information into planning is one of the most intricate steps utilities face in the climate change adaptation process.

To adapt to climate change, water utilities generally must complete four major steps:

1) Understand - understand climate science and climate model projections,
2) Assess - assess water system vulnerabilities to potential climate changes,
3) Plan - incorporate climate change into water utility planning, and
4) Implement - implement adaptation strategies.

Currently, WUCA is focused on methods for better understanding and improving climate science (step one) and improving water utility planning methods to better address the uncertainties of climate change (step three). To better address the first step of the adaptation process, WUCA commissioned a climate modeling white paper (released December 2009) titled, "Options for Improving Climate Modeling to Assist Water Utility Planning for Climate Change." The climate modeling white paper recommends several climate science improvements to better meet the planning needs of water utilities. Furthermore, the climate modeling white paper provides water utilities with an overview of climate science, climate modeling and downscaling techniques, as well as an explanation of the strengths and limitations of current climate model projections.

The present range of climate projections for many regions is great and many agencies are not comfortable selecting one projection over another. Vulnerability assessments (step two), consequently, tend to use a variety of different projections. While more sophisticated climate models and methods are in the development phase, it may be many years before the range of projections and the uncertainties about the projections are substantially narrowed (Barsugli et al., 2009). In the meantime, many water utilities will have substantial decisions to make with potentially significant financial, social, and environmental impacts that can be affected by climate change. In many cases utilities cannot wait to make these decisions and to engage in adaptation until considerable improvements in climate modeling are completed (step one). Given this imperative to adapt, and the time lag before major improvements in climate modeling are realized, for many utilities, advancing to planning for climate change (step 3) will require new multiple-outcome planning methods to address the uncertainties of climate change.

Considering climate conditions beyond historical conditions is not a conventional practice in the water industry; nor is contemplating multiple climate scenarios. While sophisticated methods for reconstructing, resampling, and analyzing weather-related conditions are used, water utility planning usually is based on static climate conditions and does not adequately address the possibilities of a changing climate. New approaches are needed to incorporate the wide range of climate projections into water utility planning.

This white paper was developed by WUCA to generate the need for new multi-outcome planning methods for climate change adaptation by water utilities. Many water utilities currently are engaged in, or considering, vulnerability assessments and will be seeking guidance on how to incorporate the large range of new information into their planning. This white paper is intended to guide those wanting to move forward with the adaptation process. At the moment there are few examples of the application of these methods for climate change planning. WUCA encourages and supports the use, and further development, of these methods for climate change planning, and is interested in collaborating on the development of case studies within the water community.

The Water Utility Climate Alliance (WUCA) was formed to provide leadership and collaboration on climate change issues affecting the country's water agencies. Comprised of ten of the nation's largest water providers, WUCA members supply drinking water for more than 43 million people throughout the United States.

If you have comments or questions about the paper, please direct them to the co-chairs of the WUCA Decision Support Committee; Laurna Kaatz, Laurna.Kaatz@DenverWater.org, 303-628-6464, or Marc Waage, Marc.Waage@DenverWater.org, 303-628-6572.

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Executive Summary

Climate change is challenging the way water utilities plan for the future. Observed warming and climate model projections now call into question the stability of future water quantity and quality. As water utilities grapple with preparing for the large range of possible climate change impacts, many are searching for new planning techniques to help them better prepare for a different, more uncertain, future. There are several promising new methods being tested in water utilities planning. This white paper will help water utilities learn about and evaluate these new planning techniques, called Decision Support Planning Methods (DSPMs), for use in their own climate adaptation efforts.

The Need for New Planning Methods

The need for new planning methods is maybe most evident in water resource planning. Traditionally, water resource planning has used recorded weather and hydrology to represent future supply conditions. Many sophisticated methods are used for reconstructing, resampling, and analyzing hydrology and other weather-related conditions. It was assumed that the hydrologic determinates of future water resources – temperature, precipitation, streamflow, groundwater, evaporation, and other weather dependant factors – would be the same as they had been in the past. While there may have been large variations in observed weather, it was assumed that weather statistics would stay the same and variability would not increase in the future. This core planning assumption is often referred to as *climate stationarity*.

Now, there is a changing climate to plan for. For many utilities, this means preparing for a wide range of possible impacts. The presented DSPMs consider multiple future conditions to incorporate more and greater uncertainties into the water planning process. This can be useful not only in planning for climatic uncertainty, but also in planning for uncertainty about regulatory, environmental, economic, social, and other conditions affecting water utilities. Using *multiple-outcome planning* also allows water utilities to better integrate their planning across all functions of their agency.

Planning is only one step in the climate adaptation process. To adapt to climate change, water utilities generally must complete four major steps:

1. Understand - understand climate science and climate model projections,
2. Assess - assess water system vulnerabilities to potential climate changes,
3. Plan - incorporate climate change into water utility planning, and
4. Implement - implement adaptation strategies.

During the first step, utilities develop an understanding of the issues surrounding climate change, including a review of climate science, climate system modeling, downscaling techniques, and current climate projections. Second, utilities assess their water system’s vulnerabilities to climate change. Using information gained in the understanding process, water utilities perform analyses to identify potential impacts to their water supply systems from climate change to assess their system's vulnerability. Vulnerability assessments are usually specific to a water system and its climate region. Third, utilities incorporate the findings from the vulnerability assessment into their planning process to develop adaptation strategies. And finally, utilities make decisions and implement strategies and actions that help them adapt to potential impacts from climate change and reduce system vulnerability. While not all four adaptations steps are necessarily linear and not all utilities follow the same steps, the general process moves from understanding, through analysis and planning, to action. To date, very few utilities have implemented adaptation strategies solely for the purpose of climate change.

The present range of climate projections for many regions is great and many agencies are not comfortable selecting one projection over another (that is, selecting a single climate model driven by a single emission scenario which automatically assumes confidence in the chosen model). Vulnerability assessments, consequently, tend to utilize a variety of different projections. While more sophisticated climate models and methods are in the development phase, it could be many years before the range of projections and the uncertainties about the projections are substantially narrowed (Barsugli et al., 2009). In the meantime, many water utilities will have substantial decisions to make, with potentially significant financial, social and environmental impacts, which may be affected by climate change. Therefore, many utilities are progressing or will move forward with the adaptation steps before considerable improvements to climate model projections (adaptation step one) are made. For many utilities, advancing to planning for climate change (adaptation step three) will be facilitated by new DSPMs methods to address the uncertainties of climate change.

DSPMs help utilities systematically characterize and comprehend multiple uncertainties. They can assist utilities in making and executing defensible water resources decisions while minimizing the threats associated with these decisions. This white paper presents five DSPMs:

1. Classic decision analysis,
2. Traditional scenario planning,
3. Robust decision making,
4. Real options, and
5. Portfolio planning.

These DSPMs were selected because of their relevance and use in the water industry. Classic decision analysis and scenario planning are the two standard DSPMs, while robust decision making, portfolio planning, and real options are variations of these two. The main difference between each method is how the DSPM handles uncertainty. Classic decision analysis assigns probabilities to uncertainties, traditional scenario planning develops equally likely scenarios based on the uncertainties, and the others combine different variations of these two approaches. The DSPMs have been reviewed, documented, and evaluated according to twenty-one evaluation criteria (see **Appendix B** for more details). Results provide guidance to utilities in choosing a DSPM to best support their specific planning needs and capabilities.

Summary of Decision Support Planning Methods

Classic decision analysis is a probability-based DSPM. It provides support for decision makers by systematically cataloging information and mathematically evaluating and ranking decision alternatives against multiple, potentially conflicting, decision objectives. Classic decision analysis illustrates the process with a decision tree or influence diagram, and handles uncertainty through the use of probabilities. Fundamentally, classic decision analysis is used to find a preferred plan with the best value, which often is the lowest expected cost.

A key data need for classic decision analysis is determining a probability for future events occurring. When considering climate change uncertainty, assigning probabilities to future conditions can be difficult and hard to defend. Currently there is no scientific consensus on the validity of assigning probabilities to climate model projections (Stainforth et al., 2007a and 2007b). (One reason for this is because projection agreement across multiple models does not imply projection confidence.) Water utilities deciding whether to use classic decision analysis for climate change planning must carefully consider their willingness, and ability, to assign probabilities to climate model projections. In situations where probabilities cannot be scientifically or mathematically determined, expert judgment is used to assign probabilities.

Decision analysis techniques have been used in some water planning applications for many years. Generally, the results are straightforward and easy to use. However, when stakeholders have not been involved in the process and analysis, the method and results may be challenging to communicate. Water utilities typically need outside expert assistance to implement this DSPM, especially when uncertainties are assigned probabilities. Computing requirements can be simple; however, if the decision situation is complex the computing requirements can be high.

Traditional scenario planning is a scenario-based DSPM. The main objective of traditional scenario planning is developing a plan that best prepares the water utility for a plausible range of uncertain circumstances. Scenarios are developed through the identification of critical uncertainties and driving forces. These driving forces might involve uncertainty surrounding climate, water quantity, water quality, demand, social and regulatory change, technology, economics, or other elements. The goal is to develop a range of future conditions that go beyond extrapolation of current trends and represent surprising but plausible conditions. Typically, scenarios are treated as equally likely to occur, rather than assigned probabilities as in classic decision analysis. Implications and future needs of each scenario are identified and adaptation strategies are developed to meet the needs of each scenario. Ideal adaptation strategies have near-term actions that are common to all or most scenarios. These are sometime called *No Regrets* or *Low Regrets* strategies. *Signposts* can be established to monitor the development of the scenarios and determine when adaptation measures are no longer common to all or most scenarios.

Scenario planning is fairly easy to understand and is familiar to many utilities, which makes it easier to perform analysis and present results. While it engages stakeholders, those with difficulty contemplating multiple alternative futures, and applying current strategies to those futures, can become frustrated with the process. The resource requirements for scenario planning can be minimal or extensive, depending on the level of detail desired in the analysis (number of scenarios, number of stakeholders, detail of the strategies, etc.). Outside experts are not essential to the process but can facilitate the development and evaluation of scenarios by challenging conventional wisdom and offering additional perspectives. The requirement to characterize plausible future conditions using a small number of scenarios can limit the ability of traditional scenario planning to completely address future uncertainty. Scenario planning also does not always simplify decision-making, as each scenario may suggest disparate strategies and the method does not guide the reconciliation of those strategies. A benefit of traditional scenario planning is that those involved in the planning process do not need to agree on a single future when developing the plan.

Robust decision making is a framework that combines features of both classic decision analysis and traditional scenario planning. The approach provides a systematic way of developing a water management strategy to best adapt to a wide range of plausible future conditions. Robust decision making uses existing or modified water management models to evaluate candidate strategies against large sets of quantitative scenarios that reflect future uncertainty. Sophisticated techniques are then used to identify major vulnerabilities within these strategies. Analysts, stakeholders, and decision makers study these vulnerabilities to develop hedging options and to design alternative strategies. Successive iterations through these steps reveal increasingly robust strategies.

Robust decision making provides decision makers and stakeholders with a small set of robust strategies to choose from, and information about what assumptions are needed for each choice to be successful. For many agencies, a completely robust strategy will not be identifiable. Robust decision making thus presents the key tradeoffs of one candidate strategy versus another. Additionally, consequences that particular future conditions might have for each strategy are identified. This enables decision makers to determine which risks to address in their long-term plans.

Robust decision making is particularly useful when agencies want to examine uncertainties that cannot easily be assigned probabilities. Also, it does not require agreement by decision makers, experts, or stakeholders on the likelihood of different future conditions occurring. The method is most useful when there are many decision alternatives and a detailed analysis of every possible variant is not possible. Expertise at this point is concentrated among a small group of practitioners and requires fairly sophisticated computing and analytic capabilities, although several applications with different water agencies are currently underway.

Real options is a method to help water managers identify water supply strategies that adjust over time and balance risks. This DSPM determines sets of strategies that maximize value by using traditional discounted cash flow approaches. Flexible investment strategies are sought that can be risk-adjusted with time and deferred into the future. Uncertainties in real options are handled through the use of probabilities. Results are flexible in that they may incorporate delaying and phasing of facility projects.

The Water Services Association of Australia (WSAA) has examined the use of the real options method for the water sector in their paper, "Real Options and Urban Water Resource Planning in Australia." To date, there are no known water utility applications of the method.

Portfolio planning is used in the financial world to select a portfolio containing a mix of assets or strategies that minimize financial exposure due to future market scenarios. Uncertainty is handled through the use of probabilities and Monte Carlo simulations, and minimized through hedging. The approach has been used extensively in the electric utility area, although no examples of its application for water utilities could be found.

This DSPM may require heavy involvement from decision makers. Because of the general familiarity with the process, communicating strategies with stakeholders should be straightforward. Communicating the assumptions, analysis implications, and decisions, on the other hand, may be challenging because they are based on the risk tolerance of the decision makers. There are no case studies to follow at this time, so utilities may need to spend significant amounts of time adopting this method to meet their needs and may need to work with outside experts.

Considerations for Selecting a DSPM

Water utilities have several DSPMs to assist them in planning for climate change. It is clear, however, that there is not a one-size-fits-all method, and that every process must be tailored to the needs and capabilities of the utility. For utilities that are not interested in methods requiring sophisticated computing or modeling, scenario planning is fairly intuitive and can be accomplished with minimal external resources. Even without going through the traditional development process, useful climate change scenarios can be derived based upon reviewing available climate model projections for the region in question and selecting plausible ranges (i.e., a +/-15% change in volumes or storm frequency) without having to use or manipulate climate data in models or assigning probabilities. On the other hand, utilities looking for, and confident in, a probabilistic assessment may look to classic decision analysis. The increasing computational power with classic decision analysis allows for the consideration of a broader range of adaptation strategies. The general lack of analysis or accepted practice for assigning probabilities to climate model projections should be recognized. Water utilities that decide to use classic decision analysis must carefully consider their willingness to assign probabilities to climate model projections. Utilities that want to invest more resources and rigor into climate change adaptation strategy development may consider more advanced computational methods or hybrid methods such as robust decision making, real options, or portfolio planning.

Conclusion

As water utilities contemplate how to prepare for the large range of possible climate change impacts, many are searching for new planning techniques to help them better prepare for the future. Several promising new methods are emerging for water utilities to consider. This white paper will help water utilities learn about and assess these new planning techniques.

1. Introduction

Introduction

Climate change calls into question the reliability of water sources and the quality of the water available, and challenges traditional water utility planning techniques. Traditionally, water resource planning is based on recorded hydrology and weather information. One core assumption behind traditional water resource planning is that climate exhibits *stationarity*. *Stationarity* means that the statistical properties of climate variables in future periods will be similar to past periods. The assumption that climate statistics will not change with time implies that hydrology and weather statistics and variability will not significantly deviate beyond the observed past and that past conditions are good representations of future conditions. The potential for significant changes in climate in the future has called into question the viability of only using historical hydrologic, weather, and demand information to make decisions regarding water supply and infrastructure investment. Unfortunately, using climate change information can be very difficult because often there is a wide range of projections. To address these new uncertainties, many water utilities will require new planning methods.

Water utilities progressing with climate change adaptation are faced with the dilemma of how to develop short- and long-range plans that incorporate the uncertainty surrounding climate change projections. The planning methods described in this white paper can aid in the transition from traditional planning based on climate stationarity to uncertainty-based planning for climate change. They also can facilitate communication of climate change planning uncertainty with stakeholders.

Today, planning under the paradigm of climate change includes a wide range of projected climate scenarios, great variability in future supply projections, temperature-driven increases in water demand, and many other sources of uncertainty (Waage, 2009). While more sophisticated climate models and methods are in the development phase, it may be many years before the range of climate projections and the uncertainties about the climate projections are substantially narrowed (Barsugli et al., 2009). In the meantime, many water utilities will have substantial decisions to make with potentially significant financial, social, and environmental impacts that can be affected by climate change. For this reason, utilities are progressing or will progress with adaptation before considerable improvements to climate model projections are completed. Additionally, the projections are coarse in nature (i.e., produced at a low resolution) compared with the scale of information utilities directly feed into their water-planning models. It is then challenging for utilities to incorporate highly uncertain, low-resolution climate change information into water planning and management decisions (Groves et al., 2008a).

Decision Support Planning Methods

For many regions of the United States, the potential implications of climate change could severely impact water managers' ability to provide long-term confidence to their customers. Efficient water supply and infrastructure decision-making requires reliable and understandable information. Water resource and infrastructure development is expensive and can require a decade or more to complete major projects (i.e., dams or other complex facilities). Developing projects too early could cause utilities to lose money in unused facilities or stranded supplies that are not used until later, if at all. But developing them too late risks the economic and social impacts of water shortages, assuming the supply is still available for development. Furthermore, the practical limits of water affordability and availability in many communities demand that such decision-making be as accurate and transparent to stakeholders (public and decision makers) as possible. To this end, water utilities are seeking better tools to guide the incorporation of significant uncertainty, such as that surrounding climate change projections, into water planning.

Decision Support Planning Methods (DSPM) incorporate multiple possible future outcomes into planning and decision-making. DSPMs also can integrate broader, non-traditional water planning assumptions necessary to account for climate change and additional uncertainties. These assumptions can include, but are not limited to, watershed development and land-use changes, water quality and quantity changes, demand changes, and social or economic shifts. Several DSPMs exist, or are emerging, that challenge traditional assumptions and planning techniques by incorporating significant uncertainty into short- and long-term water planning. DSPMs systematically assist in compiling raw data, documents, and expert knowledge relevant to a specific problem or decision to support planning and decision-making. The methods inform water managers and promote robust adaptation approaches.

The DSPMs presented in this paper for water utility planning include:

- Classic decision analysis;
- Traditional scenario planning;
- Robust decision making;
- Real options; and
- Portfolio planning.

These planning methods are discussed in detail in **Section 2**.

DSPMs are different from planning tools or strategies*,* which do not provide the framework for uncertainty planning. Utilities may be able to better prepare for uncertainties associated with climate change and other planning elements using DSPMs in conjunction with supporting tools and strategies. DSPMs are not replacements of planning tools or strategies; rather they provide the necessary methodology needed to systematically plan for significant uncertainty. A range of planning tools and strategies could be incorporated into a given DSPM. An example of a planning tool is the Water Evaluation and Planning model, also known as WEAP. This hydrologic model was developed for integrated water resources planning. WEAP could be used to assess climate vulnerabilities in a water system as well as to evaluate developed adaptation strategies. An example of a planning strategy is No Regrets planning, which generates multiple benefits that outweigh costs regardless of climate change outcomes. While they are not part of this white paper's scope, WEAP and No Regrets planning can help support water managers in making decisions about DSPMs. Both are described in **Appendix A**.

Uncertainty Management Framework

The DSPMs described in this white paper can be used to address many areas of uncertainty surrounding water utility planning. From this point forward, this white paper focuses primarily on the uncertainty associated with climate change and the DSPMs that can help a water utility adapt to them. To further describe the process surrounding climate change planning, an uncertainty management framework was developed.

Figure 1.1 illustrates a simplified example of an uncertainty management framework for incorporating climate change uncertainties into utility planning. This framework identifies three fundamental planning steps that constitute a utilities consideration of climate change:

1. System Vulnerability Assessment
2. Water Utility Planning
3. Decision Making and Implementation

Though the three steps illustrate the complete decision-making process, they rarely have a clean separation in real-world practice. The steps also are part of the greater climate change adaptation process.

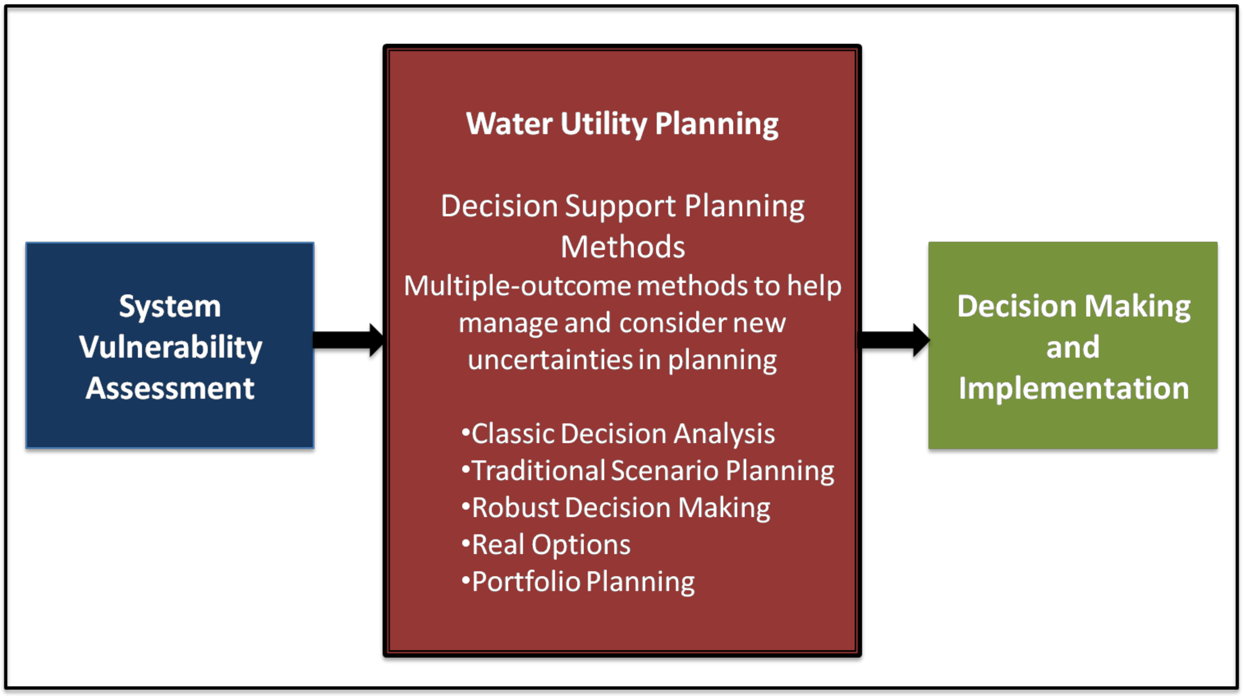


Figure 1.1 – Uncertainty Management Framework for Incorporating Climate Change Uncertainties into Utility Planning (partially adapted from Miller and Yates, 2006).

Step 1. System Vulnerability Assessment - The first step for water utilities to incorporate climate change impacts into their planning process is to conduct one or more system vulnerability assessment. The system vulnerability assessment is the process of identifying, quantifying, and prioritizing the vulnerabilities in a system, similar to a risk assessment process. System vulnerability assessments are helpful in identifying susceptible assets and moving the uncertainty management process forward to evaluate adaptation options and associated costs (USEPA, 2009a and 2009b). System vulnerability assessment findings are necessary inputs for climate change planning efforts (described in step two).

A vulnerability assessment process is comprised of three main elements (adopted from USEPA, 2009a):

1. Characterize the water system, including its mission, objectives, resources, and capabilities.
2. Identify and prioritize the potential threats to its mission, objectives, resources, and capabilities that could result in undesired consequences.
3. Evaluate and analyze the identified threats to the water system.

Although the vulnerability assessment is an important step in the full decision-making process, it does not provide the information necessary to frame and make a decision. Rather, the vulnerabilities associated with climate change are defined here for use in the planning process.

Step 2. Water Utility Planning – The next step in the uncertainty management process is to incorporate information gathered during the vulnerability assessment into the water utility planning process. DSPMs consider multiple future conditions to incorporate more and greater uncertainties into the water planning process. This can be useful not only in planning for climatic uncertainty, but also in planning for uncertainty about regulatory, environmental, economic, social, and other conditions affecting water utilities. Using *multiple-outcome planning* also allows water utilities to better integrate their planning across all functions of their agency.

For efficiency, an agency should determine the DSPM before completing the vulnerability assessment described in step one. This approach is beneficial because certain DSPMs have specific informational requirements, and having a complete plan in place will help avoid unnecessary evaluations.

Step 3. Decision-Making and Implementation – The final step is for utilities to make and implement the decision. The decision-making part of this step is not completely separate from the DSPM process of the previous step, but the acknowledgement of making a decision (and agreeing on a strategy) and moving to implementation is crucial in a successful planning process. To date, very few utilities have implemented adaptation strategies solely for the purpose of climate change.

White Paper Objectives

This white paper is a guide for water utilities researching and designing new planning methods to adapt to climate change. The paper has three objectives for guiding the use of DSPMs in water utility planning:

1. Identify and describe leading DSPMs and determine their value/limitations, uncertainty management methods, and data gaps.
2. Evaluate each identified DSPM's ability to incorporate climate change uncertainties into water planning.
3. Describe DSPMs research and development needs.

2. Overview of Decision Support Planning Methods

This section presents findings from the literature review of Decision Support Planning Methods (DSPMs). Additional details on the literature review process are included in **Appendix B**.

The literature review identified five DSPMs that could be used to incorporate climate change uncertainties into water utility planning. These DSPMs include:

- Classic decision analysis
- Traditional scenario planning
- Robust decision making
- Real options
- Portfolio planning

The presented DSPMs were selected because of their potential relevance and use in the water industry. Classic decision analysis and traditional scenario planning are the two uniquely different DSPMs, while robust decision making, portfolio planning, and real options are a combination of these two or share similar theory. Portfolio planning also was included to exemplify the potential to adopt uncertainty management methods used by other industries.

The information contained in this section is intended to assist water utilities in choosing a DSPM suitable to their specific needs, capabilities, and resources. The review of each DSPM includes a:

- Description of the DSPM
- Characterization of the typical steps of the DSPM
- Illustration of the DSPM through a flowchart and example
- Description of the potential value and limitations of the DSPM
- Description of data gaps in the application of the DSPM

Flowchart

The basic steps of each DSPM can be generally characterized into five common categories:

1. Definition of the decision elements
2. Identification or development of decision information
3. Incorporation of uncertainty
4. Development of outputs
5. Decision-making

These steps are illustrated in the generic flowchart in Figure 2.1 and are complemented with implementation steps in the context of each DSPMs discussed later in this section.

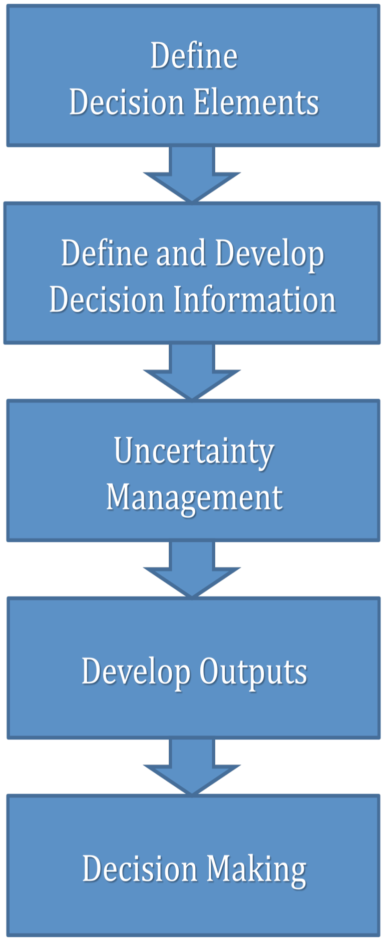


Figure 2.1 – Example of the DSPM Generic Flowchart.

The DSPMs will be further described with the Sunny City example, a hypothetical water utility, discussed below.

An Example: Sunny City

An example water utility also is presented for the decision analysis, scenario planning, and robust decision making DSPMs. Examples are not given for the other two DSPMs as they are not, to the knowledge of the authors, presently used in water utility planning. The example is simplified and hypothetical to better illustrate typical water planning decisions made by water utilities and to compare the DSPMs.

Our hypothetical water utility is the Sunny City Water Utility. Sunny City is preparing a long-range water supply plan to provide water to its customers with the following supply-demand outlook:

- Sunny City's water system provides water to a population of 100,000 people for municipal and industrial uses.
- Water is supplied from a single surface water reservoir, which is fed by snowmelt and surface water runoff.
- Based on the results from a water demand forecast model and a water system model using a 50-year historic record, forecasted water demands are expected to exceed supply in 2040.
- Uncertainties in the population forecast show that demands could exceed supply in 2020 under high-growth projections, or in 2060 under low-growth projections.
- Recent studies of potential climate change impacts on the system indicate that by 2050 supplies could decrease by 5% to 15% and average annual water demands could increase by 2% to 5%.

Alternatives being considered include:

- Operational changes and other improvements to the existing surface water supply.
- Demand management programs, including conservation and pricing structures.
- Development of a reclaimed water system using effluent from Sunny City's wastewater treatment plant.
- Conjunctive use with yet-to-be developed groundwater supplies.
- Construction of a new surface water reservoir.

This example will be used to illustrate possible recommendations for the type and timing of investments that could be made during the next 50 years to reliably provide water to Sunny City's customers. The analysis takes into account the range of probabilities of population and climate change impacts.

2.1. Classic Decision Analysis

Classic decision analysis combines various forms of information into a unified and systematic probability-based framework used to conduct analyses and to support the design of robust water supply options. There are various permutations of classic decision analysis. In fact, four of the five DSPM approaches considered in this report – portfolio planning, real options, robust decision making, and the method presented in this section – fall under the broad category of decision analysis. This section focuses on what Morgan et al. (2009) consider classic decision analysis, which describes uncertainty with well-characterized probabilities, recommends optimal strategies, and uses a number of powerful tools such as decision trees or influence diagrams to illustrate planning options.

Description

Classic decision analysis evaluates complex decisions in a systematic and rational way (Morgan et al, 2009). The approach mathematically analyzes and ranks decision alternatives against multiple, and often conflicting, decision objectives. While mathematically considering future uncertainties based on the ranking of the decision alternatives, decision makers can choose the preferred adaptation strategy or set of strategies to achieve decision objective(s). Additionally, this method has the possibility of going through multiple iterations to refine the analysis with adjusted alternatives or other considerations.

Classic decision analysis has been directly used for climate change and water resources planning applications. Examples include evaluation of climate change projections (PMSEIC, 2007; Raisanen and Palmer, 2001) and water management related to climate change (Labiosa et al., not dated; Chowdury and Rahman, 2008); floodplain management strategies (Tkatch and Simonovic, 2006; Stainforth et al, 2007a and 2007b; de Kort et al., 2007); urban water supply system management and reservoir management (Kodikara, 2008); and watershed management practices (Arabi et al., 2007).

Typical Steps

Decision analysis generally involves five steps:

Step 1: Frame the decision situation.

This first step identifies and defines the decision situation and frames the objectives of the situation (Clemen and Reilly, 2004).

- Key water planning decisions are identified and defined (e.g., what type and timing of investments does a utility needs to make during the next 50 years [planning horizon] to meet long-term water supply reliability measures?).

- Decision objectives are defined (e.g., meet future demand for the next 50 years, minimize expected cost, minimize expected risks, etc.).
- Significant effort is put toward fully understanding the objectives.
- Possible future alternatives are identified. If a decision objective is meeting future water demand, then potential alternatives to consider could be developing new supply, developing demand management programs, developing conjunctive use, constructing a new reservoir to capture current losses, and implementing operational changes.
- Decision variables affecting the decisions and other information required to make key decisions are determined (e.g., future demand, future supply availability, cost data, etc.).
- Outcomes pertinent to the decision situation are characterized.

Step 2: Develop a decision tree or influence diagram model.

Decision tree and influence diagram models are simple graphical forms used to illustrate the decision situation (Clemen and Reilly, 2004, and Howard and Matheson, 2004). They allow for the visualization and integration of various types of information, including decision alternatives, decision objectives, and uncertainties. Uncertainty is characterized as probabilities. Assignment of probabilities within these models is further described in Step 3.

Decision trees or influence diagram models also are mathematical representations of a decision, which include an analytical component (Clemen and Reilly, 2004). This analytical component is a mathematical expression that ultimately attributes a value (often times cost) to decision alternatives. The analytical component is discussed further in Step 4.

Examples of an influence diagram and decision tree are shown in Figures 2.2 and 2.3, respectively. In this example, the decision is whether to build a new dam and the objective is to minimize total costs. Costs to consider include capital and operating costs, as well as the costs associated with water shortages. The uncertainty to consider is future demand, but it could also be future supply availability under climate change. The expected cost for each combination of infrastructure decision and demand possibilities are shown at the end of each branch.

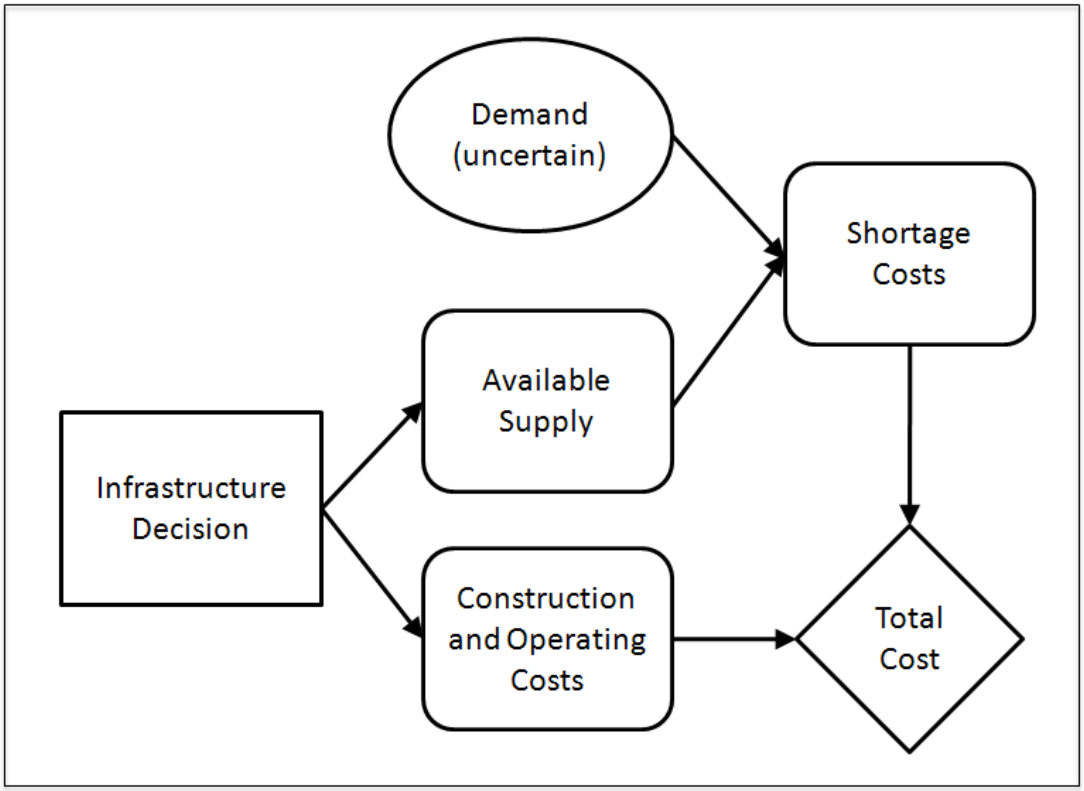


Figure 2.2 – Example of a Simple Influence Diagram. The different shapes have specific meaning. Rectangles represent decisions, diamonds represent the final consequence, rounded-corner rectangles represent mathematical calculations, and arrows represent relevance or sequence.

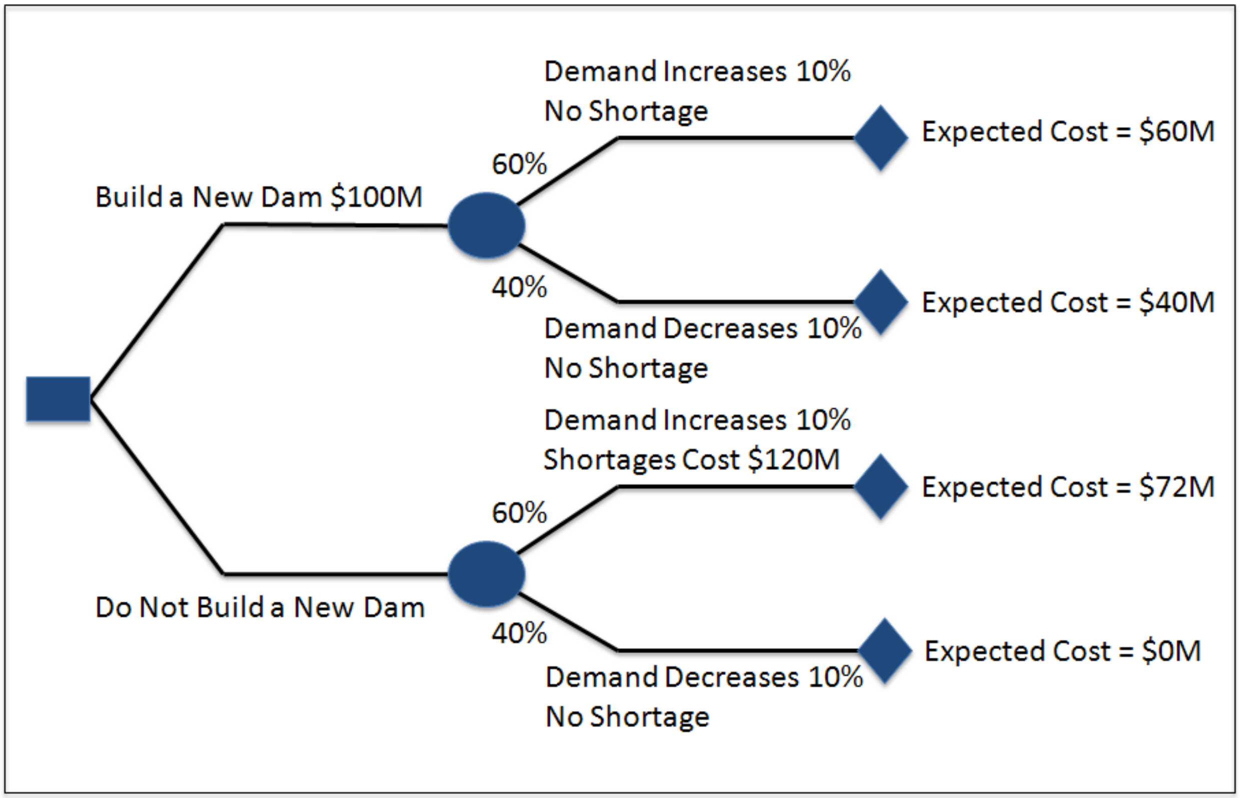


Figure 2.3 – Example of a Simple Decision Tree. In this figure, the squares represent the decision, ovals represent uncertainties, and diamonds represent the outcomes.

Step 3: Incorporate uncertainty.

Decision analysis handles uncertainties using probabilities. Probabilities are assigned to the uncertain variables of the decision tree or influence diagram model. The use of probabilities to estimate uncertainty is widely used in the water industry. Water utilities generally use classical probabilities based on historical data (e.g., maximum likelihood used to estimate to assess supply variability).

Classical probabilities assume *stationarity*, i.e., hydrology and weather statistics do not change when shifted in time or space. However, when dealing with climate change applications, *stationarity* is no longer a valid assumption. It is challenging to obtain probability distributions related to climate change per se. In this case, the use of subjective probabilities (Bayesian) is a more suitable choice (Dessai and Hulme, 2003). Subjective probabilities are created with empirical models and expert judgment. They are useful for characterizing uncertainties for complex systems and for the classic decision analysis decision-making process (Labiosa et al., not dated). There are varied approaches to subjective probabilities, but there is no best approach to characterize uncertainties related to climate change (Morgan et al., 2009). In Figure 2.3 above, the likelihood that future demand increases 10% is 60% (p=0.6), and the likelihood that future demand decreases 10% is 40% (p=0.4). Experts who use their best judgment to encode related uncertainties can assign these probabilities.

Step 4: Evaluate and rank decision alternatives.

Decision alternatives are evaluated against decision objectives and ranked by the analytical component. The analytical component compares the relative satisfaction of each decision alternative against each of the decision objectives. Probabilities are multiplied by decision outcomes to get expected values for each alternative. These expected values for each alternative are compared and ranked.

In the decision tree in Figure 2.3, two decision alternatives are evaluated against two uncertain demand levels for one decision objective – minimize expected costs:

1. Build a dam, demand increases by 10%, no shortages occur.
2. Build a dam, demand decreases by 10%, no shortages occur.
3. Do not build a dam, demand increases by 10%, shortages occur.
4. Do not build a dam, demand decreases by 10%, no shortages occur.

Uncertainties are handled with the use of probabilities of decision outcomes related to future demand. Probabilities are assigned using expert judgment to the decision outcome “future demand increases 10% by 2020” (60%) and to the decision outcome “future demand decreases 10% by 2020” (40%). Each decision alternative is attributed a value of total expected cost and is ranked based on this value. In this example, the total expected cost for building a new dam is $60 million plus $40 million, or $100 million, and the total cost of not building the dam is $72 million plus $0, or $72 million. In this instance, the decision to not build the dam is preferred because it minimizes total expected costs.

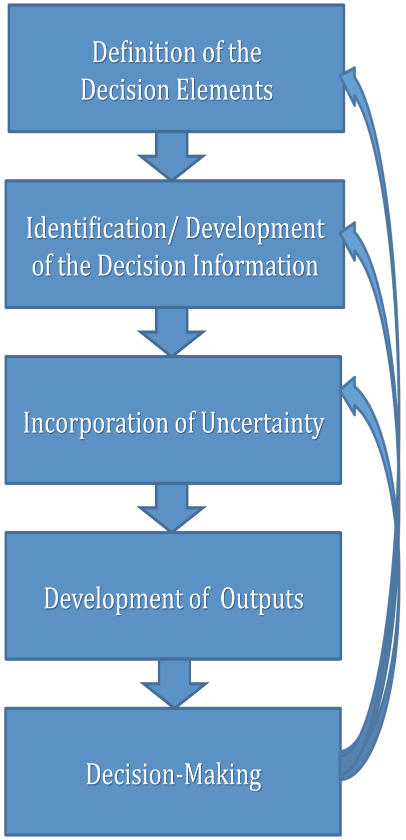
Step 5: Information valuation and decision-making.

Generally, the decision alternative with the highest (or lowest depending on the decision objectives) expected value is the preferred decision alternative. However, classic decision analysis is an iterative process and can explore the robustness of the preferred decision alternative using *information valuation.* Classic decision analysis is based on the current state of knowledge. Information valuation is simply to evaluate whether it is beneficial to collect additional information to further reduce uncertainty. This information can be obtained through experts, surveys, pilot tests, or research. Information valuation evaluates different information-gathering schemes and the cost, value, and reliability of using them (Howard and Matheson, 2004). If the value of information is high, additional information should be collected to refine the decision. If the value of information is low, decision maker(s) can be confident that based on the current state of knowledge, it is not profitable to collect more information and refine the decision.

In addition, sensitivity analysis can be performed at several stages of this DSPM and in decision-making. Sensitivity analysis answers the “What if?” or “What makes a difference in this decision?” questions (Clemen and Reilly, 2004). It further tests the robustness of the decision alternatives.

Flowchart and Example

The flowchart and example in Figure 2.4 illustrate the main steps to follow when using classic decision analysis.



Classic Decision Analysis Steps

Step 1: Frame the decision situation (key planning decisions, decision objectives, decision alternatives, decision variables, uncertainty outcomes).

Step 2: Develop an influence diagram or decision tree model.

Step 3: Estimate uncertainties using probabilities.

Step 4: Evaluate decision alternatives against decision objectives using a decision tree or influence diagram model. Rank decision alternatives.

Step 5: Perform information valuation (repeat Steps 1 through 4, if warranted) and select preferred decision alternative.

Sunny City Example

Step 1 – Decision: Type and timing of investments to make during the next 50 years to meet demand.

Key information: Future demand to exceed supply in 2040. Demand possibly increase 2%-5% annually. Supply possibly decrease 5%-15% by 2050.
Decision objectives: Minimize expected cost, maximize supply reliability.
Variables: Timing, demand, supply.
Outcomes: Demand increases 3% annually over the next 50 years.
Future decision alternatives:
1: Develop operational changes to improve reservoir management and supply efficiency by 10%.
2: Develop a reclaimed water system & demand management program to save up to 20% of supply.
3: Construct a new surface water reservoir & develop demand management programs to save up to 15% of supply.

Step 2 – Develop Influence Diagram or Decision Tree.

Step 3 – Sources of Uncertainty: Climate change impacts & population forecasts. Develop probabilities for these uncertainties using expert judgment.

Step 4 – Example outputs:
1. Expected costs of $20million & supply reliability in 70 of 100 yrs
2. Expected costs of $30million & supply reliability in 95 of 100 yrs
3. Expected costs of $99million & supply reliability in 99 of 100 yrs
Preferred decision alternative: 2

Step 5 – Information Valuation and Decision Making: Valuation is not desired in this case. Future alternative 2 provides the highest reliability for the cost.

Figure 2.4 – Classic Decision Analysis Flowchart and Example.

Value and Limitations

Several benefits of this DSPM have been highlighted in the Intergovernmental Panel on Climate Change Working Groups II and III (2001a and 2001b). One benefit lies in its ability to simplify complex problems into several decision alternatives and to systematically structure the information. Uncertainty is explicitly handled as a probability. When uncertainty is well characterized and the decision at hand is relatively straightforward, the results are relatively easy to communicate to decision makers. Classic decision analysis allows for various types of decision objectives (technical, environmental, economic, and social) to be considered in the decision and is a convenient tool to elicit knowledge and preferences (Labiosa et al., not dated). Classic decision analysis can be used in combination with other DSPMs, such as scenario planning, to assess strategies for different scenarios. This is useful to assess risk and robustness of the decision outcomes in order to improve adaptation strategies or to provide defensible ranking across the range of decision alternatives (Montibeller et al., 2007).

Decision analysis also has several limitations. One of them is the difficulty of implementing it in a complex and highly uncertain context (which often is the case when dealing with climate change). In such a context, it could be challenging to simplify the decision situation into coherent decision alternatives. Depending on the complexity of the analytical component, it could also require the need for additional computational work and coding. Classic decision analysis is useful in identifying one preferred decision alternative. In the context of climate change, it may be preferable to obtain a resilient set of alternatives rather than a single preferred alternative to understand the realm of future conditions or to have the ability to modify an alternative and achieve better performance (Morgan et al., 2009). To address this, decision makers need to have the ability to modify a decision alternative to achieve better performance.

Understanding analytical components of the decision tree or influence diagram model can be challenging for the decision maker(s) if the decision situation is complex. In addition, subjective probability assessment also can be challenging in terms of complexity and numbers of expert judgments (Kodikara, 2008). This task can be longer and more tedious if more than one decision maker or decision-making body is involved. Probabilities are based on scientific evidence and/or expert judgments; however, the best approach to characterize climate change uncertainty is still up for debate (Morgan et al., 2009). Studies evaluating classic decision analysis have revealed that the public had difficulty understanding and accepting decision trees because of the use of subjective probabilities and possible expert judgment bias (Chao et al., 1999).

Data gaps

Several data gaps were identified with classic decision analysis in its application to water utilities:

- Expert judgments need to be more explicit and transparent to better address uncertainty (Morgan et al., 2009).

- There is an opportunity to integrate the use of scenarios with classic decision analysis. This integration would help support the established scenarios for use in further reducing uncertainties to better assist decision-making.
- Future climate change assessments need to be internally consistent and explicit in representing uncertainty.
- A streamlined way of communicating the theory of the DSPM and outputs to stakeholders, including decision makers and members of the public, should be developed for water utilities. While classic decision analysis has been effectively communicated to stakeholders in a wide variety of settings for more than 40 years, there is little experience in using it in water utilities where climate change is involved.

2.2. Traditional Scenario Planning

Traditional scenario planning is a process that carefully examines trends and critical uncertainties, selects the key uncertainties, and constructs future scenarios based on those uncertainties. The scenarios are used to develop and vet strategies to cope with the implications of the scenario's conditions. By developing and assessing multiple scenarios that essentially frame future uncertainty, common strategies can be identified that represent robust approaches for managing that uncertainty. This technique can be used to identify critical uncertainties and develop possible solutions.

Description

Traditional scenario planning, also known as traditional scenario analysis, is a methodology that relies on developing future scenarios that consider a variety of potential future situations. It is used to evaluate a number of selected potential futures, to define how each potential future might be realized, and to determine what adaptation efforts might be applicable to these futures. These futures encompass the range of uncertainty that surrounds a focal question that an organization wishes to answer. Scenario planning is commonly used in short-term, long-term, and strategic planning, relying on a broader context to test the implications of various future outcomes. Using these hypothetical future scenarios, strategies can be devised to cope with the implications and uncertainties. Future scenarios are "coherent, internally consistent, and plausible descriptions of a possible future state of the world" (IPCC, 2001a; Schwartz, 1991). They are not predictions (which indicate outcomes considered most likely), but are a variety of alternate potential circumstances without ascribed likelihoods of how the future might unfold (IPCC, 2001a). The scenarios may be qualitative, quantitative, or both (IPCC, 2001b). They include dynamic, total system analysis of water portfolios, which consider any number of variables, such as hydrology, ecology, economics, climate change, and greenhouse gas emissions (O'Neil, 2008). Future scenarios also may look at demand, density, land-use changes, new water treatment requirements, or other identified areas of uncertainty. Scenario planning gained broad notoriety after the publication of one of the seminal books on the topic, "The Art of the Long View: Planning for the Future in an Uncertain World" (Schwartz, 1991).

Traditional scenario planning examines a small set of future scenarios without assigning any probability to their occurrence. This method also does not use probabilities to estimate the expected performance of key variables (Groves et al., 2008b).

The following is an example of a provocative scenario that could arise during the planning exercise. A city in an arid region has planned to contain growth to within a defined boundary. Once growth has reached city limits, the only option left for city planners is to develop up instead of out. Initially, as landscapes yield to housing, residential use decreases. But there is a threshold at which that is no longer the case. Eventually, a future with high density would result in increased demand, and additional supply would be needed to meet this new growth. In this scenario an understanding of city planning, growth, demand assessments, and timing are critical to water utility planning.

Typical Steps

Scenario planning is a methodology that relies on the development of future scenarios that consider a variety of potential future situations. It usually involves eight steps:

Step 1: Frame the Question/Issue.

The scope, context, central question or issue that will be assessed through the planning exercise is identified. In the context of climate change, this effort assumes that future climate trends may not be the same as in the past.

Step 2: Identify and Rank the Key Driving Forces.

Key elements surrounding the central question can be identified through a brainstorming session to generate a list of driving forces that have some bearing on the central questions. Many of the key driving forces are related to the various questions identified in Step 1, while others become evident through group discussions. These can be both internal and external driving forces that are qualitative and/or quantitative in nature (Schluter and Ruger, 2005). They may include internal issues, such as aging infrastructure and system reliability, and external issues, such as population density or changes to water rights. An important point is to initially capture all ideas without trying to gauge their relative importance at this stage of the process. The planning group seeks to generate the most complete list possible. In some cases, experts are used to help identify driving forces and analyze important trends. Once the list of driving forces is established, the planning group evaluates each one.

Step 3: Identify and Rank the Critical Uncertainties.

The discussion of the driving forces in Step 2 above will inevitably identify critical uncertainties related to the driving forces. The driving forces and their associated critical uncertainties are ranked based upon their relative *importance* and their relative *certainty of occurring* with respect to the central question(s). Those of greatest interest in the process are both *very important and highly uncertain* (critical uncertainties).

This step forms the fundamental basis for the balance of the scenario planning assessment. In theory, almost any number of uncertainties could be identified and used. However, as the number of uncertainties increase, the number of future scenarios increases exponentially. Therefore, the planning group must be selective and focus on issues that are most important and uncertain – the critical uncertainties. Uncertainties should be chosen based on their importance and impact they have in the given context, and they should be documented with assumptions and confidence levels.

Step 4: Create the Scenario Matrix.

Typically, the two most critical uncertainties (highest importance and greatest uncertainty) are used to form the x and y axis of a 2 x 2 matrix representing the extreme “endpoints” of the uncertainty. For example, if customer willingness to pay ranked as one of the highest uncertainties, the two elements on the x-axis would be high willingness to pay and low willingness to pay. If the climate change impact on hydrology was the other highest ranked uncertainty, the range of climate change impacts to water supply would be shown on the y-axis as high and low. The four resulting scenarios represent very broad future scenarios that bracket the range of uncertainty associated with these two critical uncertainties. Two uncertainties yield four scenarios.

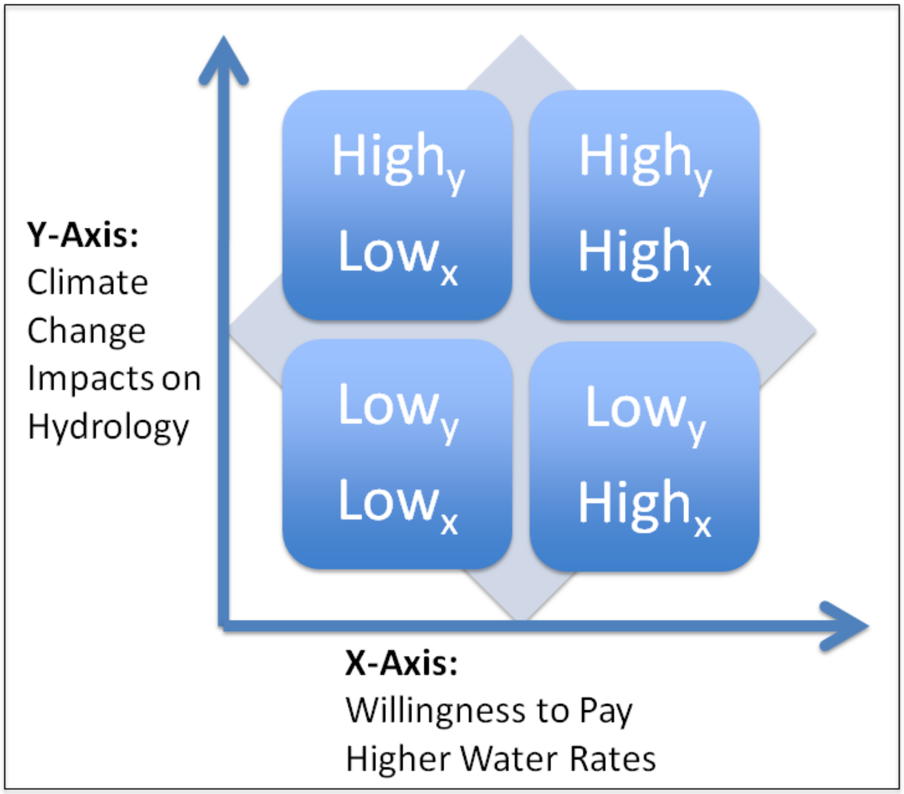


Figure 2.5 – Example of a 2x2 Critical Uncertainty Matrix Resulting in Four Different Future Scenarios.

Once the scenario matrix is created, the planning group envisions each of the possible futures identified. This begins with developing a description of each scenario. The scenarios are framed and described to be unique and clearly understood by all participants. The approach taken should be transparent and reproducible (PMSEIC, 2007). The construction of the scenarios can be done in detail or generally. As a general observation, detailed scenarios run the risk of becoming overly complex and can require significant resources to construct and analyze.

The combined effects of the two most critical uncertainties can lead to provocative and unexpected outcomes (see the initial method description for an example). This can help a utility prepare for more than the most expected future and for something different than conventional wisdom previously allowed. However, a narrative needs to be developed explaining specifically how the scenario came to be. If the narrative is not logical or plausible, the scenario should be eliminated (Schwartz, 1991).

Step 5: Create Paths to the Scenarios.

Each characterized scenario is a future that could come to pass. A plausible narrative is developed for each scenario as well as the water supply gap. The water supply gap is based on current strategy failures to meet future scenario conditions. The planning group plots a strategy to meet the needs of each of these futures based upon its specific characteristics and issues. The strategies include individual elements such as public, political, research, and technological programs, as well as various construction projects that may need to be sequenced over time to achieve the envisioned future. The strategies are developed independently from one another and are based solely on realizing each unique future. Nonetheless, similarities and overlaps do occur among the individual strategies developed. This commonality among the pathways is the essence of the next step.

Step 6: Identify the Common Elements.

The ultimate result of the scenario planning process is identifying common elements or success strategies. These common success strategies are comprised of projects and programs that are present on all or many of the individual scenario strategies. This commonality indicates that such projects and programs will be useful under a wide range of possible futures. As a result, such elements are more likely to be viable as the future unfolds.

Step 7: Identify Signposts.

In addition to common elements, planners identify “signposts,” which are developing conditions that signal the divergence of a particular scenario. Signposts can be helpful where the cost of action to address a scenario is high and the probability of the scenario occurring is low. Monitoring for the signposts can provide early warning for planners. Key signposts also can be linked to planning actions the utility can take.

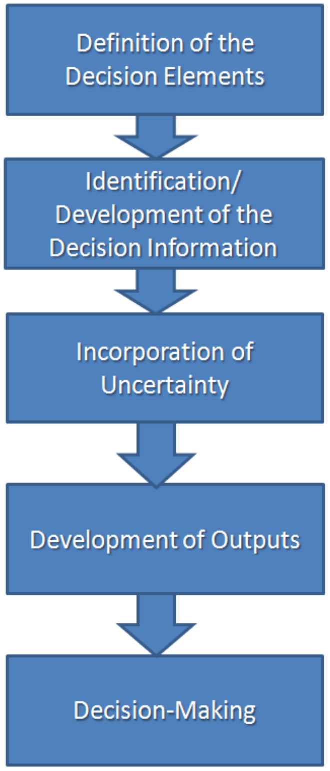
Step 8: Decision making and Implementation.

Scenario planning can be used to determine how current or proposed strategies should be adapted or incorporated into decision-making (Welling, 2008). The decisions can be linked to continuous or periodic monitoring of the critical uncertainties (i.e., developing and measuring climate change indicators) to allow the utility to re-evaluate and update management actions as signposts come to pass.

Major decisions are made in this DSPM during Step 6 and Step 7. Decision will also arise as signposts signal the divergence of one or more scenarios from the common path. The actions that are identified to be common to all future scenario strategies are incorporated into the long-term financial plans and analyzed so near-term strategies can be implemented.

Flowchart and Example

The flowchart and example in Figure 2.6 illustrate the eight general steps to follow when using traditional scenario planning.



Traditional Scenario Planning Steps

Step 1: Frame the question/issue.

Step 2: Identify & rank key driving forces.

Step 3: Identify & rank the critical uncertainties.

Step 4: Create the scenario matrix.

Step 5: Create paths to the scenarios.

Step 6: Identify common elements (test scenarios against data & assumptions).

Step 7: Identify signposts.

Step 8: Recognize decision-making.

Sunny City Example

Step 1 - Question: What is the type and timing of investments to make over next 50 years to meet demand?

Step 2 - Key driving forces:
Economy, population growth, water demand supply availability, new source availability, technology advances, etc.

Step 3 - Critical uncertainties and ranking:

1. Consumer willingness to pay
2. Climate change

Step 4 - Scenario matrix: Develop the 2×2 matrix. The four scenarios could be:

1. Low willingness to pay; high climate change impacts
2. High willingness to pay; high climate change impacts
3. Low willingness to pay; low climate change impacts
4. High willingness to pay; low climate change impacts

Step 5 - Create paths to scenarios: Develop narratives and identify strategies for each scenario. In scenario 1, an economic crisis may decrease customer willingness to pay and warming conditions have decrease streamflow significantly. Planning strategies may include demand management, public outreach, operational changes, a new reservoir, conjunctive use, or water recycling.

Step 6 - Common elements: Identify strategy elements common to all scenarios. A near-term common strategy may be demand management, public outreach, and water recycling development.

Step 7 - Signposts: A qualitative or quantitative sign will indicate a scenario is diverging from the others or it's original path. A signpost was identified 10 years into the future, where high climate change impact scenarios quickly diverge from the other two scenarios. Signposts correspond to decision-making points.

Step 8 - Decision making: Decisions are made in steps 5-7. The utility will determine which strategies are most suitable in the near-term and when to re-assess all scenarios and strategies.

Figure 2.6 – Traditional Scenario Planning Flowchart and Example.

Value and Limitations

While classic decision analysis can often be ill-suited to support long-term decision making (i.e. when the uncertainty about the future cannot be well characterized), scenario planning can be a valuable DSPM to consider because it allows the planner to determine how strategies will perform under different plausible futures. Scenario planning is a transparent process, which promotes a high level of engagement with stakeholders and is easily communicated. Outside experts are not essential to run the scenario planning process, but they can help develop scenarios and adopt the process to meet specific needs.

Information from traditional scenario planning can be used in planning to proactively manage uncertainty by implementing strategies to make systems resilient to a range of plausible future conditions and events. Traditional scenarios can be easy to understand and explain, and can be used to convey information objectively (Groves et al., 2008b). The method is sound when there is insufficient statistical information on data estimation, when probabilistic rules are not available or wanted, and/or when it is necessary to take into account information not derived from historical data (Pallotinno, 2005).

For traditional scenario planning to be successful, there must be agreement by planners, decision makers, and stakeholders on scenarios or potential futures (Schluter and Ruger, 2005), which may prove difficult in situations with many stakeholders or in potentially contentious public debates (EEA, 2009). Traditional scenario analysis requires critical uncertainties to be identified and plausible scenario paths developed. Probabilities are not assigned in traditional scenario planning, but can be applied for a more comprehensive analysis. There are practical limits to the number of scenarios that can be assessed because scenario narrative development can be time-consuming. Furthermore, if the developed strategies are sensitive to the few scenarios selected at the beginning of an analysis, stakeholders with views of the future that are not represented by one of the scenarios may challenge the entire process (Groves, 2005).

Data Gaps

The following data gap was identified:

- An approach to handling situations where a common strategy to follow for near-term action cannot be determined. This occurs when all scenario paths immediately diverge from each other.

2.3. Robust Decision Making

Description

Robust decision making is a decision analytic framework that combines features of both classic decision analysis and traditional scenario planning. The method provides a systematic approach for evaluating strategies against large ensembles of scenarios using water management models. Robust decision making identifies strategies water utilities can pursue that are robust over many scenarios reflecting a broader range of plausible future conditions (Lempert et al, 2006; Lempert et al, 2003). The method differs from traditional scenario analysis because it uses simulation models rather than detailed narratives to develop scenarios. Doing so enables planners to consider a broader range of strengths and weaknesses of proposed strategies. Robust decision making differs from classic decision analysis in two important ways. First, it evaluates robust strategies as opposed to optimal criteria. A robust strategy will perform almost as well as an optimal strategy that results from a classic decision analysis if future conditions turn out as expected, but it also will perform well if unexpected future conditions arise (Lempert and Collins, 2007). Second, robust decision making does not rely on a single set of probability distributions to describe uncertainty about the future. Rather, the approach uses either scenarios without probability distributions or it considers imprecise probability distributions, in which the probabilities take on a range of values.

Robust decision making identifies robust strategies by estimating the performance of numerous strategies over many combinations of uncertain model inputs. It then uses statistical algorithms to characterize the few model inputs most important in explaining cases in which the strategy performs poorly (Groves and Lempert, 2007). These vulnerabilities can then help identify hedging actions that managers can use to design more robust strategies. In the end, analysts and/or decision makers consider a small number of candidate robust strategies and the performance tradeoffs of each against the identified vulnerabilities. This information allows the decision makers to consider their own expectations of the future (rather than that of a particular analyst or modeler) to choose an appropriate final robust strategy.

The U.S. Climate Change Science Program has emphasized that “for both theoretical and practical reasons, there are limits to the applicability and usefulness of classic decision analysis to climate-related problems” (Morgan et al., 2009) and recommends considering robust strategies and a range of probability distributions as potential solutions to these challenges. Robust decision making incorporates both concepts. The method is useful when standard decision making methods cannot easily be applied because (1) the complete set of strategies is not known at the onset of the analysis, (2) uncertainties about the future strategies are too great to be uniquely characterized, or (3) there is disagreement among decision makers and/or stakeholders about how to value the potential outcomes of strategies (Groves, 2005). Robust decision making also can prove useful in developing robust contingency plans that help address the “act now” versus the “act later” question, helping water utilities determine what actions they need to take in the near-term and which can be deferred until later. To date, Robust decision making has helped several California water agencies develop and evaluate strategies for responding to climate change (see Groves et al, 2008a, 2008b, and 2008c for an example).

Typical Steps

Robust decision making can be implemented in eight iterative steps (derived from Groves, 2008c):

Step 1: Frame the decision analysis.

Define the key elements of the decision analysis, including:

- Initial set of management options that can comprise an alternative
- Key uncertain factors that could affect the outcomes of the alternatives
- Performance metrics to evaluate alternatives
- Key relationships among the alternatives and outcomes, subject to uncertain future conditions (typically represented in quantitative models)

Step 2: Develop or adapt water management models to evaluate strategies under different scenarios.

Water management models often are not configured to evaluate numerous water management strategies against many different scenarios. In this step, planning models are adapted or developed in order to run individual cases reflective of a single management strategy under a single set of assumed future conditions. For some models, this requires utilities to develop new hydrologic input data reflective of different future climate projections (Groves et al., 2008d). Generally, any model parameter representing uncertain future conditions needs to be identified and configured to accept alternative specifications as part of a scenario. For others, it involves developing scripts or connecting the model to software to execute the model under many different configurations and collect input and output data into a single database for analysis.

Step 3: Specify large ensembles of scenarios reflecting uncertainty and define initial set of candidate policies.

Scenarios are specified in the method by assigning different values for the uncertain model parameters. When a large number of uncertain, continuous parameters are defined, it is not possible to evaluate all combinations. Techniques such as Latin Hypercube Sampling (McKay and Beckman, 1979) can be used to define a small number of scenarios that span the range of plausible values for all the uncertain parameters.

Combining various management options into complete management packages specifies initial candidate strategies. It is typical to include the current long-term management plan as a strategy. As robust decision making is iterative, it is not critical that every possible combination of options be considered at this stage. However, it is important to include a wide array of options being considered. Often at this stage, strategies are defined statically – that is, a sequence of management options are defined and do not depend upon the evolving of the water management system. On subsequent iterations, options changing with time are typically introduced.

Step 4: Evaluate strategies against scenarios.

Each candidate strategy is evaluated against each scenario developed in Step 3. For each simulation, select model output representing the performance metrics defined in Step 1 is saved. The scenario inputs and simulation outputs are then collected in a single database for analysis in subsequent steps.

Step 5: Characterize future conditions that lead to poor performance of best-performing strategies.

In general, water managers face many uncertainties about the future, including climate change, future economic and demographic trends, technology advances, environmental constraints, and future regulatory constraints. To characterize this broad range of uncertainties, robust decision making evaluates which future conditions (as represented by the scenarios) would lead to poor performance of the best-performing strategies. To do this, each result is classified as having acceptable or not-acceptable performance. In cases when performance is represented by multiple criteria, multiple-criteria decision analysis approaches can be used to develop a single performance score. Statistical data-mining or search algorithms can be used to identify which uncertain conditions lead to poor performance of promising policies (Groves and Lempert, 2007). These vulnerabilities can be described through ranges about the uncertain inputs. If these vulnerabilities are of sufficient concern, then this information can be used to develop better-hedged strategies in Step 7.

Step 6: Calculate performance tradeoffs for the candidate robust strategies in the key vulnerabilities.

Once key vulnerabilities are identified, robust decision making calculates the performance tradeoffs of the candidate strategies under the vulnerability conditions and under non-vulnerability conditions. These tradeoff curves reveal strategies that may sacrifice some performance over non-vulnerability conditions, yet perform considerably better under the vulnerable conditions. Often this step involves identifying probability thresholds for particular vulnerable scenarios (Lempert et al., 2006; Groves and Lempert, 2007). That is, the probability a decision maker would need to assign to that vulnerable scenario to justify a change in the proposed strategy. For instance, the analysis might suggest that a water utility's proposed investment strategy was appropriate if the probability of very dry future conditions was less than some value, but that the utility might consider additional investment of the probability of future dry conditions exceeded that value. These probability thresholds can then be compared to the best available probability estimate in the scientific literature, even when these estimates prove imprecise. These tradeoffs curves can inform the development of hedges in Step 7 or selection of a final strategy in Step 8.

Step 7: Develop hedges to key vulnerabilities and iterate with revised strategies.

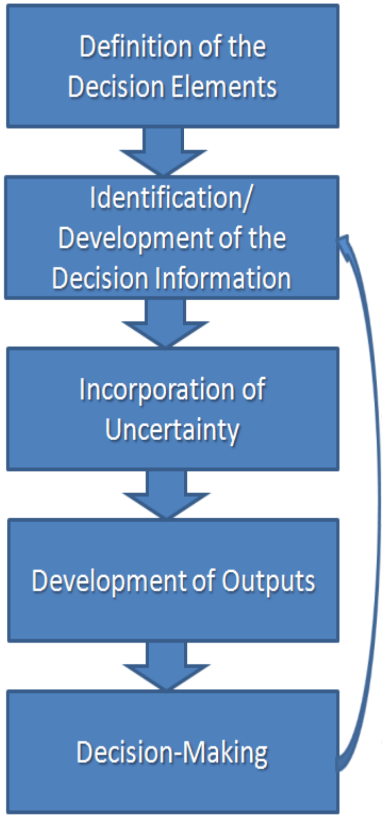
By examining the key vulnerabilities of promising strategies, the analysts and decision makers together can craft a new, expanded set of better-hedged strategies. Hedging is a standard tool for dealing with uncertainty and is not unique to this approach. In robust decision making studies, hedging often is accomplished through adaptation. Adaptive strategies consist of near-term actions, specified by conditions that suggest additional or alternative actions should be taken, and deferred actions that could be taken if conditions warrant. These new, expanded sets of strategies are then re-evaluated across the scenarios in Step 4. The process (from Step 4 through 7) can be repeated until feasible hedging options have been explored and/or the remaining vulnerabilities are deemed of little concern to the water agency.

Step 8: Choose final robust strategy based on trade-off information and decision-maker expectations of future conditions.

Once all hedging options have been explored, the robust strategies and remaining uncertainty are presented to decision makers so that they can assign their own subjective assessment of the likelihood of the critical scenarios and select the final robust strategy.

Flowchart and Example

The flowchart and example in Figure 2.7 illustrate the eight main steps to follow when using robust decision making.



Robust Decision Making Steps

Step 1: Frame the decision analysis (management options, uncertain factors, performance metrics, relationships or models).

Step 2: Develop or adapt water management models to evaluate strategies under different scenarios.

Step 3: Specify large ensemble of scenarios reflecting future uncertainty and define initial set of candidate strategies.

Step 4: Evaluate strategies against scenarios.

Step 5: Characterize future conditions that lead to poor performance of best-performing strategies (i.e., vulnerabilities).

Step 6: Calculate trade-offs for performance of the different candidate robust strategies in the key vulnerabilities.

Step 7: Develop hedges to the key vulnerabilities and iterate with revised strategies (Steps 4-6).

Step 8: Choose final robust strategy based on trade-off information and decision makers expectations of future conditions.

Sunny City Example

Step 1 - Decision analysis: What combination and timing of management actions will ensure adequate supplies to meet demand over futures uncertain climate conditions and demographic trends?

Step 2 – Develop models and collect data: Adapt Sun City Water Management Model to evaluate strategies against numerous scenarios. Group management actions into 20 strategies. Obtain downscaled climate data and ranges of demographic forecasts.

Step 3 – Develop experimental design: Specify 36 different scenarios reflecting 12 different climate projections and 3 different demographic growth projections.

Step 4 – Evaluate strategies against scenarios: Evaluate model 720 times (once for each strategy/scenario combination).

Step 5 – Identify Vulnerabilities:
Strategy 1 performs poorly under climate scenarios 2, 5, and 6 and demographic growth pattern 2; *Strategy 2* performs poorly under climate scenarios 1, 4, and 9 and demographic growth pattern 1, *etc.*

Steps 6 and 7 – Develop Hedges and evaluate tradeoffs: Specify reservoir construction to be contingent on degrading hydrologic conditions. Iterate.

Step 8 – Choose robust strategy: Implement new efficiency and conjunctive management now, monitor hydrologic conditions, and build reservoir in 10 years if conditions degrade.

Figure 2.7 – Robust Decision Making Flowchart and Example.

Value and Limitations

Several benefits of this DSPM have been highlighted by the U.S. Climate Change Science Program (Morgan et al., 2009) and by the Intergovernmental Panel on Climate Change Working Group III (2001c). The use of computerized simulations allows the broad range of possible futures to be evaluated. As compared to traditional scenario planning, robust decision making provides information on the quality and performance of scenarios across large ensembles of plausible futures, which can be particularly advantageous to decision makers. Robust decision making scenarios provide concise descriptions of a strategy's potential vulnerabilities and help suggest the development of new strategies to reduce those vulnerabilities. Robust decision making can assist in arriving at a decision on near-term actions without having to agree on expectations about the future. Even when no single robust strategy exists, the robust decision making analysis may provide some guidance to decision makers on where they need to invest in research to reduce key uncertainties or find ways to expand their options.

Robust decision making expertise at this point is concentrated among a small group of practitioners and requires sophisticated computing and analytic capabilities. Formal evaluations conducted by the RAND Corporation comparing traditional scenarios, classic decision analysis, and robust decision making approaches suggest that robust decision making may produce more useful information but may be more difficult to understand and explain than traditional scenario planning and requires a high level of decision-maker engagement (Groves et al, 2008b). In addition, robust decision making requires some potentially subjective judgments by the analysts, including what level of adverse performance qualifies as vulnerability and how robustness is defined, which may influence the results. The success of a robust decision making\analysis often depends on the ability to find strategies that are robust.

Data Gaps

Several data gaps were identified with robust decision making:

- Robust decision making relies on hypotheses about what is most useful to decision makers rather than proven relationships. Significant research is ongoing and should continue to be invested in robust decision making to improve its performance.
- Robust decision making can be difficult to understand and explain. Although designed to select key scenarios through a systematic, objective process of identifying vulnerabilities to candidate strategies, robust decision making can be perceived to be less objective than traditional scenario planning because the methodology is less familiar. More examples of applying robust decision making to water management may alleviate this current problem.

2.4. Real Options

Description

The real options method is a type of financial-based DSPM. The method combines classic decision analysis with financial theory. Generally real options consists of an extension of traditional cash flow analysis that includes flexible strategy implementation (WSAA, 2008). This approach looks at a strategy's uncertainty based upon a comparison to costs whose risks are closely correlated with the strategies (Rogers et al., 2003). It can be applied in highly uncertain environments (Rogers et al., 2003).

Real options has been widely used in the finance, pharmaceutical, medical, energy, transportation, real estate, and product manufacturing fields, as well as in planning and designing of engineering systems. It offers great potential for applications to water planning. This DSPM was used to analyze river-run hydropower stations for a river basin in China (Wang and deNeufville, 2004). Another study featured a hypothetical case study that used real options to analyze changes to streamflow for urban water planning in Australia (WSAA, 2008).

Typical Steps

Real options uses a set of techniques that combines classic decision analysis (decision trees) and financial theory (hedging concepts). It usually involves seven steps:

Step 1: Define key questions, key decision strategies, key decision objectives, and key uncertainties.

The first step of real options consists of defining the following:

1. The scope, context, central question, or issue that will be assessed through the planning exercise. For example, "what type and timing of investments does a utility need to consider to meet water demands during the next 50 years?"
2. Key decision objectives, such as level of reliability required/desired, cost (affordability or rate objective), level of acceptable performance, risk, etc.
3. Key decision strategies (also known as "options"). These are the various actions that could be implemented to achieve key water supply objectives. These strategies are then evaluated by the DSPM. Examples of key decision strategies include all the classic and novel water resource options. Key areas of uncertainties represent the unknown factors affecting key decision strategies. Examples include: climate change impacts, population forecasts, consumer willingness to pay, regulatory and permitting risk, water demands, etc.

Step 2: Develop an analytical model.

The analytical model for applying real options is based on a combination of the classic decision analysis theory and financial theory. Several techniques have been used to apply real options. The techniques include the traditional analytic method, such as Black-Scholes option-pricing method; lattice; Monte Carlo simulation procedure with stochastic optimization model; log-transformed binomial approach with correlation; and risk-adjusted decision trees/dynamic programming. These methods (in the order listed) range from the simplest/most restrictive to the most involved/widely applicable methods (WSAA, 2008). Also, in the order listed, these methods incorporate an increasing level of flexibility. Off-the-shelf decision tree and Excel spreadsheet software can be customized to implement real options; however, the WSAA paper (2008) asserts that better results will be obtained if a real options model is developed from scratch and tailored to the needs of a utility.

Step 3: Compute a baseline.

This step consists of analyzing the defined strategies/options by calculating their financial value using the analytical model. The values of distributing possible outcomes associated with strategies/options over time are estimated in this step. The analysis results in a value for a particular strategy/option or element of a system (WSAA, 2008). In the example of traditional water planning, baselines for demand and supply are estimated and several strategies are evaluated (e.g., building a dam, building a water reuse facility). This is then combined with a traditional “cash flow” financial model. The outcomes consist of attributing a cost to each strategy over time.

Step 4: Evaluate strategies/options under uncertainty.

In this DSPM, uncertainty is handled with probabilities. Uncertainty can be addressed using statistical methods to improve parameter quality; aggregating forecasts to reduce errors; and correlating strategies/options and uncertainties. Sensitivity analysis can be completed for key variables.

Step 5: Conduct options analysis.

The strategies/options defined in Step 2 are fixed (non-flexible). Options analysis allows adaptive and incremental decisions over time (WSAA, 2008) to be included. For example, the decision to develop a direct potable reclaimed water system may not be made today because the construction of such a system may not be politically feasible. With flexibility, this strategy/option can be reconsidered with new information about direct potable reclaimed water systems in five or 10 years and may be implemented if feasible. In practice, the analytical model evaluates the flexible options and provides the risk profile of each strategy/option. The risk profile represents the net present value of the strategies against the probability of occurrence and corresponds to the complete range of potential outcomes for a specific strategy/option and associated probability (WSAA, 2008). In general, flexible strategies/options increase net present value, reduce risk, and are more complex to implement in comparison to fixed strategies.

For example, a utility is evaluating the following key strategies/options to meet future 50-year demand: demand management programs, system operational changes, and reclaimed water systems. A flexible option would be for this utility to implement all three strategies but doing so immediately may come with the risk of incurring implementation costs for options that are not necessary in hindsight. Results of options analysis could reveal that the best current strategy is to implement demand management programs. In five years, results indicate there will be a 50% chance that demand management programs need to continue, a 25% chance that system operational changes need to occur, and a 15% chance that development of a reclaimed water system needs to be considered. In 10 years, results indicate there will be a 50% chance that development of a reclaimed water system needs to be considered, a 25% chance that demand management programs need to continue, and a 25% chance that system operational changes need to continue. This example shows that it makes sense for the utility to start by implementing demand management programs, but as time goes by and demand increases, be prepared to consider a reclaimed water system to handle the increase in demand. The development of probabilities is informed by expert input (internal or external to the utility) and can be somewhat subjective.

Step 6: Conduct monitoring.

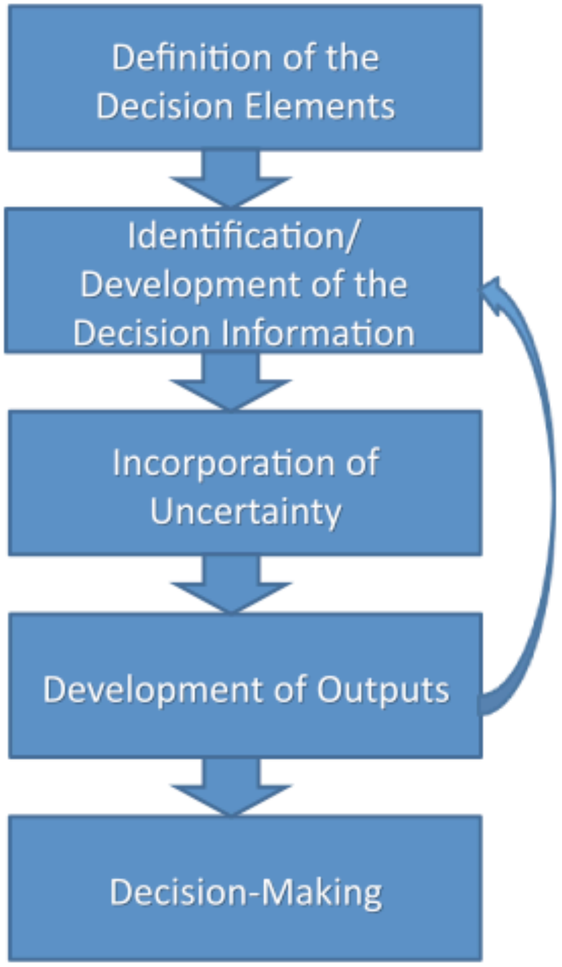
Real options allows decision makers to choose the appropriate investment opportunity based on current information available and to defer investments into the future (Reid, 2007). With time, changes in underlying variables, such as costs, result in changes in future probability of occurrence. For this reason, options for making an investment are flexible and consistently reevaluated over time. This step consists of monitoring the conditions to understand when a strategy/option can be implemented or abandoned. The evaluations of uncertainties are monitored to ensure the decision makers obtain full value from the system and to determine when it is appropriate to keep existing strategies/options versus developing new ones.

Step 7: Decision Making.

Real options helps determine which strategies/options maximize value while balancing its risks (WSAA, 2008).

Flowchart

The flowchart in Figure 2.8 illustrates the steps comprising real options.



Real Options Steps

Step 1: Define key planning decisions, key decision objectives, key strategies or options, and uncertainty at highest value and lowest risk.

Step 2: Develop an analytical model.

Step 3: Compute a baseline.

Step 4: Evaluate the strategies or options under uncertainty.

Step 5: Conduct options analysis, measure flexibility, and analyze options.

Step 6: Monitor and re-evaluate options of low value/high uncertainty with new information every 1-5 years.

Step 7: Select the strategy or option with high value/low uncertainty.

Figure 2.8 – Real Options Flowchart.

Value and Limitations

Real options is useful in highly uncertain situations. Real options is based on identifying and analyzing strategies/options by determining the value of each. The value is dependent upon future conditions. Real Options can overcome the flaws of discounted cash flow analysis and increase reliability (deNeufville, 2003). The main advantages of using the real options method are that it can help identify flexible and unique investment strategies, while providing flexibility within projects because they can be adjusted over time (WSAA, 2008). This method promotes management of risks instead of reacting to them (deNeufville, 2003). Real options is helpful when comparing the benefits of one project over another is difficult, which is generally the case when evaluating future climate scenarios (WSAA, 2008).

Water utilities considering real options must carefully consider their willingness, and ability, to assign probabilities to climate model projections. In situations where probabilities cannot be scientifically or mathematically determined, expert judgment is used to assign probabilities. Real options can be complicated and time-consuming because of the inputs, analysis required, and high computing requirements (Brautigam and Esche, not dated). In complex settings (as would be the case for climate change) real options is most applicable for evaluating local solutions because it does not offer a solution of exact strategy/option cost (Wang and deNeufville, 2004). Decision makers must be heavily involved in this method. The process, results, and concept of flexibility are difficult to communicate. In addition, there is little guidance about how to monitor information for re-evaluating value and uncertainties over time. Real options is complex and relatively unknown to the water industry, which might make it difficult to embrace and trust. In addition, adopting flexible options may be unrealistic for many utilities as changing strategies after spending public money would be politically difficult.

Data gaps

Data gaps include:

- There is a lack of examples where real options planning has been applied in the context of climate change. Guidance for water utilities would be needed to implement planning for climate change applications.
- Options analysis usually treats options independently. In reality, options may interact with each other, which may also lead to misguided or unusable results. There needs to be improved understanding of the interdependencies of various resource strategies in the context of climate change.

2.5. Portfolio Planning

Financial portfolio planning is included in the presentation of DSPM as a suggested example of how other sectors handle uncertainty. This method currently is not used in water planning, to the knowledge of the authors, but this inclusion is intended to exemplify the potential use of other uncertainty management methods by the water industry. Though many other examples exist, portfolio planning was selected because of the general familiarity many have with financial planning.

Description

Portfolio planning, developed to deal with uncertainty inherent in the financial world, is used to select a portfolio to minimize risk and to hedge against uncertain future scenarios. Hedging here is an investment strategy to reduce the risk of adverse price movements in an asset. A hedge is a position established in one area in an attempt to offset exposure to the price risk in another area. In water resources, diversifying your water supply portfolio with water sources that are not susceptible to the same types of risk would be a type of hedge. For example, seawater desalination would not be directly subject to the risk of drought (although drought could affect energy costs, which could affect the cost of desalination). Demand management would not be subject to permitting risk associated with indirect potable reuse. Recycled water development would not subject the utility to the financial volatility of demand management.

A portfolio is composed of a combination of assets and strategies. For water planning purposes, a portfolio could be a mix of ground and surface water supply sources, demand management programs, water contracts, emergency supplies, pricing structures, reliability standards, or operational changes. The objective of the portfolio planning DSPM is to identify a robust set of assets and strategies applicable to equally probable future scenarios. The concept is similar to others described in this white paper.

Portfolio planning goes beyond assessing individual security (such as a stock or bond) risk and evaluates single security contributions to the overall performance of the portfolio. A portfolio is usually selected to include diversified components that are suited to one or more, but not all, future scenarios (Crowe and Parker, 2008). Diversification of a portfolio usually increases its robustness.

In addition to having multiple financial applications, portfolio planning has been used in power utility long-term planning (CEC, 2007) and the gas supply planning process (McNeil, 2006). The portfolio planning model could be applicable in the context of climate change with an assumption that over time, the values of assets and strategies vary depending upon the climatic conditions. The literature review identified one study that used portfolio planning for reforestation under climate change scenarios. In this study, portfolio planning assisted in selecting an optimal set of sources used to regenerate forests under numerous possible future climatic conditions (Crowe and Parker, 2008). The concepts of analysis of return and risk, as well as diversification that are inherent to this DSPM, suggest its potential application to water planning in the context of climate change.

Typical Steps

The objective of the portfolio planning DSPM is to identify a robust set of strategies applicable to equally probable future scenarios. It generally involves six steps:

Step 1: Select portfolio and define future scenarios.

This first step deals with selecting elements of the portfolio. Elements consist of assets and strategies. Diversifying the elements of a portfolio creates more robustness. Scenarios describing future conditions and covering a wide range of possible futures are developed. The selection of portfolio elements and scenarios is similar to the approach used in scenario-based methods.

Step 2: Identify the expected returns and risks.

The goal of portfolio planning is to provide the highest possible return for a specified level of risk, or conversely, the lowest risk for a specified level of return (CEC, 2007). To do so, the average return and risk of return for each portfolio element are quantified and each pair of assets is correlated. The following values are computed:

- Expected return of each portfolio element (for water, this could be quantifying reliability or minimizing costs)
- Expected risk or volatility of return (measured by the expected variance of each portfolio element's return over time)
- Expected contribution of each portfolio element to the overall performance of the portfolio (measured by the expected covariance of each portfolio element's return with every other portfolio element's return)

Step 3: Construct the portfolio optimization model.

A portfolio optimization model is constructed. In this model, a mathematical expression is defined to minimize the variance and covariance (i.e., risk) of the selected portfolio elements to a lower bound on the total expected return for all portfolio elements over possible future scenarios.

Step 4: Incorporate uncertainty.

In portfolio planning, uncertainty is managed though hedging portfolio elements over a wide range of future scenarios. Uncertainty also can be addressed by generating probabilities of associated returns and risks for all key portfolio elements. Monte Carlo simulations and Latin Hypercube Testing (generation of a distribution of plausible collections of parameter values from a multidimensional distribution) can be used to provide random samples of correlated input data to the portfolio optimization model. Then the optimization model is run for each set of correlated data and the results of all sets are used to derive key probability information for a portfolio element.

Step 5: Develop outputs.

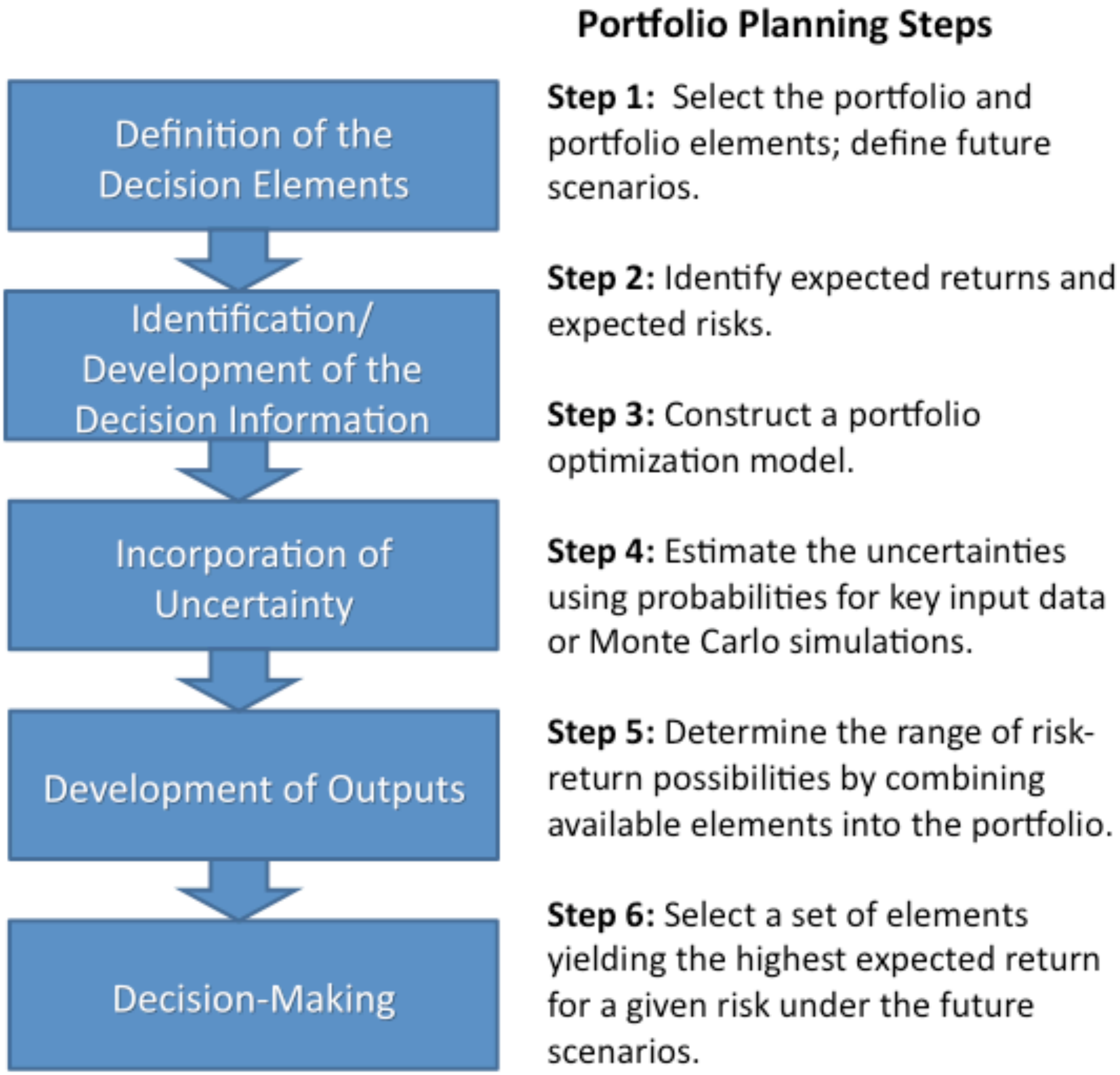
Outputs of the portfolio optimization model determine the range of risk-return possibilities from combining available portfolio elements (CEC, 2007). The outputs of this DSPM are usually a robust set of assets applicable to equally probable future defined scenarios. Each output component is not selected to perform well in all plausible futures but rather to specialize in particular scenarios.

Step 6: Decision Making.

The solutions, combined into an optimal portfolio, are determined by the selected elements of minimized total variance and covariance (lowest expected risks) on the total expected return for all selected assets across all the scenarios (Crowe and Parker, 2008).

Flowchart

The flowchart in Figure 2.9 illustrates the steps to follow when using portfolio planning.



Portfolio Planning Steps

Step 1: Select the portfolio and portfolio elements; define future scenarios.

Step 2: Identify expected returns and expected risks.

Step 3: Construct a portfolio optimization model.

Step 4: Estimate the uncertainties using probabilities for key input data or Monte Carlo simulations.

Step 5: Determine the range of risk-return possibilities by combining available elements into the portfolio.

Step 6: Select a set of elements yielding the highest expected return for a given risk under the future scenarios.

Figure 2.9 – Portfolio Planning Flowchart.

Value and Limitations

Climate change and the financial environment share deep uncertainty. The Intergovernmental Panel on Climate Change Third Assessment Report (2001b) suggests the portfolio planning method could be used to help utilities embrace the uncertainties of planning for multiple possible future scenarios irrespective of their probability. The authors could find no examples of the practical application of this DSPM to water resources planning (with or without climate change).

A limitation of this DSPM is that it requires heavy involvement of decision makers. While the process can be easily communicated to stakeholders, communicating the assumptions, analysis implications, and decisions, which are based on the decision makers' risk tolerance, can be more challenging. In addition, outside experts may be required to implement this DSPM as computing requirements are high. As there are no applications of the portfolio method to water planning available at this time, its application would require fundamental methods development by the utility pursuing the method.

The portfolio planning method allows utilities to identify an optimal portfolio of fixed assets and strategies (e.g., water resource and infrastructure). A water portfolio could be optimized to provide a robust solution for maintaining supply reliability in multiple, equally probable, future changes in climate. An optimal portfolio would contain diverse portfolio elements to react differently to different future climate scenarios while being independent of these scenarios (Crowe and Parker, 2008). Different portfolio elements can perform differently to subsets of, and not all, plausible future. Climate scenario probability information could be produced for all key portfolio elements or assumed to be equally probable. Portfolio planning offers the advantage of testing risk-return possibilities over a larger range of options, thus yielding better and more robust decisions (McNeil, 2006).

The portfolio method application to climate change could be limited because of the effect of interdependence (Crowe and Parker, 2008). Portfolio planning inherently assumes that portfolio elements are independent from each other and each portfolio element can be evaluated in isolation from the other portfolio assets. This assumption is not always valid when considering the elements of climate change (Crowe and Parker, 2008) or water system assets. For example, in drying climates, effects would occur for surface supplies (less yield), groundwater (less recharge), and recycled water (higher salinity with less volume). This level of dependence would need to be understood and embedded into the portfolio method (as risk of portfolio element failure or success and/or cost).

Data gaps

Data gaps were identified with portfolio planning:

- There are no examples of real world application of portfolio planning to water resources planning with or without the context of climate change. Accordingly, fundamental

method development and application to utilities are needed in order to assess the true potential of this DSPM. Water utilities would require clear guidance in its application.
- Understanding the interdependence of water supply sources in the context of climate change would be needed.
- Unlike financial assets, diversification of water supply operating assets (treatment plants, pipelines, reservoirs, etc.) is generally not cost-effective. Portfolio planning elements would need to focus on the water supply portfolio but consider operational risk as well (e.g. water quality effects of climate change on reliability).

3. Case Studies

This section presents case study summaries for water utilities that have used the presented DSPMs to incorporate climate change uncertainty in their water planning. The DSPMs described below include decision analysis, scenario planning, robust decision making, and real options. The case studies were based on discussions with Water Utility Climate Alliance (WUCA) members with experience using the DSPMs. Applications of DSPMs by other water utility are also summarized based on available literature sources.

3.1. Classical Decision Analysis

Seattle Public Utilities, Seattle, Washington

Seattle Public Utilities used classic decision analysis for its 2007 Water System Plan (2007) to help make water supply investment recommendations to decision-makers, senior management, and stakeholders by considering risks, uncertainties, and the triple bottom line. With this DSPM, Seattle Public Utilities evaluated water supply strategies, including which source to develop and when the source would come online. The utility's application of the DSPM integrated outputs from Seattle Public Utilities' existing yield, demand, conservation, and cost models in a decision tree framework to explore a range of uncertainties, such as demand forecasts, source development, loss of supply due to legal/regulatory changes, climate change and variability, and cost. Uncertainty in supply, cost, and demand was quantified using probabilities assigned by internal subject matter experts. Other uncertainties, such as climate change, were not assigned probabilities but were explored in separate sensitivity analyses. The probabilities and decision tree framework were used to compute the expected costs to invest in various water supply strategies to meet future demands. A model was constructed to assign scores to the non-monetary impacts associated with the supply options, including public health, regulations, and ease of development. Output from the analysis was represented in a graphical form that compared expected costs to the non-monetary values of supply alternatives. Seattle Public Utilities performed sensitivity testing to validate the DSPM results by varying assumptions and inputs to the evaluation. The utility's use of classic decision analysis determined that greater use of existing supplies by changing reservoir operating parameters had a greater benefit as compared to other new supply options, such as investing in reclaimed water projects. Based on the results of the analysis, Seattle Public Utilities concluded that investments beyond the planned conservation programs were not needed at this time. However, because of uncertainties in the decades to come, Seattle Public Utilities will keep the supply alternatives for possible use in the future.

Case Study Findings

Seattle Public Utilities described the DSPM results as transparent and understandable, but it felt that the decision tree analysis process and use of expected values was difficult to communicate to stakeholders. SPU found the level of expertise and time intensiveness of classic design analysis to be fairly high and indicated a need for outside expertise to use this DSPM. Further, Seattle Public Utilities found that computational requirements were intensive and limited the number of alternatives that could be analyzed. Also, agreeing on the probability of uncertain events was challenging. Seattle Public Utilities stated that the resulting data from the analysis were easily exportable to spreadsheets for graphical representation and analysis. In the future, planners at Seattle Public Utilities would like to increase the number of uncertainties analyzed and they think certain aspects of the DSPM could be used again.

Portland Water Bureau and Regional Water Providers Consortium, Portland, Oregon

The Portland Water Bureau and Regional Water Providers Consortium (Consortium) conducted a decision tree analysis to evaluate its ability to meet water demands in the context of climate change and other uncertainties (Regional Water Providers Consortium, 1996 and 2004; Stickel, 2007). To perform the analysis, the consortium used a hybrid approach, which relied on a decision tree, future scenarios based on a 60-year record of weather, and the probability of meeting future demands for the proposed scenarios. The consortium developed the Confluence model to perform this analysis, which integrated the decision tree and scenario evaluation. Confluence used input data on existing and future supply sources, water demand, future conservation programs, water rights constraints, contract requirements, operating constraints, quantities of supplies, future costs, and environmental criteria.

Input data for hydrology, water quality, water demand, and conservation program savings were taken from other utility models to perform the Confluence analysis. Climate temperature and precipitation data were used to develop water demand forecasts. Strategies were adjusted to meet three different water demand forecasts at three different levels of reliability. Uncertainty was measured through the amount of water demand that could not be met in a given scenario and by assigning numeric ratings to represent the quality of data and environmental costs. Sensitivity analysis was performed using Monte Carlo simulations with user defined time steps.

Case Study Findings

The model results were displayed for high, medium, and low demand growth rates. The DSPM results considered the ability to meet the three different reliability levels and the associated timelines to develop new supplies or programs. Model outputs were easily extractable for further analysis to an Excel spreadsheet.

The consortium relied on an external consultant to construct and implement the DSPM. Participants needed to have a high level of expertise to use this DSPM. The consortium felt that the complexity of the model was the biggest drawback, which created issues associated with not understanding the inner workings of the model. Environmental impacts were ranked based on subjective judgments by the consortium, which was a concern to stakeholders. The consortium found this DSPM was hard to understand and that results were not transparent; however, with guidance from a consultant, results could be and were communicated effectively.

The Confluence model has been improved and updated over the years since the Portland Regional Water Supply Plan was developed. Recently, the model has been updated to include the ability to evaluate climate change impacts.

Southern Nevada Water Authority, Las Vegas, Nevada

Southern Nevada Water Authority conducted a decision tree analysis to evaluate uncertainties in its 1995 Integrated Resource Plan (IRP) to ensure the appropriate resource and facility decisions would address rapid growth and potential water resources shortfalls. Southern Nevada Water Authority recognized that traditional approaches to water planning may not have been as effective for this type of analysis, so the Authority worked to develop an IRP that incorporated extensive public involvement; supply (resources and facilities) and demand-side (conservation) solutions; community goals; and trade-offs between different and sometimes conflicting objectives. The IRP made recommendations on resource planning, conservation goals, new treatment facilities, and long-term water supply strategies.

The IRP addressed uncertainties pertaining to the availability of water from potential new supply sources, future demand, return flow credits (indirect reuse), and Colorado River Water availability. A decision tree was used to illustrate 12 combinations of potential outcomes that integrated these uncertainties. Probabilities were assigned to each uncertainty to calculate the expected cost and reliability of four possible water resource strategies.

Case Study Findings

The Southern Nevada Water Authority considered uncertainties in its future water demands and supplies, which made the possible strategies more complicated. The Southern Nevada Water Authority's 1995 IRP had to make short-term facility decisions while minimizing future water supply risks based on various uncertainties associated with the utility's mix of potential future water demands and supplies. Thus, possible strategies were represented by decision trees rather than by a specific course of action. These "trees" represented possible outcomes and their likelihood, which were easier to understand by the advisory committee and industry professionals than the general public (primarily because of the lack of familiarity with probabilistic methods). Additional information on the Southern Nevada Water Authority's 1995 IRP is available in the "Water Resources Planning Manual of Water Supply Practices M50" (American Water Works Association, 2001).

Southern Nevada Water Authority's IRP process resulted in the utility adopting 19 recommendations for its short- and long-term course in water resources, facilities, conservation, finances, and planning (SNWA, 1996).

In 2004 and 2005, Southern Nevada Water Authority conducted a second integrated water planning process to re-evaluate its course. This recent effort relied more on scenario-based planning than a decision-tree based approach, in part because of the challenges associated with assigning probabilities to outcomes. The scenario-based approach provided value in assessing possible outcomes and the efforts necessary to adapt to a range of potential outcomes. This more recent planning effort resulted in a series of 22 recommendations, providing a foundation for the Southern Nevada Water Authority to reliably meet the community's water needs into the 21st century (SNWA, 2009).

Southern Nevada Water Authority planners would consider applying both decision-tree analysis and scenario planning in their future planning efforts. Information available to support the chosen approach is, from the utility's experience, the key to using these methods (e.g. level of details on probabilities and/or qualitative information).

Tampa Bay Water, Tampa, Florida

Identified through literature review, Tampa Bay Water was another utility that has used classic decision analysis to evaluate water resource planning alternatives. Tampa Bay's study is described in a 2006 Water Research Foundation report. A multi-attribute utility theory was developed to examine trade-offs between various short and long-term water supply source options. Inputs to the DSPM included demand forecasts, water system data, water quality data, and potential supply scenarios. Tampa Bay found that outputs from the DSPM were easily extractable into an Excel spreadsheet for further analysis. The utility also found the DSPM was well-structured and highly flexible over a range of water supply scenarios, which captured the dynamic nature of the water system. Tampa Bay found a key challenge to building the model for this DSPM was the need to simplify the assumptions and objectives. Tampa Bay Water also found that the time and effort to construct the DSPM were intensive.

3.2. Traditional Scenario Planning

Denver Water, Denver, Colorado

Denver Water chose to use traditional scenario planning in its Integrated Resource Plan 2010 (IRP) to address the inherent uncertainties in long-range water planning. Traditional scenario planning was used to identify and rank the critical uncertainties that surrounded the central decisions and issues for Denver Water. In addition to planning for future uncertainties, Denver Water selected scenario planning because it facilitated out-of-the-box thinking by combining variables in diverse ways that produce a spectrum of impacts.

To develop the scenarios, Denver Water constructed several logical and plausible future conditions, or Planning Futures. These Planning Futures all were considered equally likely. Once the Planning Futures were developed, a strategy was mapped to address the diverse characteristics associated with each future. Considering multiple Planning Futures is a break from past practices that planned for one future based on a traditional supply and demand model.

Climate change was integrated into one of the Planning Futures. The scenario assumed a temperature increase based on an analysis of Denver Water's raw water collection system area using 112 statistically downscaled global climate model projections available at a public access website[1]. The elements of the scenario, dubbed "Hot Water," are included in Table 3.1 below. Each element represents a condition in which planners must respond.

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[1] "Statistically Downscaled WCRP CMIP2 Climate Projections," available at http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/.

Table 3.1 Key Elements of the Denver Water Scenario Planning Climate Change Scenario

Hot Water Planning Futures	
Key Assumptions:	Average annual temperature increase 5° F by 2050. Frequency and severity of droughts increases.
Supply	Average annual streamflow declines. Evapotranspiration increases. Potential loss from a Colorado River Compact call.
Reuse	High demand for reuse.
Demand	Movement away from bluegrass.
Water Quality	Decreases due to sedimentation from forest fires, more intense rainfall, increased turbidity, and concentration of contaminants.
Regional Role	No binding change. Pressure increases to help others and provide leadership.
Economic Impacts	Growth slows in region.
Regulatory	Increasing complexity. Relaxed in response to increasing scarcity.
Social Tenor	Paradigm shift in water use. More customer activism.
Supply Competition	Dramatic increase.
Cost of Energy	Dramatic increase.

Case Study Findings

While the study is ongoing, Denver Water has found the DSPM thus far to be very transparent and easy to understand. Denver Water planners believe this type of planning is ideal for incorporating the various viewpoints and expertise of staff from all sectors. Scenario planning is not computationally intensive; however, Denver Water is engaging external consulting help to guide the process.

Denver Water found that considerable staff time was required to adapt the business approach of scenario planning to work for water utility planning. This included shifting from a traditional planning methodology language to a scenario-planning language. This has lengthened the process, but it has led to more robust planning futures. Denver Water found that developing scenarios to test a single driving force without overlapping between the scenarios or creating contradictions requires careful thought. Denver Water also noted that it could be difficult to represent a number of key uncertainties in only five scenarios. Keeping the number of scenarios to a manageable level is very important in using this DSPM. Denver Water is likely to use scenario planning again.

Tucson Water, Tucson, Arizona

Tucson Water used scenario planning as a structured technique for exploring the implications of potential futures (Means et al, 2005). Identifying key uncertainties was the basis for developing each scenario that was evaluated. Information on local climate effects can be useful in making scenarios more realistic. Other data, such as hydrology and water quality, also can be integrated into the scenarios. Defining these scenarios helped to define common strategies that eliminated uncertainties and informed planning. The utility found that developing scenarios was time intensive because of the degree of detail involved. Both the DSPM and results were found to be very transparent and easy to understand. Results also were easy to communicate to stakeholders, although more so if stakeholders were present when planners developed scenarios. Outside expertise and training was found to be desirable for this DSPM but not required because scenario planning does not necessarily have intensive computing needs. The DSPM was found to be very flexible and outputs were easily transported into spreadsheets for graphical representation.

Phoenix Water Services Department, Phoenix, Arizona

The Phoenix Water Services Department used scenario planning in their 2005 Water Resources Plan Update. The plan, which is updated every five years, looks at a variety of factors that may affect water demand projections and water supply conditions. Three key factors were identified based on their potential significance for water resource planning: delivery of surface water supplies, growth and development patterns, and water conservation levels. Phoenix then identified the variables that influence these three factors and put those variables in defined ranges of future possible conditions. These factors were combined to generate 144 scenarios of water supply and demand. Of these 144 scenarios, there were 9 that explicitly varied the climate. Phoenix identified two types of adaptation strategies to implement in its 2005 Water Resource Plan: robust short-term strategies and a worst case infrastructure time line for drought response. Robust strategies that work well across a wide range of scenarios were identified for implementation. The basis for Phoenix' worst case time frame was to assume that current precipitation trends in the watersheds reflect what could be the early stages of the most severe water shortage scenario, a 30-year dry period. A time line of critical trigger points for deployment of new infrastructure and water resources were identified based on different growth or user demand scenarios.

Palm Beach County Water Utilities Department, Palm Beach, Florida

Through a Water Research Foundation study (O'Neil, 2008), Palm Beach County Water Utilities Department developed a dynamic decision support system (D2S2) that incorporates future uncertainty related to water supply management in the context of climate change. The D2S2 is a hybrid DSPM that uses Water Evaluation and Planning model, a combination of dynamic simulation/scenario testing, and decision analysis. The decision analysis was further used to incorporate triple bottom line criteria. The D2S2 approach is composed of iterative and adaptive steps that address uncertainty through scenario analysis. D2S2 outputs are GIS-based and have dynamic links to spreadsheets and other models. Further results from this study will be available in 2010.

Monocacy River Watershed, Maryland

The Monocacy River Watershed, Maryland, used scenario planning to support decision-making (Johnson and Weaver, 2009). This assessment was conducted as a screening level analysis to determine the potential water quality impacts from climate change. The utility chose scenario analysis because it had computing limitations. Within this framework, uncertainties were evaluated using sensitivity and scenario analysis. Results were used to guide decision-making using a risk management process. Scenarios included potential changes in temperature and precipitation data through the use of contour plots generated by Environmental Protection Agency's BASINS Climate Assessment Tool. Contour plots were interpolated using either synthetic (climatic attributes changed arbitrarily) or model-based climate change (using simulations from seven global climate models and two emissions storylines from 2010-2039) scenarios. The findings of the study revealed that climate change could be approached from a risk-management perspective rather than from an attempt to predict consequences. This study also identified a need for close collaboration and communication with stakeholders to have a successful scenario planning process.

3.3. Robust Decision Making

The Metropolitan Water District Case Study, Los Angeles, California

The Metropolitan Water District of Southern California is using robust decision making as part of the technical phase of its Integrated Water Resource Plan Update process. Metropolitan Water District currently is in the process of applying this DSPM by incorporating the following basic steps (MWD, 2009):

1. Configure water resource simulation modeling suite, called IRPsim, to incorporate various areas of uncertainty and risk.
2. Evaluate Metropolitan Water District's current water resource plan against a large ensemble of uncertainty-based scenarios.
3. Identify and characterize key vulnerabilities to the current water resource plan.
4. Develop more robust strategies based on the key vulnerabilities.
5. Evaluate new strategies against a large ensemble of uncertainty-based scenarios.
6. Present key performance tradeoffs (versus uncertainty and multiple metrics).

The uncertainties integrated into this analysis include future hydrologic conditions from multiple downscaled Global Circulation Model output, demographic and economic growth patterns, energy and strategy implementation costs, new regulation and restrictions on supplies, and customer response to various agency programs in conservation and local resource development. The analysis also will combine the use of Multiple-Criteria Decision Analysis to evaluate the performance of a wide range of regional strategies informed by robust decision making.

Case Study Findings

Metropolitan Water District anticipates that robust decision making will effectively reflect and communicate uncertainty about future climate and other management conditions to its member agencies through the IRP process. Metropolitan Water District selected RDM in part because it incorporates a wide range of possible climate change scenarios and does not require them to be weighted probabilistically. The method also is very flexible to adjustments in inputs, assumptions, and considered outputs. Although complex, the information generated by robust decision making is anticipated to be relatively straightforward to communicate. Metropolitan Water District expects to employ user-friendly data visualization software to better enable the quantitative robust decision making results to be shared with its member agencies and stakeholders. A high level of outside expertise is required to perform robust decision making analyses, along with knowledge of the system, scenarios, and uncertainty. Computing and physical modeling requirements also are high for this DSPM, particularly if no comprehensive system models exist. Metropolitan Water District was able to incorporate robust decision making fairly easily because its planning and modeling protocols were adaptable to the robust decision making framework. The Computing, resource, and technical support required can make robust decision making relatively expensive to use.

Denver Water, Denver, Colorado

Denver Water currently is working on a robust decision making pilot project to see if the method will provide additional information that cannot be gained using traditional scenario planning. Interest by Denver Water in this DSPM comes from its potential to build on the existing water plan, test for strategy failures, and identify how water plans can be improved. Robust decision making specifically tests the technical capability and value of running dozens of scenarios using Denver Water's water system planning tools.

The main focus of the pilot project will be to evaluate uncertainty about future climatic conditions and future treated water demand within Denver Water's service area. The full robust decision making methodology is not being completed in this pilot because the main objective is to determine how robust decision making might improve the traditional scenario planning approach Denver Water is pursuing in current IRP efforts.

Denver Water is following a framework that identifies uncertainties, models, strategies, and reliability targets that will be used in their assessment. The robust decision making pilot consists of the following components: climate change parameters (temperature and precipitation projections) and impacts are the uncertainties; modeling water system over time using PACSM (raw water system model) and a demand model; strategies and near-term actions; and system reliability. A large number of strategy ensembles will be developed based on running the uncertainty scenarios through the models. Strategies to address system failures under different scenarios will be developed, hedged, and measured based on system reliability.

Case Study Findings

Denver Water is not very far into the process, but it has identified general problems in the DSPM implementation. These problems include: understanding the process and altering it to meet Denver Water's needs, understanding and using new terminology, and accepting the 'black box" nature of the scenario generation step. According to Denver Water, this DSPM is a good quantitative approach to scenario planning. It requires heavy modeling and analytical assessments, and reaches a solution after going through multiple iterations. The nature of the methodology entails the necessity of outside expertise.

Inland Empire Utilities Agency, California

The Inland Empire Utilities Agency worked with the RAND Corporation, as a part of a multi-year National Science Foundation study, to examine how three decision-making methods could be used to assist the utility in adapting its 2005 Regional Urban Water Management Plan to better accommodate climate change. The study evaluated traditional scenario planning, probabilistic assessment, and robust decision making (Groves et al. 2008b).

The study team developed a water management simulation model using the Water Evaluation and Planning system to evaluate how various water management programs for the Inland Empire Utilities Agency region would perform under different scenarios of climate and other management conditions. Climate scientists from the National Center for Atmospheric Research developed local sequences of future weather conditions for the Inland Empire Utilities Agency region reflective of the climate changes predicted by the scientific community's global climate models. For the robust decision making analysis, the team first evaluated the performance of the simulation model under 200 different scenarios reflecting different assumptions about the natural, management, and cost uncertainties. Next, the utility performed a statistical analysis to identify the characteristics of the scenarios that lead to high-cost outcomes. Finally, the agency evaluated a large number of alternative plans to identify those with the lowest vulnerability to negative outcomes. They then ranked the various alternatives by decreasing vulnerability (as measured by the number of high-cost outcomes). The best-performing plans were those that are adaptive (i.e. those with updates) and those that include the near-term implementation of more water use efficiency.

The project effort included a series of four workshops that explored each of these methods in turn (two workshops were held to demonstrate robust decision making). Workshop participants reported that the traditional scenario approach was the easiest to understand and to explain to decision makers, although it provided little guidance as to how to respond to climate change. The probabilistic assessment analysis was more difficult to understand. Robust decision making was rated as providing the most valuable information for planning, although workshop participants indicated robust decision making was harder to understand and to explain (Groves et al, 2008b).

3.4. Real Options

Real options and urban water resource planning in Australia

The case study summarized is based on literature review. Real Options was used to address future demand and potential future shortfall in water supply for a hypothetical urban water utility experiencing drought (WSAA, 2008). Optimal investment strategies to develop potential new assets were determined. The study evaluated building a new dam, reusing water, and desalinating saltwater. Desalination costs and catchment inflows were defined as critical uncertainties. Results of the real options analysis revealed that the most flexible strategy provided about \$2.7 billion in value and reduced portfolio risk by \$500 million compared with the best single strategy. Authors of the case study noted that the identification of metrics, options, and uncertainties, as well as the involvement of decision makers at an early stage of the process, are important steps in using the DSPM.

4. Conclusions, Discussion, and Future Research Needs

Conclusions

This document has presented five promising DSPMs that can be used by water utilities to incorporate significant uncertainties in water planning, particularly those surrounding climate change. They include classic decision analysis, traditional scenario planning, robust decision making, real options, and portfolio planning. Classic decision analysis, traditional scenario planning, and robust decision making are most commonly known in the water industry. There are specific examples of their use and incorporation of climate change information to inform water supply planning. The other two DSPMs show promise, though they are relatively unfamiliar to water planners and have an incomplete track record of application.

The presented DSPMs manage uncertainty in two basic ways. Classic decision analysis, real options, and portfolio planning use probabilities to handle uncertainty. Scenario planning uses equally likely scenarios to manage uncertainty. Robust decision making uses both scenarios and probabilities. Probabilities allow utilities to assess distributions of possible outcomes and add a quantitative element that may be more attractive to some utilities, yet increase the computational requirements. Water utilities must carefully consider their willingness, and ability, to assign probabilities to climate model projections.

Discussion: Selecting a Method

Choosing a suitable DSPM to incorporate climate change uncertainties into water planning can be challenging for utilities. Utilities manage different water systems under different geographic circumstances, climate patterns, and organizational, political and regional contexts. A utility's decision to use a particular DSPM in its planning should be based on the utility's unique needs and capabilities. There is no one-size-fits-all DSPM when it comes to climate change; utilities are encouraged to select a DSPM, or a combination of DSPMs, that will help them best achieve their objectives and recognizes their level of expertise and need for external assistance. There are several questions a utility should consider as they explore their DSPM options.

- How do you want to deal with probability?
- How much time do you want (or have) to invest in assessing uncertainty?
- How important are quantitative results to your audience and "selling" the outcome?
- What internal modeling skills do you have?
- How much money do you want to invest?
- What is your willingness to hire external help?
- To what level do you want (or have) to include stakeholders in the analysis and how technically sophisticated are the stakeholders?
- How will you use the results?

Answering these questions and considering the following comments will help the utility select the appropriate DSPM.

Classic decision analysis, robust decision making, real options and portfolio planning are more computationally intensive than the traditional scenario planning approach. Traditional scenario planning can be an excellent method for addressing climate change uncertainties that surround water supply planning. Scenario planning is transparent, relatively easy to communicate, and does not require significant technical expertise (although experienced and informed participants are essential to its outcome). Utilities can combine scenario planning with other tools and strategies, such as the Water Evaluation and Planning model (WEAP) or No or Low Regrets analysis to identify sensible adaptation strategies that can offer multiple benefits to the utility (see **Appendix A** for more details on WEAP and No or Low Regrets analysis).

Classic decision analysis can augment scenario planning. Classic decision analysis allows the utility to rank environmental, social, and other issues of concern without assigning monetary values (unless desired). Adding classic decision analysis to traditional scenario planning can yield a more comprehensive analysis of the uncertainties surrounding climate change. Including stakeholders in classic decision analysis can improve understanding and support for actions suggested by the analysis.

More advanced methods, such as robust decision making, real options, and portfolio planning, can be valuable in identifying the key uncertainties and strategies a utility may consider from a much wider range of possibilities. Robust decision making also can provide quantitative analysis when scientists or decision makers lack confidence in the probability distributions provided or when there are disagreements among stakeholders about the relative importance and/or likelihood of the uncertainties facing the utility. These increasingly quantitative DSPMs are more time, cost, and computationally intensive, and typically require specific expertise in their application. Also, no applications of the real options or portfolio planning within water planning were identified in our research.

Future Research Needs

The following research needs were identified:

- Identifying, understanding, analyzing, and modifying these DSPMs for water utilities has now started and should continue. Developing in-depth guides and cases studies on these DSPMs would help expand effectiveness and awareness of the methods and their applications.
- Improving science to effectively address uncertainties related to data collection, modeling capabilities and statistical methods.
- Improving communication of methods and uncertainties to stakeholders and developing guidance to do so. This includes research institution communication with water utilities about uncertainties in the global climate models and emission scenarios.

- Developing "hybrid" methods that combine conditional probabilities with scenarios relevant to climate decision-making appears promising and should be explored. Some of the DSPMs evaluated in this report only apply to certain aspects of water utility planning and decision-making. New frameworks to analyze uncertainties should be supported.
- Including more climate uncertainty into the real options and portfolio planning DSPMs.
- Developing real options and portfolio planning for water resource planning and applying real options and portfolio planning to an actual water supply could add value to this endeavor.
- Sponsoring a session at a major conference to present case studies of the applications to the utility community would be highly valuable.

The development and application of decision support methods in water utility planning is a growing science. As these methods become more commonly used by utilities for climate change planning, lessons will be learned about effectiveness, efficiency, informational needs, probabilities, and communications with stakeholders. It is imperative that as understanding and proficiency increases, the lessons learned are communicated among users. Climate change will affect all water utilities in one way or another. Developing these and other planning methods will be crucial to prepare the industry for impeding change and the unknown.

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Glossary

Asset – Item with an economical value owned by a company or individual.

Climate – The statistics of weather elements, such as temperature, humidity, atmospheric pressure, wind, rainfall, atmospheric particle count and numerous others, in a given region over long periods of time.

Climate change – Any trend or persistent change in the statistical distribution of climate variables over a significant period of time (the World Meteorological Organization uses 30-year periods).

Climate feedback – An indirect change to the climate system in response to climate forcing(s).

Climate forcing – A natural or manmade mechanism, such as variations in oceans circulation, fluctuations of the earth's orbit, composition of the atmosphere (e.g., greenhouse gases concentrations) that alters the earth's global energy balance and make the climate to change.

Climate stationarity – Terminology used to describe the idea that climate statistics based on the recorded past will not change and variability will not increase in the future, that is, the past climate statistics will not change over time.

Climate variability – This denotes deviations of climate statistics from long-term climate statistics (also called anomalies) over a given period of time. More simply, climate variability is the range of climate conditions over time. A well-known process that causes climate variability is the El Niño-Southern Oscillation (ENSO), an interaction between the ocean and the atmosphere over the tropical Pacific Ocean that has important consequences for weather.

Covariance – Measure of the strength of the correlation of two random variables.

Critical uncertainty – An uncertainty that is important to the focal planning issue.

Decision alternative – A course of action or a strategy that can be chosen by a decision maker when compared against decision objectives.

Decision objective (or criteria) – Basis or standard used for comparing, ranking, and eventually making a decision.

Decision Support Planning Method (DSPM) – A set of procedures used to aid organizations, groups, and individuals in the multiple-outcome planning process. DSPMs are intended to systematically assist decision makers in compiling raw data, documents, and expert knowledge relevant to a specific problem to support decision-making and help generate results.

Decision tree – Visual and analytical decision support tool that graphically shows decisions and their potential outcomes.

Divergent – Drawing apart from a common point or tending to move in different directions.

Downscaling – Approach used to translate general circulation model data to a smaller scale, such as a region or watershed. Taking low-resolution information and turning into high-resolution information. (A cautionary note: downscaling does not imply better or higher quality information.)

Driving force (or driver) – Part the traditional scenario planning process, a conceptual force identified by decision makers and planners to describe trends that leads to an uncertainty unfolding in the future. Driving forces are key to the development of future scenarios.

Expected return – The average of the probability distribution of possible returns. Return is the estimation of the value of an investment.

Expected risk – The idea that the value of an actual return will be different than expected.

Expected value or expected cost – The probability-weighted sum of possible values. This is generally not the same as the most probable value. (For example, if there is an 80% likelihood that a $100 million dam is built and a 20% likelihood of implementing a $15 million conservation program, then the expected cost is 0.8*100+0.2*15 = $83 million.)

Forecast – Calculation or estimation of future events or conditions (e.g., weather, water use, etc.) by analysis of data, usually less precise than a prediction.

General Circulation Model (GCM) – Computerized models depicting the Earth’s atmosphere, oceans, land surface, sea ice through mathematical equations. Also known as global climate models, the models divide the world into grid cells and solve the governing physics at the boundaries of each cell. Currently the grids are too large to resolve processes at a local level such as thunderstorms, but GCMs generally represent large-scale processes with some skill.

Hedging/Hedge – Hedging is the strategy of making an investment to reduce the risk of a loss if adverse conditions develop in the future. In finance, a hedge is a position established in one market in an attempt to offset exposure to the price risk of an equal or opposite position in another market, used to increase economical security or contract that can be assigned a value and traded. An example of hedging in water resources planning is the development of new water supplies while also implementing demand management programs to deal with risks surrounding future supply availability and growth in demands.

Influence diagram (also known as decision network) – Visual representation of a decision situation that shows interactions or relationships between different decision components and outcomes. Usually a simpler representation of a decision compared to a decision tree.

Planning Tools – Analytical constructs that allow data analyses and provide information but do not provide procedures or framework to help make decisions. Planning tool differs from Decision Support Planning Methods (DSPM), but can aid in the DSPM process.

Portfolio – Collection of assets and strategies.

Prediction – Statement or claim that a particular event will occur in the future in more certain terms than a forecast.

Probabilities – Expression of the likelihood of an event occurring. Probabilities can be used as part of a probabilistic framework (i.e., a conceptual structure describing a complex process that can include a set of assumptions, concepts, values, and practices that represents reality).

Projection – A prediction made by extrapolating from past observations.

Resource – Consists of a person, asset, or material that can be used to produce wealth, results, or to accomplish a goal.

Risk (or volatility of return) – Variance of each portfolio element's return over time. Usually calculated by multiplying the probability by the consequence.

Robustness – Management decision strategy made against multiple future scenarios and critical uncertainties in order to enhance the flexibility and likelihood of a successful outcome.

Scenario – A synthetic description of a plausible series of events, combinations and permutations of fact, and related social changes.

Scenario tree – Decision tree featuring scenarios as decision outcomes.

Security – Instrument representing ownership or right or ownership. Examples in the water planning context are a water supply source, demand management program, water contract, or emergency supply.

Stochastic process (also called random process) – Non-deterministic probability process consisting of a family of random variables indexed against some variables or set of variables.

Strategy – Plan of actions associated with a particular set of decision outcomes designed to achieve set decision objective(s).

Traditional Water Planning – A planning technique that relies on historical weather and hydrology records to plan for future supply and demand for a given time horizon. It usually assumes climate stationarity (i.e., climate statistics and variability of the past will continue on into the future).

Triple Bottom Line – Economic, environmental, and societal system of values and criteria used to measure organization success. Also refers to expanding the traditional reporting framework to take into account ecological and social performance in addition to financial performance.

Uncertainty – This term is used in subtly different contexts in different fields. Uncertainty can be the lack of knowledge about an outcome or event (unknown), the predictability of future outcomes, or a physical measurement. The main focus of this document is to evaluate the ability of various DSPMs to handle climate change uncertainty. This use incorporates all three definitions of uncertainty, handling the unknown, GCM predictability, and physical uncertainty of observed information.

Variance – Measure of the statistical dispersion of a variable.

Vulnerability – In the context of water planning and dealing with climate change, refers to the degree to which a system is susceptible to an adverse effect.

Weather – The statistics of meteorological elements, such as temperature, humidity, atmospheric pressure, wind, rainfall, and numerous other factors, in a given (local) region over periods up to two weeks. (Weather happens in your backyard, climate happens over your region.)

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Appendix A. Strategies and Tools

This section describes No and Low Regrets strategy and the Water and Evaluation Planning (WEAP) tool. They are not decision support planning methods but help support planning and decision-making.

No and Low Regrets Strategies

No and Low Regrets strategies can be used to help support decision-making in DSPMs. By identifying common themes and elements through scenarios identified, No Regrets options may be selected, which are robust across multiple possible outcomes. No Regrets strategies are advantageous in that proactive adaptation planning and investment also can help reduce the impacts of climate events while at the same time meeting other important objectives for water utilities.

No Regrets strategies yield more immediate economic, environmental, and/or social benefits and are beneficial irrespective of future climate conditions. Adaptation strategies, such as No Regrets, will generate multiple benefits that outweigh costs, whether or not the pattern of climate change impacts unfolds as predicted.

Low Regrets is another strategy that can be used in tandem with a scenario planning approach. This strategy identifies options where cost implications are modest while the benefits under future climate change are potentially large, albeit uncertain (ODPM, 2004).

Ideally, planning for adaptation to the impacts of climate change would be based upon the best available climate models and scenarios of likely impacts. However, the early impacts are taking place now and often much faster than expected. Given the long lifetime associated with water infrastructure, it is becoming essential to consider climate change in design and operations (Kiparsky & Gleick, 2003). Information from global climate models can be used as extra information to guide the choice of the best No or Low Regrets options based on associated risk (Stainforth et al., 2007a and 2007b). While continual improvements to the accuracy of climate models are being made, it is increasingly important to begin the process of climate change adaptation by investing early in No and Low Regrets projects such as:

- Increase efficiency of water, energy, and material use.
- Implement conservation and demand management programs.
- Limit footprint of development to preserve and protect habitat areas.
- Consider and minimize the carbon footprint of projects and operations.
- Develop emergency preparedness plans, such as for floods or droughts, to reduce damage.
- Treat water to be “fit for purpose” (e.g., non-potable supplies, reuse, recycled water projects, and programs) to stretch potable supplies.
- Diversify water resource portfolio to be more robust and resilient to weather variability.

- Implement water operational and maintenance projects that improve efficiency or flexibility of supplies.

No and Low Regrets strategies typically have the benefits of increasing resilience and reducing vulnerability to weather events, regardless of climate change uncertainty. Further, these strategies provide additional protection for public well-being by encouraging development of sound strategies that will serve us well in drought, flood, fire, tidal wave, and various temperature conditions. By adopting a “wait and see attitude,” more expensive solutions are likely to be required or the impacts more damaging in the future.

The downside to these strategies is that they require consensus on priority measures, as well as plans and partnerships for their implementation. There also is a potential risk for entities that have taken early action on adaptation because ”grabbing the low hanging fruit” may not benefit from allocation of global climate change adaptation funds, if and when these become available. Further, the challenge in using these strategies is to understand the likelihood and uncertainty associated with performing these actions (Kiparsky & Gleick, 2003). There is a risk that some No and Low Regrets strategies may mitigate adverse climate effects while others may work to worsen them (Gleick, 1997).

Water Evaluation and Planning

The Water Evaluation and Planning (WEAP) tool was developed by the Stockholm Environmental Institute. WEAP is a useful tool that can support a portion or all of the modeling requirements of required by the DSPMs. WEAP is an integrated decision support system that aids water planning by balancing water supply, water demand, and environmental requirements and accounts for multiple and competing uses of water systems.

WEAP has a transparent structure that engages diverse stakeholders in an open process. The WEAP database maintains water demand and supply information to drive a mass balance model and calculate water demand, supply, runoff, infiltration, crop requirements, flows, storage, pollution generation, treatment, discharge, and in-stream water quality under varying hydrologic and policy scenarios. WEAP can be linked to outside spreadsheets and models such as Computer Assisted Reasoning Systems (CARs) that can perform large ensembles of simulations to represent uncertainty and potential adaptation strategies (Groves et al., 2008b).

WEAP can perform simulations with user-defined variables and equations. The tool is designed to handle multiple what-if scenarios, which can help to address uncertainty. Through these capabilities, WEAP can evaluate a full range of water development and management options and account for competing uses of water systems.

The WEAP method was used by the Portland Water Bureau (a 2006 Water Research Foundation study) to evaluate decision-support systems for sustainable water supply planning. WEAP was used to help evaluate long-range water management options in the Portland area. WEAP was compared to an existing Stella Storage and Transmission Model to determine what benefits it could offer the utilities operational strategies. For example, WEAP can be used to anticipate potential changes in future water supply planning, such as levels of water transfers, how fish flows might constrain operations, and how the system performs under a range of demand and growth (WRF, 2006).

A different example of a WEAP application is for a climate vulnerability assessment across the northern headwaters in Colorado. The model will be used to evaluate changes in undepleted flows at 18 gage locations in the upper portion of the Colorado, South Platte, and Arkansas rivers. The changes are based on analysis of 112 statistically downscaled global climate model projections across the region of interest. Though this project ends with altered undepleted flows, participants may pursue the development of the model to include their water rights and system for use in planning. The anticipated release of this study, titled, "The Joint Front Range Climate Change Vulnerability Study," is Spring 2010 through the Water Research Foundation (Kaatz, 2009).

WEAP places equal importance on supply and demand, which allows planners to evaluate alternate water development and management strategies. This tool can help to address a wide range of issues (water conservation, water rights and allocation priorities, and hydropower), which feed into a scenario planning analysis. This tool also can be adapted to local conditions with user-defined variables for storm water, reuse, demand management, and wastewater.

The limitations to WEAP are that each analysis is conducted in a single area (watershed or small geographic region). Thus climate change projection data must be available at this scale, requiring downscaling of global climate models and introducing uncertainty. WEAP relies on established scenarios with assumptions about future conditions; hence the accuracy of these scenarios is of extreme importance in using this tool. Water balance data also must be available to explore potential future outcomes. Uncertainty from these data will impact the accuracy of the scenario analysis and ultimately decision-making.

Appendix B. Evaluation Approach and Results

Appendix B presents the evaluation of each Decision Support Planning Method's (DSPM) ability to incorporate climate change uncertainties into water planning. Also described are the DSPM literature review, the case study questionnaire, and the approach that was applied to evaluate the DSPMs.

Literature Review

Most of the research performed regarding the impacts of climate change on water utilities has focused on water supply vulnerabilities because of changes in precipitation, snowmelt, streamflow, and recharge. The current body of research is very limited in terms of studying the effects of climate change on water system planning and design, and further, the leading practices that utilities can apply to adapt to or address the risks associated with climate change.

The literature review for this white paper relied on existing and ongoing research to assess the benefits and limitations of the various decision-making and long-term planning methods used to address the range of potential impacts due to climate change. The review focused on existing relevant literature and studies on leading DSPMs used for water planning in the context of climate change (or other uncertainty planning practices if no application to climate change or water utility planning was found). The objectives of the literature review were to derive the information needed to identify and determine the value, limitations, and data gaps for the DSPMs most suitable for addressing the range of future planning possibilities for water utilities in response to a changing climate. The DSPMs reviewed included:

- Classic decision analysis;
- Traditional scenario planning;
- Robust decision making;
- Real options; and
- Portfolio planning.

Information from numerous major research organizations was included in this review, including relevant articles, publications, and studies. The literature was taken from a variety of reputable sources, including:

- Governmental organizations (California Energy Commission, U.S. Climate Change Science Program)
- International organizations (International Panel on Climate Change)
- Research organizations (Climate Assessment for the Southwest (CLIMAS) at University of Arizona, Climate Impacts Group at the University of Washington, Pacific Institute, Scripps Institute of Oceanography, National Center for Atmospheric Research, Water Research Foundation, American Water Resources Association, RAND Corporation)

- Peer-reviewed and non-peer-reviewed journals (*Southwest Climate Outlook, Southwest Hydrology, Nature, Journal of Hydrology, Climate Change, Hydrological Processes,* and *Environmental Management,* among others)
- Proceedings of the National Academy of Sciences
- International organizations from Australia and Europe.

More than 95 articles and studies were reviewed. Findings of the literature review are presented below.

Water Utility Climate Alliance (WUCA) and other Case Studies

A questionnaire was given to WUCA members to document the use of DSPMs by water utilities. The questionnaire requested details on the DSPMs they have utilized and more specific information on the DSPMs resource, input, and output requirements. The objective of the survey was to obtain information on issues associated with using a specific DSPM and to gain further insights on applying the DSPM. The four of WUCA members who have used a DSPM responded to the questionnaire. Respondents provided information on classic decision analysis, traditional scenario planning, robust decision-making, or a combination thereof. In addition, six other utilities that have used DSPMs were identified in the literature review. The information from WUCA members and from the findings of the literature review for the other utilities is summarized in **Section 3**.

DSPM Evaluation Approach

A process was designed to evaluate the DSPMs for their strengths and weaknesses, to provide fundamental guidance to utilities, and to assist utilities in choosing which DSPM is the best fit for different situations (specific drivers, concerns, decisions) and utility capabilities. WUCA members developed the evaluation process, which is outlined below.

Twenty-one DSPM evaluation criteria were developed and grouped into four categories:

- general characteristics,
- resource requirements,
- input data and models, and
- output and results.

These evaluation criteria are defined below.

General Characteristics

1. Reasons for using DSPM - Suitability of DSPM: This criterion is a general description of the rationale behind the use of the DSPM and how suitable it is for specific utility planning objectives.

2. Application to water utility climate change planning: This criterion determines whether the DSPM has been used for climate change analysis specific to water resources and/or water utility planning.
3. Planning Horizon: This criterion determines for which type of planning horizon (short-term or long-term) this DSPM is most suited.
4. Ease in output use: This criterion defines the ability for a utility to make decisions based on results/outputs obtained using the DSPM.
5. Transparency of DSPM: This criterion defines the understandability of the DSPM's inner workings; to be able to modify the model. It also defines whether the DSPM is open source or proprietary.
6. Involvement of decision makers in DSPM implementation: This criterion defines the need for input from decision makers/high level management for DSPM implementation and subsequent decision making.
7. Communicability: This criterion defines the ease in communicating the process and results of the DSPM to stakeholders (public and key decision makers), and the difficulty or ease in understanding and explaining the DSPM process, results, and analysis implications.
8. Cost analysis approach: This criterion determines whether the use of cost analysis is included in the DSPM or is required to support DSPM decision making.
9. Need for probability information: This criterion defines the need for probability distribution data for climate, water system, and water quality to implement the DSPM.
10. Uncertainty Management: This criterion determines how the DSPM treats and handles uncertainty.

Resource Requirements

1. Level of expertise required: This criterion defines the need for expert(s)/expertise to develop and implement the DSPM and/or perform modifications at a later stage. This criterion also addresses the need for external expert(s)/expertise.
2. Intensiveness: This criterion defines the level of effort, modeling resource time and staff training/learning curve needed to develop and implement the DSPM.
3. Computing requirements (hardware and software): This criterion considers the computational power needed to develop inputs, run the DSPM and produce outputs. This criterion depends on complexity, types, and number of models and/or simulations to run; complexity of mathematical expressions or probabilities; linearity or non-linearity capabilities; time to run simulations; using stochastic generation of data or historical data; granularity. This criterion also considers the type of equipment and materials needed to develop and implement the DSPM (e.g., software), availability of tools or software applications to implement method, and the DSPM ownership and specificity of DSPM for a type of analysis (open source or proprietary).

Input Data and Models

1. Climate data needs: This criterion considers the type of data needed to run the DSPM (nature, assumptions, and amount including relevance; availability; nature; collection; preparation/processing; uncertainty). It also considers the source and type of information/data needed for climate modeling (e.g., IPCC scenarios vs. local climate data, projections).
2. Water system data needs and water quality information: This criterion considers the type of data needed to run the DSPM (nature, assumptions, and amount of input hydrologic/watershed data and water quality input data, including relevance, availability, nature, collection, preparation/processing, and uncertainty). It also considers the source and type of information/data related to the utility (e.g., hydrologic records and projections, other watershed data, demand data).
3. Data Complexity and Model Scale: This criterion defines the ability of the DSPM to work with existing hydrologic/water system data, the need to process and simplify data prior to use, the flexibility of the DSPM to revise and adjust inputs and assumptions, the intricacy and interdependence of data, and the relation to uncertainty of the DSPM. This criterion also evaluates the data needs and degree of uncertainties acceptable when using the DSPM.
4. Time to calibrate model: This criterion considers the amount of time and effort required to calibrate the model(s).
5. Ease of running models (model incorporation): This criterion evaluates how several models (or modules) of the DSPM are integrated with each other and with existing utility planning models (hydrologic, forecasting, integrated), assesses model interdependencies and resulting uncertainties from models, and evaluates model granularity.
6. Model validity: This criterion evaluates the closeness of the DSPM to reality, the degree to which inferences drawn from the model hold for the real system, measurements and predictions of input data values, and the relationship to reality of the results.

Outputs and Results

1. Nature of outputs: This criterion defines the nature and robustness of outputs, output interdependencies, granularity, uncertainty, accuracy, sensitivity, and practicality (what-if analysis).
2. Graphical quality: This criterion considers the ability of the DSPM to represent the outputs with a common user interface to visualize and modify input and output data, and the importability of output into software for graphical interpretation.

Each DSPM is then evaluated according to these criteria. Evaluation of each of the 21 criteria consists of either one specific description or one word qualifier, low, medium, or high accompanied with an explanatory description. This evaluation was based on findings from the literature review and other sources of information described above. All the criteria are given equal weight.

The five evaluated DSPMs are compared and contrasted in Table B.1 in terms of general characteristics, resource requirements, inputs and models, and outputs and results. Detail evaluation and supporting information are included further below.

Table B.1 Summary Evaluation Matrix

Criterion	Decision Support Planning Methods				
	Classic Decision Analysis	Scenario Planning	Robust Decision Making	Real Options	Portfolio Planning
General Characteristics					
Reasons for using DSPM / Suitability of DSPM	-Develops and ranks decision alternatives against decision objectives to obtain preferred strategy -Integrates multiple decision objectives -Works well for known probabilities and independent outcomes	-Develops a small but wide-ranging set of future scenarios to test and make planning decisions more robust -Can address a wide range of uncertainty and identify No Regrets solutions and decision points -Agreement between stakeholders is not required on likelihood of future conditions -Uses concepts familiar to stakeholders -Is more suitable for higher-level decision making	-Helps select climate adaptation strategies without agreeing on potential futures -Is used in circumstances of deep uncertainty -Guides decisions from wider range of strategies to ensure strategies selected are more agreeable across viewpoints -Is useful when standard decision making cannot be easily applied	-Helps determine which strategy maximizes the value of a set of strategies while balancing risks -Identifies flexible and unique strategies adjustable over time future scenarios.	-Selects portfolio to minimize risk in order to be financially protected against uncertain future scenarios -Identifies robust set of strategies applicable to probable

Criterion	Decision Support Planning Methods				
	Classic Decision Analysis	**Scenario Planning**	**Robust Decision Making**	**Real Options**	**Portfolio Planning**
Application to water utility climate change planning	Medium Some use for climate change and water utility planning	Medium Some use for climate change impacts on water utilities	Medium Limited number of applications for water utility planning at present	Low Seldom used for water utility planning at present	Low No known applications for water utility planning at present
Planning Horizon	Short-term or long-term horizons	Short-term or long-term horizons	Often intended for long-term horizons	Intended for long-term horizons	Intended for long-term horizons
Ease in output use	High -Chooses preferred decision alternatives by running decision tree analytical component	Medium to Low - Does not often provide enough detail to make decisions -Choice of scenarios and strategies can appear arbitrary	Medium to Low -Can be difficult to make a decision based on information	High -Generates flexible investment results	Medium -Depends on risk tolerance of decision makers
Transparency of DSPM	Medium -Highly recognized but availability of model information varies	Medium to High -Open source, transparent, easily implemented and understood	Medium to Low -Less complex to improve transparency/efficiency -Sophisticated nature and reliance on outside experts creates "black box" issues	Medium - Model information available but potential "black box" issues	High -Modeling information largely available
Involvement of decision makers in DSPM implementation	Medium to Low -Involvement in early stages and in decision making	High -Involvement required of decision makers throughout process	High -Involvement in providing direction and assessing robust strategies/remaining uncertainty/make final strategy decisions	High - Involvement and engagement of decision makers at all times to deal with flexibility and adjustments	Medium to High -Involvement in selecting portfolio and defining assets and long-term risks

Criterion	**Decision Support Planning Methods**				
	Classic Decision Analysis	**Scenario Planning**	**Robust Decision Making**	**Real Options**	**Portfolio Planning**
Communicability	Medium to High -Process and results can be difficult to understand and to communicate -High if good communicator	Medium to High -Opportunities for stakeholder engagement improves understanding and communicability	Low to Medium -It is more difficult to explain than traditional scenario planning and can be perceived as less objective	Low -Process, results, and concept of flexibility are complex to explain	Medium - Process can be easily communicated but assumptions, analysis implications and decisions based on risk tolerance are more challenging to communicate
Cost analysis approach	Costs minimized as output	Cost analysis performed external to the evaluation using utility preferred method	Cost of various strategies and scenario outcomes monetized for comparison	Total value of options maximized	Cost analysis included as maximized total value
Need for probability information	Required -Are used to express uncertainties	Not Required -Can be used to express uncertainties and define the likelihood of outcome	Not Required -Provides a means to incorporate imprecise probabilistic information systematically into the analysis	Required -Are used to express uncertainties for input parameters	Required /Optional -Are used for key inputs but are optional for scenarios if treated equally

Criterion	Decision Support Planning Methods				
	Classic Decision Analysis	**Scenario Planning**	**Robust Decision Making**	**Real Options**	**Portfolio Planning**
Uncertainty Management	-Explicitly handled through probabilities	-Managed through scenarios and the identification of common or No Regrets strategies and future decision points	-Brought to light through iterative process -Provides "probability thresholds" for vulnerable scenarios that decision makers can use to decide whether hedging actions are justified -Embedded in evaluation due to subjectivity in policy/scenario selection	-Handled through the use of probabilities and through flexibility and ability to adjust options with time	- Handled through the use of probabilities -Risk minimized through hedging. Only deals with one aspect of overall planning decision making
Resource Requirements					
Level of expertise required	High -Requires outside expertise to develop and run analysis	Medium to Low -Requires familiarity with process -Often requires external consultant; however, internal staff can be trained	High -Requires outside expertise to develop and run analysis	High -Requires outside expertise to develop and run analysis	High to Medium -May require outside expertise to develop and run analysis
Intensiveness	Medium -Is not developed by internal staff but requires relatively intense training and learning curve for internal staff to run analysis	Medium -May be developed by internal staff, may require training	Medium to High -Is not developed by internal staff but staff engaged to guide the analysis	High -Is intensive to develop and run and is very intensive to train staff	Medium -May be developed and run by internal staff, may be intensive to develop and run, and is relatively intensive to train staff

Criterion	**Decision Support Planning Methods**				
	Classic Decision Analysis	**Scenario Planning**	**Robust Decision Making**	**Real Options**	**Portfolio Planning**
Computing requirements (hardware and software)	Low to High -High-end desktop needed -Computational requirements possibly intense depending on situation -Potentially software and code language are needed	Medium -Does not require extensive computing power -More sophisticated analysis requires substantial computing capabilities	High -RDM may be comprised of hundreds to thousands of cases for exploratory analysis	High -Intense computational requirements, high-end desktop, software, and code language are needed	High -Intense computational requirements, high-end desktop, software, and code language are needed
Inputs and Models					
Climate data needs	-Data obtained from GCM outputs -Downscaled global climate model data can be used for local data -Data can directly or indirectly used as input to the DSPM				
Water system data needs and water quality information	-Data needs depends on DSPM objectives -Water demands, supply/yield, and quality obtained water system model outputs				

Criterion	**Decision Support Planning Methods**				
	Classic Decision Analysis	**Scenario Planning**	**Robust Decision Making**	**Real Options**	**Portfolio Planning**
Data Complexity / Model Scale	-Input data extracted from other models (demand, yield, etc.) -May need manual extraction and data processing -Changes in assumptions, inputs, and objectives would require rerunning suite of simulations	-Input data extracted other model output -May be done manually or require data processing -DSPM can accommodate changes in assumptions, inputs, and objectives depending on structure	-Input data extracted other model output -May be done manually or require data processing -DSPM can accommodate changes in assumptions, inputs, and objectives depending on structure	-Input data extracted from other models (demand, yield, etc.) -May need manual extraction and data processing -Changes in assumptions, inputs, and objectives would require rerunning suite of simulations	-Input data extracted from other models (demand, yield, etc.) -May need manual extraction and data processing -Changes in assumptions, inputs, and objectives would require rerunning suite of simulations
Time to calibrate model	High -Extensive if models cannot reproduce existing conditions	Medium -Moderate amount of time for traditional scenario model -For more sophisticated analysis of scenario planning results, probabilities, risks, and other preferences can be assigned to the results to provide more information to aid in decision making	Medium to High -Dependent on number of scenarios and strategies and type of robustness criteria	High -Extensive if models cannot reproduce existing conditions	High -Extensive if models cannot reproduce existing conditions

Criterion	**Decision Support Planning Methods**				
	Classic Decision Analysis	**Scenario Planning**	**Robust Decision Making**	**Real Options**	**Portfolio Planning**
Ease of running models (model incorporation)	Medium -Typically relies on other output models	Low -Can rely on outputs from other models -If DSPM not integrated with other models, output data manually fed into DSPM	Medium -Can use outputs from other models for water supply, demand, and strategies	Medium -Relies on outputs from other models	Medium -Relies on outputs from other models
Model validity	Dependent on inherent DSPM structure	Dependent on DSPM structure, data inputs, and assumptions	Dependent on DSPM structure, data inputs, and assumptions	Dependent on definition of strategies	Dependent on definition of assets and risks
Outputs and Results					
Nature of outputs	-Range of solutions obtained from decision trees -Increased robustness through iteration process	-Identification of common, near-term (No-Regrets) strategies that work well across the range of scenarios -Identification of key future decision points	-Options for strategies robust over many scenarios -Identify any remaining vulnerabilities of strategies -Identify actions that should be taken now and those that can be deferred until later	-Flexible investment strategies adjustable with time -Investment strategy deferrable into future	-Robust set of assets applicable to probable futures -High robustness of results
Graphical quality	-Results easily presented in graphs to compare costs of strategies -Data generally exportable to Excel spreadsheets for analysis	-Results easily presented in graphs to compare costs of strategies -Data generally exportable to Excel spreadsheets for analysis	-Provides visualizations that consider performance of robust strategies in scenarios and key vulnerabilities -Results easily presented in graphs to compare alternatives using Excel spreadsheets	-Results easily presented in graphs to compare costs of strategies -Data generally exportable to	-Results easily presented in graphs to compare costs of strategies -Data generally exportable to Excel spreadsheets for analysis Excel spreadsheets for analysis

Classic Decision Analysis Evaluation

Decision analysis criteria are defined and evaluated in Table B.2 below. The evaluation is based on findings from the literature review and information from questionnaires of utilities that have used the DSPM (where available).

Table B.2 – Classic Decision Analysis Evaluation

Criterion	Evaluation	Evaluation Description
General Characteristics		
Reasons for using DSPM / Suitability of DSPM	--	Decision analysis allows the development and ranking of alternatives against objectives to obtain a preferred strategy or set of strategies. It allows the inclusion of multiple and varied objectives (technical, environmental, and social). It is a convenient tool to elicit knowledge and preferences. It works well when probabilities are known to develop independent decision outcomes.
Application to water utility climate change planning	Medium	Decision analysis currently is used in some water resources planning. Several applications to water utility climate change planning are available, including water supply and program investment decisions, and other water resources management decisions.
Planning Horizon	Short-term and long-term	Short-term and long-term horizons are applicable; however, the short-term horizon is more appropriate, especially if the DSPM needs to be rerun to make course corrections.
Ease in output use	High	Decision analysis ranks alternatives by running decision tree analytical component to calculate expected value of an alternative. The preferred decision strategy is the alternative with the highest (or lowest) expected value. Classic decision analysis results are easy to use because the result obtained is a preferred strategy or set of strategies.
Transparency of DSPM	Medium	Classic decision analysis is highly recognized, and can be tailored to a utility's specific needs. In some cases, it uses complex analytics that can affect transparency. In addition, the availability of DSPM information varies and impacts the end result. If an external party is involved in developing the DSPM and/or it is proprietary, then it may not be fully transparent, creating "black box" issues and difficulty in fully understanding the model's structure and inner workings. Some proprietary models, though, may be the best alternative, particularly if they have been field tested on similar issues and problems.

Involvement of decision makers in DSPM implementation	Medium to Low	The involvement of decision makers consists of giving input on the development of alternatives, decision tree, and objectives. Decision makers are mostly involved in the beginning stages of analysis to define the decision elements (key decision elements, key information, and decision objectives) and at the end of the process when outputs are presented and choices need to be made.
Communicability	Medium to High	Process and results can be difficult to understand and to communicate to stakeholders. The decision tree process can be obscure and classic decision analysis can use subjective probabilities. If classic decision analysis is proprietary, obtaining access to all parts of the process may be difficult depending on the contractual arrangements. However, communication can be successful if communicator is talented.
Cost analysis approach	--	Decision analysis typically uses a total cost approach where minimized expected cost is an output. This DSPM includes total life cycle direct costs, and it can be challenging to include other additional costs to further evaluate economic and financial data.
Need for probability information	Required	Probabilities are used to express uncertainties and define the likelihood of an outcome. Efforts to generate these probabilities can be intensive. They require either the use of experts, the use of subjective (or Bayesian) methods, or the development of emerging approaches that require further research.
Uncertainty Management	--	Uncertainties are explicitly handled by using discrete or continuous probabilities to define the likelihood of decision outcomes. Other methods of uncertainty management can include Monte Carlo simulations.
Resource Requirements		
Level of expertise required	High	The development of a classic decision analysis model is more efficient if done by a person familiar with it (most likely outside experts or external consultant). Internal staff can be trained to use the DSPM for future runs unless the DSPM is proprietary and the flexibility in model runs is limited. A good communicator and/or decision analyst are needed.
Intensiveness	Medium	Internal staff does often not develop decision analysis models, but internal staff can be trained to use the model for future runs unless it is proprietary. Intense training and learning curves are necessary for internal staff to run the model.

Computing requirements (hardware and software)	Low to High	Decision analysis usually only requires high-end desktop computers, but there is a potential need for specific costly software and code language. In addition, it can have intense computational requirements, and running classic decision analysis can be highly demanding depending on the level of detail desired.
Inputs and Models		
Climate data needs	--	Climate data generally are obtained from GCM outputs. Downscaled GCM data can be used to obtain more local data. Climate data can be used directly as input to classic decision analysis or indirectly through inputs of other models, and those models' outputs are used as inputs to decision analysis.
Water system data needs and water quality information	--	The need for water system data is highly variable as it depends on classic decision analysis objectives. For water planning cases, data related to water demands and supply/yield are needed and can be obtained from outputs from other water system models. Water system data may or may not be needed as input to decision analysis. The need for water quality data also depends on the decision objectives.
Data Complexity / Model Scale	--	Decision analysis input data usually is extracted from outputs from other models (demand, yield, etc.), which may need to be extracted manually and may require data simplification or processing. Usually, classic decision analysis is flexible and can accommodate changes in assumptions, inputs, and objectives. However, this flexibility to adjust and revise inputs and assumptions varies depending on its structure. If initial inputs change or sensitivity analysis of inputs is needed, then rerun of the whole suite of models could be necessary.
Time to calibrate model	High	If models cannot reproduce existing conditions, time to calibrate model can be extensive.
Ease of running models (model incorporation)	Medium	Classic decision analysis typically relies on outputs from other models. If this DSPM is not integrated with other models, output data is manually extracted into spreadsheets and fed into classic decision analysis model.
Model validity	--	Closeness of model to reality is dependent on inherent structure of classic decision analysis model, which is unique to each utility. Uncertainties related to lack of data and DSPM structure could impact model validity.

Outputs and Results		
Nature of outputs	--	A range of solutions can be obtained from the decision tree analytical runs. Sensitivity analysis and the iteration process can improve robustness of outputs and uncertainties.
Graphical quality	--	Results can be easily presented in graphs and charts comparing cost of decision outcomes and evaluating sensitivity of results to factors influencing outcomes and input assumptions. They are generally exportable to spreadsheets but sometimes have to be exported manually.

Traditional Scenario Planning Evaluation

Scenario planning DSPM criteria are defined and evaluated in Table B.3 below. The evaluation is based on findings from the literature review and information from questionnaires of utilities that have used the DSPM (where available).

Table B.3– Traditional Scenario Planning Evaluation

Criterion	Evaluation	Evaluation Description
General Characteristics		
Reasons for using DSPM / Suitability of DSPM	--	Internal and external stakeholders are familiar with this methodology, which enhances the utility's ability to perform the analysis in a timely manner, present results, and arrive at final decisions. This DSPM is more suitable for higher-level decision making rather than highly analytical and formulated processes.
Application to water utility climate change planning	Medium	Scenario planning is a commonly used approach in addressing climate change impacts on water utilities.
Planning Horizon	Short-term and long-term	For climate change evaluations, long-term horizons are more appropriate.
Ease in output use	Medium to Low	By itself, traditional scenario planning often does not provide enough detail to make decisions and the choice of scenarios and strategies can appear arbitrary. Analysis methods that assess the risks associated with the given scenarios are often used to interpret results and arrive at decisions.
Transparency of DSPM	Medium to High	Scenario planning is open source, a transparent process, and can be easily implemented and understood.
Involvement of decision makers in DSPM implementation	High	A significant level of engagement is required of decision makers throughout the scenario planning process from framing the scenarios and strategies to making a final decision.
Communicability	Medium to High	Scenario-based exercises provide opportunities for stakeholder engagement throughout the process, thus improving the understanding and ease of communication associated with the DSPM.
Cost analysis approach	--	Cost analysis can be performed external to the evaluation using a utility preferred method.
Need for probability information	Not Required	Probabilities can be used to express uncertainties and define the likelihood of an outcome. They are not required for

		traditional scenario planning, but can aid decision making.
Uncertainty Management	--	Uncertainties are handled by selecting critical uncertainties, and constructing plausible but contrasting future scenarios to address the wide range of possible futures and uncertainties in the evaluation. Each scenario is framed and described to be unique and clearly understood by all participants.
Resource Requirements		
Level of expertise required	Medium to Low	Scenario planning requires some familiarity to run the process and drive decision making. An external consultant can be used to facilitate discussions and promote stakeholder engagement. Internal staff can be trained to apply the DSPM for future studies.
Intensiveness	Medium	DSPM may be developed by internal staff, but may require training to develop the skills required.
Computing requirements (hardware and software)	Medium	Traditional scenario planning does not require extensive computing power. For more sophisticated analysis of results multiple integer stochastic methods may be required, which would necessitate substantial computing capabilities.
Inputs and Models		
Climate data needs	--	Climate data are generally obtained from GCM outputs. Downscaled GCM data can be used to obtain more local data. Climate data can be used directly as input to the scenarios or indirectly through inputs of other models, and those model's outputs are used as inputs to scenario planning. Climate data can also be part of the scenario description.
Water system data needs and water quality information	--	The need for water system data is highly variable as it depends on DSPM objectives. Data related to water demands, supply/yield, and quality can be obtained from outputs from other water system models and readily applied.
Data Complexity / Model Scale	--	DSPM input data is usually extracted from outputs from other models (demand, yield, etc.), which may need to be extracted manually and may require data simplification or processing. The DSPM is flexible and can accommodate changes in assumptions, inputs, and objectives. However, the flexibility to adjust and revise inputs and assumptions varies depending on its structure. If initial inputs change or sensitivity analysis of inputs is needed, the model scale and complexity would increase.

Time to calibrate model	Medium	Traditional scenario planning does not require a “model.” However, empirical modeling data can be incorporated in scenario planning if desired.
Ease of running models (model incorporation)	Low	DSPM can incorporate outputs from other models as required by the study’s objectives.
Model validity	--	Closeness of model to reality is dependent on inherent structure of DSPM, data inputs, and assumptions unique to each utility. Uncertainties related to lack of data and DSPM structure could impact model validity.
Outputs and Results		
Nature of outputs	--	Success strategies are developed and incorporated in the long-range water resources/capital facilities plan.
Graphical quality	--	Results can be easily presented in tables, graphs and charts comparing success strategies and costs of decision alternatives.

Robust Decision Making Evaluation

RDM criteria are defined and evaluated in Table B.4 below. The evaluation is based on findings from the literature review and information from questionnaires of utilities that have used the DSPM (where available).

Table B.4 – Robust Decision Making Evaluation

Criterion	Evaluation	Evaluation Description
General Characteristics		
Reasons for using DSPM / Suitability of DSPM	--	Robust decision making is most beneficial in that it helps decision makers to select climate adaptation strategies without having to agree on potential futures. It can be used in circumstances of deep uncertainty. Even if robust strategies cannot be identified, robust decision making provides valuable information to guide decision-making. Robust decision making can guide decisions from a wider range of strategies and help to ensure the strategies selected are more agreeable to people who have opposite views on climate change impacts and uncertainty.
Application to water utility climate change planning	Medium	Robust decision making can help water utilities navigate through potential strategies to help select strategies that are robust across uncertain futures. There are a limited number of robust decision making applications for water utilities at present.
Planning horizon	Long-term	Robust decision making typically is intended for long-term horizons.
Ease in output use	Medium to Low	Although decision makers find the amount of information obtained through robust decision making valuable, it can be difficult to understand and explain.
Transparency of DSPM	Medium to Low	Models used for robust decision making can be designed to be less complex to provide more transparency and efficiency and to support the analysis of a wide range of plausible futures. However, the sophisticated nature of robust decision making and reliance on outside experts creates "black box" issues, such as lack of understanding of the DSPM's inner workings.
Involvement of decision makers in DSPM implementation	High	Decision makers stay involved throughout the process. The involvement consists of giving input on strategies and objectives in the beginning stages and then at the end to assess robust strategies and remaining uncertainty to assess

		tradeoffs and make final strategy decisions.
Communicability	Low to Medium	Robust decision making is more difficult to explain than traditional scenario planning, particularly the generation of scenarios and strategies, and can be perceived as being less objective.
Cost analysis approach	--	The cost of various strategies and scenario outcomes can be monetized to aid in comparison.
Need for probability information	Not required	Robust decision making can use probability information, but it is not required. In particular, robust decision making provides a means to use imprecise probabilistic information.
Uncertainty Management	--	Uncertainties and key vulnerabilities are brought to light through the iterative robust decision making process, which identifies the most problematic scenarios and the most robust strategies to address potential impacts.
Resource Requirements		
Level of expertise required	High	Robust decision making requires outside experts familiar with this DSPM to develop and run the analysis.
Intensiveness	Medium to High	Robust decision making is developed and performed by external expert organizations that engage the utility to guide the analysis. Internal staff does not develop this DSPM, though staff may still be involved in the development of scenarios.
Computing requirements (hardware and software)	High	Computing requirements exist to perform exploratory analysis and evaluate combinations of strategy and futures, which may be composed of hundreds to thousands of cases.
Inputs and Models		
Climate data needs	--	Climate data are generally obtained from global climate model outputs. Downscaled global climate model data can be used to obtain more local data. Climate data can be used directly as input to the DSPM or indirectly through inputs of other models which outputs are used as inputs.
Water system data needs and water quality information	--	The type of water system and quality data is highly variable as it depends on DSPM objectives. For water planning cases, data related to water demands, supply/yield, and quality are needed and can be obtained from outputs from other water system models.

Data Complexity / Model Scale	--	DSPM input data is usually from outputs of other models (supply, demand, and yield) and literature sources, which may need to be extracted manually and may require data simplification or processing. If initial inputs, criteria, or assumptions change then additional runs could be necessary.
Time to calibrate model	Medium to High	Dependent on the number of scenarios and strategies considered as well as the robustness standard selected because robust decision making is an iterative process.
Ease of running models (model incorporation)	Medium	DSPM can use outputs from other models for water supply, demand, and strategies.
Model validity	--	Closeness of DSPM to reality is dependent on data inputs, selected criteria, and scenarios selected by each utility. Uncertainties related to subjectivity of strategies, procedures, and scenarios used could impact model validity.
Outputs and Results		
Nature of outputs	--	A range of robust strategies that can be used across key vulnerabilities along with key uncertainties. Visualization is a key component to presenting output results.
Graphical quality	--	Robust decision making provides visualizations that consider the performance of the robust strategies in scenarios representing their key vulnerabilities. This enables decision makers to apply their own assessments of the likelihoods of the different scenarios. Results can be easily presented in graphs and charts, such as histograms and scatter plots, to compare alternatives using Excel spreadsheets.

Real Options Evaluation

Real Options criteria are defined and evaluated in Table B.5 below. The evaluation is based on findings from the literature review.

Table B.5 – Real Options Evaluation

Criterion	Evaluation	Evaluation Description
General Characteristics		
Reasons for using DSPM / Suitability of DSPM	--	Real options helps determine which investment maximizes value of a strategy/option while balancing risks. It is useful in making decisions in highly uncertain situations. It can help identify flexible and unique strategies/options and provide the ability to adjust the projects over time. It allows decision makers to choose the best investment opportunity based on current information including investment deferral.
Application to water utility climate change planning	Low	While real options has great apparent potential for use in water planning and has been widely used in finance, there are no examples we could find of its use in water.
Planning Horizon	Long-term horizon	Real options generates better results for long-term horizons.
Ease in output use	High	This DSPM generates flexible results that can be adjusted over time. It helps determine the best investment opportunity based on current information including deferral of investment.
Transparency of DSPM	Medium	Real options has been used for multiple types of analysis but not in the context of climate change or in the water industry. Some model information but some of the “black box” models can be quite complex.
Involvement of decision makers in DSPM implementation	High	Decision makers need to be involved at all points in the analysis, including definition of key decisions, objectives, strategies/options, and uncertainties. This requires critical thinking and engaged communication through the options analysis stage to evaluate flexible options.
Communicability	Low	The process and results of this DSPM are complex. It is challenging to explain initial assumptions and changes to assumptions with time.
Cost analysis approach	--	This DSPM maximizes total value of the options. Cost data and market price information are required.

Need for probability information	Required	Probabilities are used to estimate input parameters. They are computed for each future.
Uncertainty management	--	Uncertainty is explicitly handled using probabilities to define input parameters. Flexibility and the ability to adjust options with time help better manage uncertainty. Uncertainties are not regarded as negative in this context.
Resource Requirements		
Level of expertise required	High	Data gathering, data modeling, and analysis is very complex. It likely would require outside expertise.
Intensiveness	High	This DSPM is quite intensive to construct and run. It requires experts with specialized skill sets. Staff can be trained, however; the learning curve can be intensive.
Computing requirements (hardware and software)	High	There can be numerous time consuming simulations to run. There is a potential need for specific costly software and code language. It has intense computational requirements.
Inputs and Models		
Climate data needs	--	Climate data are generally obtained from global climate model (GCM) outputs. Downscaled GMC data can be used to obtain more local data. Climate data can be used indirectly through inputs of other models in which outputs are used as inputs.
Water system data needs and water quality information	--	The need for water system data is highly variable as it depends on DSPM objectives. There are usually inputs for the cash flow model (financial model). For water planning cases, data related to water demands and supply/yield are needed and can be obtained from outputs from other water system models. Water system data may or may not be needed as input to DSPM. DSPM does not usually require water quality data. Cost data and market price information are needed.
Data Complexity / Model Scale	--	DSPM input data usually is extracted from outputs from other models (demand, yield, etc.), which may need to be extracted manually and may require data simplification or processing. Any changes in assumptions, inputs, and objectives would require rerunning the models to obtain new flexible options.
Time to calibrate model	High	Time to calibrate is intensive because this DSPM includes long-term planning horizons.

Ease of running models (model incorporation)	Medium	DSPM relies on outputs from other models. If DSPM is not integrated with other models, output data is manually extracted into spreadsheets and fed into DSPM. Models are complex and running them can require special skills. Learning curve can be intensive but can be transferable to staff.
Model validity	--	Closeness of model to reality is dependent on how investments, markets, and uncertainties are defined. Uncertainties related to time to make decision and DSPM structure could impact model validity.
Outputs and Results		
Nature of outputs	--	Results obtained are flexible strategies that can be adjusted for risk with time. It allows decision makers to choose the best investment opportunity based on current information available and it is possible to defer investments into the future.
Graphical quality	--	Results can be easily presented in graphs and charts comparing the cost of decision alternatives. They are generally exportable to spreadsheets but sometimes have to be exported manually.

Portfolio Planning Evaluation

Portfolio planning criteria are evaluated in Table B.6. The evaluation is based on findings from the literature review.

Table B.6 – Portfolio Planning Evaluation

Criterion	Evaluation	Evaluation Description
General Characteristics		
Reasons for using DSPM / Suitability of DSPM	--	Portfolio planning consists of selecting an optimal mix of assets and strategies to minimize risk in order to hedge against uncertain future market scenarios. Portfolio planning goes beyond assessing risk of individual securities but rather evaluates how any single security contributes to the overall performance of the portfolio. The objective of the portfolio planning method is to identify a robust set of investments applicable to equally probable future investment scenarios.
Application to water utility climate change planning	Low	Portfolio planning has been used extensively in the financial sector. It has also been used for power utility and gas supply long-term planning. The concepts of this DSPM suggest its potential applications to the water industry to address climate change uncertainties.
Planning Horizon	Long-term	This DSPM allows integration of long-term risks in the analysis.
Ease in output use	Medium	Results are a robust set of risk-return possibilities from combining available portfolio elements over future scenarios. Decisions reflect the risk tolerance of decision makers.
Transparency of DSPM	High	Portfolio planning has been used for multiple types of analysis in the financial and petroleum sectors but not in the context of climate change. Model information is readily available.
Involvement of decision makers in DSPM implementation	Medium to High	The involvement of decision makers consists of selecting an optimum portfolio and defining portfolio elements, expected return, and long-term risks. Decision makers are also involved in selecting a set of portfolio elements that yield to the maximum return for an acceptable risk.

Communicability	Medium	Portfolio theory is widely used and can be easily explained to stakeholders. However, assumptions, analysis implications, and decisions based on risk tolerance may be more difficult to communicate to stakeholders. The estimation of long-term risk often is subjective.
Cost analysis approach	--	Typically included as maximized total value.
Need for probability information	Required/Optional	Probabilities are required for key input parameters (assets, risks) but are optional for scenarios as scenarios can be treated as probably equal.
Uncertainty Management	--	Uncertainties are handled by using probabilities to define input parameters and long-term risks. Other methods of uncertainty management can include Monte Carlo simulations. Risk is minimized through hedging.
Resource Requirements		
Level of expertise required	High to Medium	This DSPM requires understanding of financial theory of portfolio planning and using computer languages to construct the portfolio optimization model. It can be done in-house and requires an economist and a programmer.
Intensiveness	Medium	This DSPM is quite intensive to construct and run. It has to be run over several dates and scenarios and relies on some inputs from outside models. Staff training and learning curve can be intensive.
Computing requirements (hardware and software)	High	There can be numerous simulations to run, which can be time consuming. There is a potential need for specific costly software and code language. In addition, it has intense computational requirements.
Inputs and Models		
Climate data needs	--	Climate data are generally obtained from global climate model outputs. Downscaled global climate model data can be used to obtain more local data. Climate data can be used indirectly through inputs of other models which outputs are used as inputs. There also is a need for data from various future climate scenarios.

Water system data needs and water quality information	--	The need for water system data and water quality information depends on DSPM objectives. They would be used to estimate risks. For water planning cases, data related to water demands and supply/yield are needed and can be obtained from outputs from other water system models. Water system data may or may not be needed as input to DSPM.
Data Complexity / Model Scale	--	DSPM input data is usually extracted from outputs from other models (demand, yield, etc.), which may need to be extracted manually and may require data simplification or processing. Any changes in assumptions, inputs, and objectives would require rerunning the suite of simulations.
Time to calibrate model	High	Portfolio optimization model needs to be calibrated to ensure accuracy. Time to calibrate can be intensive.
Ease of running models (model incorporation)	Medium	DSPM relies on outputs from other models. If the DSPM is not integrated with other models, output data is manually extracted into spreadsheets and fed into the DSPM.
Model validity	--	Closeness of model to reality is dependent on how portfolio elements and risks are defined. Uncertainties related to lack of data and DSPM structure could impact model validity.
Outputs and Results		
Nature of outputs	--	Results of the portfolio optimization model determine the range of risk-return possibilities from combining available assets in the portfolio. The outputs of this DSPM are usually a robust set of assets applicable to equally probable future defined scenarios. However, each output component is not selected to perform well in all plausible futures but rather to specialize in particular scenarios.
Graphical quality	--	Results can be easily presented in graphs and charts comparing the cost of decision alternatives. They generally are exportable to spreadsheets but sometimes have to be exported manually.

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