Final
Analyzing Uncertainty and Risk in the Management of Water Resources for the State of Texas

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Executive Summary

Why should uncertainty be considered in water planning?

Water supply planning in the United States is typically carried out in a deterministic framework, where reference values (for example, average, best case, or worst case values) are used for key factors such as population growth, demand and water availability, even though these values are likely to be uncertain. Texas is no exception. Every one of the water management strategies proposed in the 2007 State Water Plan contains some degree of uncertainty.

Uncertainty in water management strategies has been discussed in the 2007 State Water Plan. Uncertainty is currently addressed in a non-quantitative manner by the planning group members when they decide on water management strategies for regional plans. While the non-quantitative uncertainty analysis approach has utility, there are benefits of directly quantifying uncertainty in water resources planning. In particular, quantifying uncertainty in water resource planning can improve the reliability of the water management strategies chosen, reduce the cost of implementation, and help water supply managers adapt more effectively to unexpected changes in circumstances (for example, a drought worse than the drought of record or a failure of an existing major water supply).

How does this study contribute towards these goals?

The purpose of this study is to propose a methodology that allows various sources of uncertainty to be incorporated into the water resources planning framework in Texas in a quantitative manner. The approach proposed is a generalized methodology for dealing with uncertainty and risk that allows water resources planning to be carried out without being restricted to a single model, scenario, approach, or set of assumptions. The proposed methodology preserves the fundamental elements of the well-established planning process and promotes an incremental approach to adding different levels of uncertainty and risk into the decision-making environment.

To demonstrate the concepts, a hypothetical case study has been developed. The case study steps through the process of quantifying the uncertainty (in supply, demand, and future water needs) and also demonstrates how these uncertainties can be incorporated in the process of planning under uncertainty.

What are the broad elements of the methodology being proposed?

The methodology to assess the impact of uncertainty in a water plan can be broken down into two main parts. The first part consists of selecting, analyzing, and quantifying uncertainties inherent in the water plan. This process of 'uncertainty quantification' yields a set of alternative scenarios for future water needs. These future water-need scenarios form the core of the methodology for uncertainty-based planning which considers multiple scenarios, i.e., a range of water needs, for planning purposes instead of relying on a single projection for future needs (as is the case with the current Texas water management plan).

The second part of this process, which can be classified as 'planning under uncertainty', can be broken down into two sub-components: a) assessing the reliability of water management strategies to satisfy a range of water-need scenarios (as obtained from combining the scenarios for future water demand and supply), and b) improving the overall reliability of the selected water management strategy (if needed) by adding or modifying the water management strategies used in the plan.

How does this study quantify uncertainty in the different elements of the water planning process?

The three main drivers in the water management planning process are: a) future demand for water, b) future supply (the difference of these two gives the water need – when demand is more than supply), and c) the additional supply that is expected from the water management strategies considered. This study discusses the approaches to quantify the uncertainty for both demand and supply for future water needs. Demand and supply projections are impacted by two main sources of uncertainty: a) assumptions regarding future climate conditions while assessing water supplies, and b) assumptions regarding population growth and water usage while assessing future water demand.

The process of uncertainty quantification consists of defining and quantifying the main uncertainties in these components. The approach followed here is to define alternative scenarios for each uncertain factor that are used as inputs in predicting demand or supply (these include future climate conditions, population, water usage rates, among others). Broadly speaking, three ways of quantifying uncertainty have been proposed in this report:

- Develop multiple scenarios with different assumptions for underlying factors and use these to quantify uncertainty in future estimates. This is the approach used for characterizing the uncertainty in water supply (due to climate change) and in the population projections used for estimating municipal demand.
- Compare past projections to actual data, and use the 'misfit' to bound the uncertainty of projections. This is the approach used for characterizing uncertainty in irrigation demands.
- Assess the historic variability for a particular demand factor and use this to quantify the uncertainty in the projections. This is the approach used for characterizing the uncertainty in per-capita usage rates (used for municipal demand).

How does this study address the uncertainty in future water supply projections due to climate change?

The methodology to account for uncertainties in projections for future surface water supplies due to climate change is as follows:

- Select a suite of appropriate global climate models that can be used to provide a range of plausible predictions for future climate change.
- Select multiple 'emission futures' (depending on assumptions of how society, at large, will respond to climate change) to feed into the global climate models.
- Run multiple emission futures with multiple global climate models to obtain an ensemble of 'climate scenarios', each consisting of a series of average rainfall and temperature projections in the future.
- Run a hydrologic model to assess the response of water resources to the climate conditions in the form of 'naturalized streamflows', representing modeled flows which would have occurred without any man-made influences (e.g., diversions).
- Using the naturalized streamflows and the respective net evaporation-precipitation data (for different climate scenarios) assess the maximum amount of water supply which is consistently obtainable through drought conditions in the projected time-period via a water availability model (WAM). Each climate scenario therefore leads to a projection of water supply under drought conditions.

- Groundwater availability models (GAMs) may be run with inputs (such as recharge and evapotranspiration) derived from climate scenarios to predict groundwater supply.
- The resulting ensemble of supply projections may be assigned different likelihoods based on expert judgment.

How does this study address the uncertainty in future water demand projections due to population growth?

The methodology to account for uncertainties in projections for future demand due to population projections is as follows:

- Create multiple population scenarios with different birth, death, and migration rates assumptions. Typically migration is the most significant source of uncertainty; hence it can be varied while keeping the other two factors (birth and death rates) constant.
- Use historic variability in water usage rates to develop feasible scenarios for low, high, and expected usage rates for low rainfall years.
- Combine different population projections with different usage rates to create an ensemble of municipal water demands.
- The resulting ensemble of demand projections may be assigned different likelihoods based on expert judgment.

Once multiple scenarios for demand and supply have been created, they can be combined in turn to provide multiple water-need/-surplus projections. Each water-need scenario would correspond to certain climate conditions as well as population growth and water usage assumptions. The likelihood for each water-need/-surplus projection can be calculated from the likelihoods of corresponding supply and demand projections. The ensemble of water-needs projections can then be aggregated in the form of a probability distribution for water needs that can be used to assess the reliability of a certain set of strategies for meeting projected water needs.

What is the proposed approach for planning under uncertainty?

The figure below shows the '**planning under uncertainty**' framework, comparing it to the (existing) '**deterministic planning**' framework.

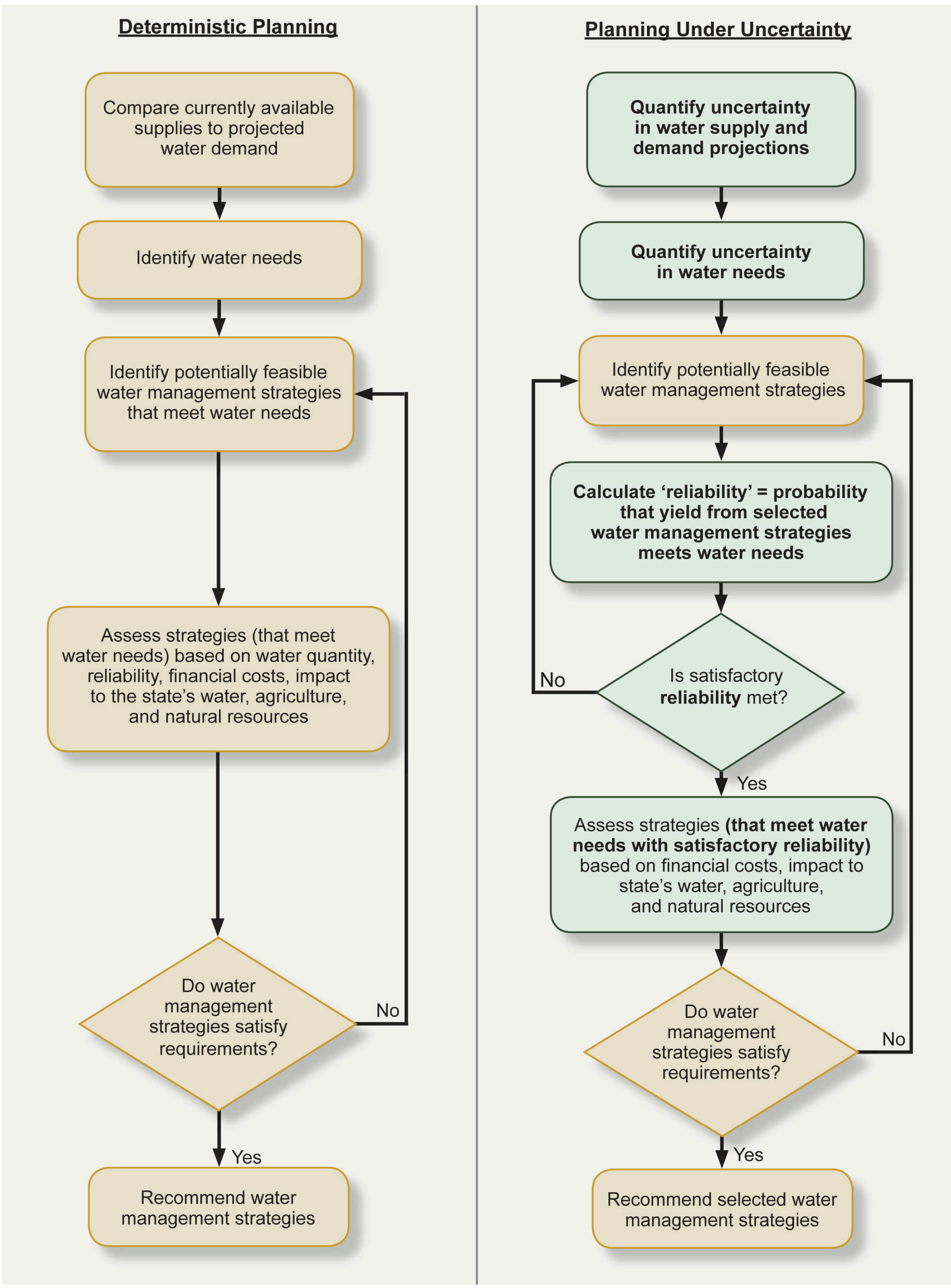

Figure E-1 Deterministic versus uncertainty-based water planning frameworks.

A key difference in the methodology for planning under uncertainty is that it considers multiple alternatives for future water needs rather than a single water–need projection used in deterministic planning. With uncertainty in the planning framework, it becomes necessary to acknowledge that there may be certain scenarios when water needs may not be met by the proposed set of strategies. To quantify the impact uncertainty has on the decision-making process, it is useful to calculate the 'reliability' of meeting projected water needs for a given set of water management strategies. Reliability is defined as the likelihood that a certain strategy (or set of strategies) will meet projected water needs. The goal of the planning process then is to identify strategies that have an acceptable level of reliability (i.e., there is a sufficiently high likelihood of meeting future water needs) while also accounting for other important criteria like cost, yield, environmental impacts, socio-economic factors, political feasibility, etc. Thus, the fundamental difference between planning under uncertainty and the deterministic planning framework is that *the driver in the planning process is the reliability of the selected strategies in meeting a range of projected water needs instead of a single deterministic water-need projection*.

Once multiple future water-needs scenarios have been developed, the combined yield for a set of strategies can be assessed for its reliability of meeting these projected water needs. For example, if there are a total of 10 water-need scenarios - with equal likelihoods - and the water yield from a given water management strategy is sufficient to meet 9 out of the 10 water-need scenarios, then the water management strategy has a 90 percent reliability of meeting projected water needs. If the reliability is deemed too low then other sets of strategies with higher yields, which lead to higher reliabilities, may be considered. Finally, trade-offs in the various factors such as costs, yields, reliabilities, project feasibility, socio-economic and environmental impacts, among other considerations will need to be considered before proposing a set of strategies. The choice of an acceptable reliability level is a decision that depends on various factors including the risk-averseness of decision-makers, confidence in the uncertainty quantification process, and other subjective considerations.

What are the main conclusions and recommendations of this report?

- The methodology to incorporate uncertainty into the water planning process should be incremental, building on the existing planning framework.

- The approach proposed in this study is to use a set of alternative scenarios to represent the uncertainty in different elements of the water planning process. This is an intuitive and easy to understand approach that fits in seamlessly with the existing planning framework.
- It is infeasible to try to quantify all possible sources of uncertainties. Thus the focus should be on the areas of uncertainty which are of most importance to stakeholders and would create the largest impact on the projections of demand and supply. The methodologies proposed in this report are generalized enough to be adapted to other demand and supply factors.
- The choice of which uncertain factors to quantify and which methodology to use for quantification depends on the stakeholders and available data sources. Uncertainty may be characterized using alternative model assumptions or by assessing historic variability.
- Consideration of uncertainty adds value to the planning process by allowing the reliabilities of water management strategies to be assessed and incorporated into the decision-making framework, allowing for a more robust water management plan.
- Instead of a single deterministic water-need projection, the driver for planning under uncertainty is the reliability of meeting a range of plausible projected water needs.
- Using this approach the trade-offs in cost, benefits, and reliabilities of alternative sets of strategies may be assessed. This trade-off information can be useful in selecting the final set of strategies.
- Assessing the impact of different sources of uncertainty on the reliabilities of water management strategies can not only inform the water planning process, but can also aid future efforts in data-collection and model refinements by identifying uncertain factors that the planning process is most sensitive to.
- This study represents a ‘first step’ in the incorporation of uncertainty in the planning framework. It is important to acknowledge the caveats and limitations of the approach proposed. Many of these can be further addressed in future studies. Some important limitations of the study are:

- A simple scenario-based approach has been used in this study. Other more sophisticated uncertainty quantification approaches exist and can be addressed in future work.
- The study assumes that demand and supply uncertainty are independent. However, factors that influence supply uncertainty (such as climate change) can also influence demand. This link can be made explicit in future studies.
- The study considers uncertainty only in demands and supplies. In many cases the yields as well as the implementation of proposed water management strategies can also be uncertain. Future work should address the quantification and incorporation of these uncertainties in the planning framework.
- Future work should also consider more sources of uncertainty. Among others, these may include: a) modeling uncertainties in WAMs and GAMs, b) scaling issues related to inputs and outputs of the WAMs and GAMs, and c) uncertainty in other demand types (apart from municipal and irrigation.

1.0 Introduction

In 1996 the state of Texas was experiencing a significant drought, one of many that had occurred in the 40 years of water supply planning in Texas. The number of water shortages and threats to community supplies across the state that occurred during that drought were a testament to the fact that top-down water planning was not working in Texas. In the subsequent legislative session, Senate Bill 1 mandated a bottom-up approach to planning where 16 regional water planning groups develop their own plans, with funding and guidance provided by the Texas Water Development Board (TWDB). The regional plans are subsequently rolled up into a state water plan by staff at the TWDB.

The delivery of the 2007 Texas State Water Plan to the public and members of the legislature in January of that year marked the conclusion of the second round of planning using this regional water planning process. Combined, the regional water planning groups proposed 4,500 water management strategies to meet future demand at a cost of over $30 Billion. Implementation is expected to occur over the entire 50 year planning horizon with funding being provided by a large number of local, state, and federal sources.

The success of the regional water planning process in Texas is due in part to the large number of stakeholders represented on the planning groups and the fact that more local issues are considered when developing water management strategies to meet future water needs. The regional planning group members, many of whom are responsible in some way for the development or use of large quantities of water in their region, are more involved and engaged in the process than they were in the development of state water plans prior to Senate Bill 1. Environmental groups and other organizations with a stake in the future viability of the region's water resources are also active participants.

The process of developing a state water plan is repeated every five years. In other words, every five years the regional water planning groups revisit population projections, water availability and supply, other key issues in their region, and reconsider the water management strategies that they will need to implement in order to meet projected demands over the 50 year planning horizon. This adaptive management approach ensures flexibility in the planning process and ample opportunity to adapt to changing conditions. It also enables planners to deal with some of the important uncertainties inherent in long-term water supply planning.

Water supply planning in the United States is typically carried out in a deterministic framework, where reference values (for example, best estimates or worst case scenarios) are used for key factors such as population growth, demand and water availability, even though these are likely to be uncertain. Texas is no exception. Every one of the water management strategies proposed in the 2007 State Water Plan contains some degree of uncertainty. This is especially true for the demand and supply projections on which water management strategies are based. The underlying sources on uncertainty in the planning process are currently addressed in a non-quantitative way by the planning group members when they are prioritizing water management strategies for the regional plans. In weighing the costs, yield, environmental impacts and other factors of each potential water management strategy, the members may also consider the likelihood of getting additional yield from the strategy.

Incorporating uncertainty into planning in a quantitative way can improve the reliability of the selected water management strategies by avoiding overly conservative or overly optimistic planning assumptions. This may also reduce the cost of implementation by avoiding expensive projects that may not necessarily reduce the risk of not meeting projected water needs. Perhaps more importantly, addressing uncertainty can help water supply managers adapt more quickly to unexpected changes in circumstances, for example, a drought worse than the drought of record or a failure of an existing major water supply. Quantitative assessments of risk and uncertainty have been used in other sectors of our economy for decades. Investment banking and emergency management are just two examples. Engineers assess risk when designing flood retention structures, most of which have a pre-determined and accepted probability of failure.

The purpose of this study is to propose a methodology to incorporate these various sources of uncertainty into the water resources planning framework in Texas in a quantitative manner. The approach proposed is a generalized methodology for dealing with uncertainty and risk. However, to demonstrate applicability of the methodology, a case study was developed wherein a few sources of uncertainty were chosen, quantified, and propagated to outcomes of interest. These uncertainties were then translated into *reliabilities* (the likelihood of not meeting projected water needs), which in turn can be used in decision-making.

Careful consideration was given throughout this study to the existing (and successful) framework for water resources planning in Texas. Such consideration preserves the fundamental elements of a well-established planning process, promotes incremental steps to adding different levels of uncertainty and risk into the decision-making environment, and is therefore a pragmatic approach that is likely to be accepted by the majority of stakeholders. It also provides an approach whereby highly uncertain aspects of water resources planning, such as the future climate can be incorporated, in a quantitative way, and without having to choose a single model, scenario, approach, or set of assumptions.

This study represents a 'first step' in the incorporation of uncertainty in the planning framework. It is expected that the methodology laid out in this report will help water planners begin to think about how uncertainty can be incorporated into their processes to reduce cost, improve reliability, prioritize use of resources, improve decision-making and increase adaptability. It will also help provide comfort to stakeholders that sources of uncertainty, such as climate change, are being considered and addressed by water resources managers.

The rest of this report is organized as follows. Section 2 discusses the current framework for water planning in Texas and identifies some of the key sources of uncertainty therein. Section 3 outlines the methodology to: a) quantify uncertainty in water supply (primarily due to climate change), b) quantify uncertainty in municipal demand (due to population projections and usage rate estimates) and irrigation demand, c) aggregate the different sources of uncertainty to calculate different water-need projections, and d) incorporate the uncertainty in projected water needs into the existing water planning framework. Section 4 discusses a hypothetical case-study that is used to demonstrate some of the salient concepts introduced in the methodology section. Finally, Section 5 presents conclusions and recommendations from the study, while also discussing the limitations of the proposed methodology and identifying areas for future work. For all sections, technical terminology has been defined, where appropriate, in call-out boxes that accompany the text.

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2.0 Important Sources of Uncertainty in the Planning Framework

2.1 Existing Framework for Water Resources Planning

Before describing the various sources of uncertainties in the water resources planning process, it is instructive to lay out the current framework for water planning in Texas. The methodology used for water planning in Texas is shown in Figure 2.1.

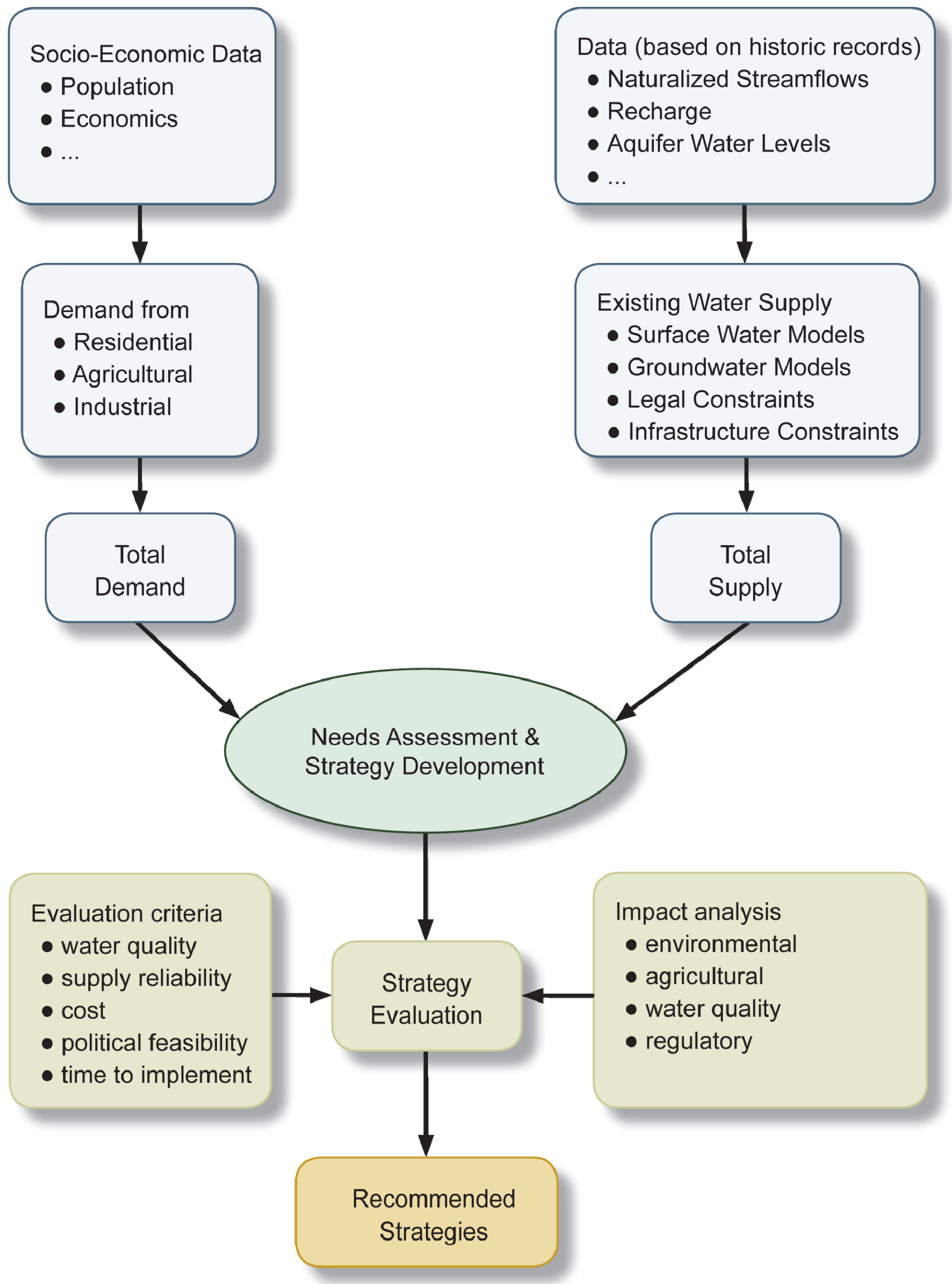

Figure 2-1 Existing framework for water resources planning.

The current approach follows a series of steps carried out at the regional level. The TWDB and Regional water planners collect and analyze necessary information from a variety of sources to determine the present and future demands and supplies of water for each water user group within the planning area. From this information, the regional water planning group determines when and where water needs will arise. Solutions to meeting the future water needs are developed as water management strategies to be implemented over time. Water demands and water supplies from the present day through the 50-year planning horizon are determined before future water needs can be known.

Water demands over the planning horizon are calculated for different use types – municipal, irrigation, livestock, industrial, mining, and steam-electric – and summed to give the total water demand. Each of these projections are based on a number of factors such as population and per-capita water use (for municipal demand), crop acreage and crop water needs (for irrigation), livestock water consumption (for livestock), etc.

Future water supplies are estimated independently from future demands. A fundamental assumption within water supply planning is that future hydrologic variability is adequately expressed in historical records (this assumption is referred to as the 'assumption of climatic stationarity'). As required by Senate Bill 1 - Texas Water Code §16.053(e)(4)), supplies used for planning are based on the worst drought conditions in the historical hydrological record (the '**drought of record**'), thus ensuring that the supply estimates are conservative in nature. Planning groups utilize available historical and modeling datasets in conjunction with surface water availability models (WAMs) and groundwater availability models (GAMs) to estimate the water availability. They then consider various infrastructural and legal factors to estimate the existing water supplies.

> ***Drought of Record**: Period of time during recorded history when natural hydrological conditions provided the least amount of water supply.*

Existing water supplies are defined as the maximum amount of water that is physically and legally available during a repeat of the worst drought conditions in the historical hydrologic record.

> ***Existing Water Supplies**: Maximum amount of water, physically and legally, available during a repeat of the drought of record.*

Existing water supply differs from **available water** in that the latter denotes the maximum amount of water available (also during a repeat of the drought of record) for use regardless of physical and legal constraints.

> ***Available Water****: Maximum amount of water available during a repeat of the drought of record (regardless of physical or legal considerations)*

Future surface water supplies are estimated using the Texas Commission on Environmental Quality (TCEQ) WAM. The TCEQ WAM System is a generalized modeling software package and a set of basin specific input files that can be used to predict the amount of water in a river or stream under a specified set of conditions. Each river basin in Texas has a set of input files which provide historical naturalized hydrology and the legally authorized surface water permits. Naturalized hydrology is represented as historical monthly **naturalized streamflow** volumes (created by removing the influence of historical water management usages from historical streamflow records) and net evaporation-precipitation. WAM naturalized hydrology generally covers a 40-year to 60-year period of record for each river basin and is estimated at locations throughout the basin to provide broad spatial coverage. The WAM accounts for all legally authorized surface water permits, impoundments, and diversions of water to estimate available water supplies that may be used to meet the demands of water users. Regional water planning groups may make adjustments to the WAM to reflect physical constraints on the ability to exercise permits. Adjusting reservoir capacity for future levels of sedimentation is a common modification made by regional planning groups.

> ***Naturalized Streamflows****: Modeled flows which would have occurred without any man-made influences such as upstream reservoirs, diversions, return flows, etc.*

Future groundwater supplies are typically estimated using the TWDB GAMs, wherever these are available and appropriate. TWDB GAMs are numerical groundwater flow models (that have been developed for all of the major and most of the minor aquifers in the State of Texas). The purpose of the GAM program is to provide reliable and timely information on groundwater availability within the context of the water resource planning process.

> ***Desired Future Conditions (DFCs)**: The quantified condition of groundwater resources at a specified time or times in the future or in perpetuity as identified by GCDs.*

The TWDB uses GAMs (where available and appropriate) to calculate or verify 'managed available groundwater' based on **desired future conditions (DFCs)** (Mace et al., 2008) of aquifers as identified by the Groundwater Conservation Districts (GCDs) as part of a Groundwater Management Area (GMA). The desired future condition of an aquifer is the quantified condition of groundwater resources at a specified time or times in the future or in perpetuity as identified by GCDs in a GMA. Examples of DFCs include minimum water levels (or maximum drawdowns), water quality standards, and maintenance of baseflow and spring flows. DFCs establish constraints on the total pumping possible from an aquifer. A GAM can be used to test how much pumping would be allowable in an aquifer before the DFC is violated, which in turn allows for the calculation of the total managed available groundwater for that aquifer. The regional planning groups will incorporate these managed available groundwater values as part of the annual groundwater supplies that go into the regional water planning process.

Total water supply is given by the sum of surface water and groundwater supplies for a particular region. In addition, total water supply may also include wastewater reuse as an additional component. **Total water demand** is, similarly, given by the sum of the individual demand types. The water planning process then continues with assessing whether there is enough projected water supply to meet projected water demand. A 'surplus' of supply occurs when estimated water supply exceeds the estimate of water demand. Conversely, a 'water shortage or need' occurs when demand exceeds the supply. Water needs that occur less than 30 years into the planning horizon are considered near-term needs, while needs identified as occurring 30 years to 50 years into the planning horizon are considered long-term needs. The identification of (short- and long-term) water needs in the planning horizon leads the regional water planning group into the process of developing specific water management strategies to address water needs in the planning horizon. Examples of water management strategies include advanced conservation of existing supplies, constructing a new reservoir, groundwater development, pipelines to move water to areas of need, and others. Planning groups also estimate the financial costs of strategies and assess how they impact the state's water, agricultural, and natural resources. Based on all these factors, water management strategies are proposed for different times in the planning horizon depending on timing of need.

It is important to note that the water planning process described above is iterative and adaptive. Water management strategies are developed to meet future needs. These future needs are inherently uncertain. The plan is revisited every five years allowing the planning groups to incorporate new information (better demand and supply projections), technological advancements, and new policies to refine and change the water management strategies where needed. This adaptive nature ensures that the planning groups can address and reduce many of the unavoidable risks and uncertainties that are part of the planning process.

2.2 Sources of Uncertainty in the Planning Framework

Risk and uncertainty have been recognized as significant factors in water supply planning in Texas. Chapter 12 of the 2007 State Water Plan discusses the risks and uncertainty in the water planning framework. The 2007 State Water Plan describes the risk in the water plan as:

> *'For water planning, the risk is not having enough water for the population, economy, and environment. The likelihood of water shortages depends on demand for water, which is related to population and water use, the reliability of our water supplies, and climate – especially drought. The results of not having enough water could be dire: residential shortages, failed crops, stalled factories, and stressed environments.'*

Risk is intrinsically linked to uncertainties in the water planning process, such as the *'uncertainty in how many people there will be in the future, how much water they will need, what the climate will be, and whether or not the* [water management] *project can be implemented'* (2007 State Water Plan).

As described in the previous section, the water planning process in the State of Texas addresses this risk by using well-grounded scientific methods to develop projections for future water supplies and demands and proposing water management strategies to deal with water shortages. These projections and strategies are reviewed every five years and updated based on new data and information, thus improving their accuracy and reliability. Furthermore, the risk of not meeting water shortages is reduced by considering water supply during drought conditions (since the risk of not meeting water demands is highest during a drought). Despite all this, some degree of risk remains due to various sources of uncertainty as discussed below.

The 2007 State Water Plan highlights the sources of uncertainty in the water planning framework. These are summarized below:

- **Uncertainty in Demand Projections**: Projected demands depend on various factors that are sensitive to uncertainties, such as population growth, per-capita water use, and industrial and agricultural water use. Future population may vary depending on various factors, most importantly migration rates, that are difficult to ascertain with certainty. Industrial and agricultural demand projections are dependent on assumptions of economic growth, price of energy, crop prices, all of which are either difficult to predict and/or highly volatile.
- **Uncertainty in Drought Conditions Used for Planning**: Water Planning in Texas is based on the 'drought of record'. The drought of record for most of Texas is the historical drought from the 1950s, which lasted for about eight years and affected every area of the state. However, it is important to note that the period of record available for planning purposes is a relatively short one. There is evidence to show that worse droughts have occurred in the past, and may, in fact, occur again in the future. Thus, there is uncertainty in the drought conditions that are used as the basis for the planning process.
- **Uncertainty Due to Climate Change**: The current planning framework is based on the assumption of climate stationarity (i.e., future climate variability is captured in historic climate records). Climate is a very important driver for predicting water supplies as well as the expected yields from different strategies. In addition, climate can also impact demand projections by impacting usage rates, crop yields, and population growth, among other things. There is reason to believe that climate trends are turning away from existing conditions. While there is broad scientific consensus that the global climate conditions are changing, there are considerable uncertainties in the models used to make these predictions. These uncertainties in predicting future climate lead to uncertainties in the water planning process.
- **Uncertainty Due to Natural Disasters and Terrorism**: Natural disasters such as floods, hurricanes, tornadoes, and fires can have a number of short term impacts on water resources, especially as related to water quality and the ability to distribute water. Out-of-state natural disasters such as hurricane Katrina can also impact water demands, by

increasing the number of people moving to Texas (thus increasing demands). Man-made disasters, specifically through acts of terrorism add yet another layer of complexity and uncertainty on water management.

- **Uncertainty in Future Technologies**: The water planning framework proposes strategies to deal with water needs of the future. Due to the rapid change in technology, water management strategies may change or evolve over time. For most intents and purposes, this form of uncertainty has a positive influence on the risk of meeting future water needs. For example, desalination has become a feasible water management strategy in the recent past due to the technological improvements.
- **Uncertainty in the Sustainability of Water Resources**: The 2007 State Water Plan defines sustainability of water resources as the '*development of water in such a manner that it is maintained for indefinite time without causing unacceptable social, economic, and environmental consequences*' (2007 State Water Plan). While sustainability, itself, does not contribute to the uncertainty in the water planning process, as a planning objective it is impacted by uncertainty in future available supplies and demands. Sustainability of surface water resources, in particular, is highly dependent on climate conditions and other environmental factors (such as sedimentation in reservoirs). Groundwater sustainability is more predictable, as aquifers typically store more water and respond less to short-term changes in climate. Planning for groundwater sustainability also depends on GAMs and hence can be impacted by the uncertainties therein.
- **Uncertainty in Permitting, Policy, and Legislature**: The feasibility of strategies proposed in the water plan may often depend on permits being granted in the future. For example, a reservoir may not be granted a permit due to environmental considerations, or a well field may not be implemented as policy changes decrease groundwater availability. Changing and evolving laws and water policy add yet another dimension of uncertainty to the planning process. These changes may impact how much and where water is available to address future needs.

The above sources of uncertainty can be broadly categorized into two types of uncertain factors: a) factors that cannot be effectively predicted (natural disasters, acts of terrorism, advancement in technology, and, legislative and policy change), and b) and factors that can be predicted, albeit with uncertainty (demand and supply projections and climate change).

This study focuses on the more predictable uncertain factors that can be quantified and, thus, more easily be incorporated into the planning process. The quantifiable sources of uncertainty have been divided into three categories[1]: a) uncertainty due to climate change, b) uncertainty in water supply models, and c) uncertainty in demand projections. Each of these is discussed in more detail below.

2.2.1 Climate Uncertainty

> ***Climate**: The weather (temperature, precipitation, and wind) averaged over a long period of time. The standard averaging period is 30 years, but other periods may be used depending on the purpose.*

As highlighted in the 2007 State Water Plan, climate change can have a profound impact on the water planning process. Future water supplies depend on future **climate**. Before any forecasts can be made about water supply, assumptions need to be made concerning climate conditions. Climate conditions impact precipitation, temperature, and surface evaporation that serve as inputs in models that predict available water supply (for both surface water and groundwater). In the existing framework the fundamental assumption is that past variability in climate is an adequate representation for future variability in climate. The surface water and groundwater supplies used for planning purposes are based on information obtained from historical data. The plan is then designed to meet the worst drought conditions (drought of record) from the historical dataset. However, there is reason to believe that future climate variability will be different from past climate variability due to changes in **climate forcings**.

> ***Climate Forcings**: Any natural or man-made factor that can impact the climate leading to climate change.*

Research indicates that overall climate trends may already be changing with global average surface temperatures increased by about 1°F over the 20th century (Houghton and others, 2001)

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[1] Note that these categories are considered distinct for organizational purposes. In reality, cross-connections and feedbacks may exist across categories. For example, climate change may impact demand projections (by impacting population growth or water usage rates) as well as modeling assumptions in the water supply models. These cross-connections and feedbacks can make analysis very difficult. As this report represents a first cut at incorporating uncertainties into the planning process, these interactions have been ignored for now.

and many of the hottest years in record occurring in the last few decades. While these global changes do not necessarily hold for Texas, recent research (Ruosteenoja and others, 2003) with multiple state-of-the-art climate models has shown that temperatures in Texas are expected to increase significantly in the next 100 years.

While there is broad consensus that climate is changing over time, there is uncertainty regarding the exact nature of these changes and what impact they will have on water supplies. This uncertainty arises due to: a) the uncertainty in the state of knowledge about the processes in the climate system, and b) uncertainty about the factors (especially carbon emissions) that will likely impact future climate.

Global Climate Model (GCMs)*: Mathematical formulations of the processes that comprise the climate system. Climate models can be used to make projections about future climate under different climate forcings.*

The first source of uncertainty is due to the fact that it is infeasible to model all the complex processes and interactions that govern climate in any computer model. While much progress has been made in climate modeling, there exist multiple **global climate models,** each based on different assumptions and approximations and each leading to different predictions for future climate. It is important to note that global climate models are best suited to represent global-scale processes. Regional climate predictions (critical for water supply predictions) are considerably more difficult, especially when there are multiple processes and interactions that govern a regions climate. Thus, the models used to predict future climate are, in of themselves, inherently imperfect and uncertain.

The second source of uncertainty is due to the fact that future human activities (unknown, to a large degree, at the moment) that lead an increase or decrease in CO_2 emissions may have a major role in shaping future climate forcings. Different human responses to climate change can lead to different 'emission paths', which in turn will impact climate in different ways. For example, a move towards 'green' technology would likely lead to lower emissions, while maintaining the status-quo would likely lead to higher emissions.

2.2.2 Uncertainty in Water Supply Models

Water supply projections typically rely on mathematical models that predict water supply for a given set of climatic and hydrogeologic conditions. Surface water availability is typically predicted using a WAM which uses inputs such as naturalized streamflows and net evaporation-precipitation (for drought of record conditions) to predict water availability during a repeat of conditions experiences over the period of record, taking into account existing water permits for impoundments and diversions. Similarly, groundwater availability can be predicted using a GAM that determines the maximum yield expected from an aquifer under certain DFCs. While both types of models – WAMs and GAMs – are constructed using the best available data and science, they are still based on approximations and may use imperfectly known (uncertain) inputs and parameters. Uncertainty can impact both WAMs and GAMs to different extents. Although their names are similar, WAMs and GAMs are quite different in the way they simulate water supply. A WAM is in essence a water accounting system that simulates the allocation of surface water (in the form of naturalized streamflow) in a river basin under existing water rights and using the prior appropriation doctrine. A GAM, on the other hand, is a numerical model that simulates the flow of groundwater, predicting groundwater response to external stresses such as pumping. Unlike a WAM, a GAM *is* calibrated by matching predictions to field observations as much as possible. Due to these conceptual differences uncertainty in WAMs and GAMs are discussed separately in the sections below.

Uncertainty in Surface Water Supply Models

As mentioned above, surface water supply modeling that occurs for regional planning uses the a particular set of WAMs, the TCEQ WAM System. The WAM System consists of two components, basin specific input files and a generalized modeling package referred to as the Water Rights Analysis Package (WRAP), which simulate water availability under various management conditions. The WAM System has been developed for all 23 major and coastal river basins in Texas. The WRAP model requires input of both management and hydrologic conditions. The base hydrologic information consists of "naturalized" flows (flows without various man-made diversions and impoundments) that occurred over the period of record. The naturalized flows are estimated using various methods and historical data specific to each basin.

As with any modeling system, there are modeling assumptions in WAMs which may be characterized as having varying degrees of uncertainty. For example, the naturalized stream flow and net evaporation-precipitation period of record for the WAM System is assumed be representative of the range of hydrologic conditions which may be experienced in the future. A fundamental assumption within water supply planning is that of ‘hydrologic stationarity’, i.e., future hydrologic variability is adequately expressed in historical records. This assumption allows one to use historic hydrologic records while modeling future water availability. The assumption of hydrologic stationarity is key to applying the WAM System's period of record to the future period of assessment. Climate change, as discussed in Section 2.3.1, may challenge the notion of hydrologic stationarity depending on the number of years into the future the analysis is being conducted and the degree to which the climate is expected to change over that time. Changes in groundwater contributions to stream flow due to groundwater management practices and changes in surface runoff due to land use management practices are additional factors which may affect the assumption of hydrologic stationarity.

The rate of reservoir sedimentation is another important modeling assumption which may be a source of uncertainty in making water supply projections. Regional plans use forecasts of reservoir storage capacity over time that are adjusted for future sedimentation. Changes in land use over time could not only affect the production of surface runoff and groundwater infiltration, but reservoir sedimentation could be affected likewise. Climate change may affect vegetation and soil conditions in addition to any human efforts to manage land use and rangeland conditions.

Uncertainty in Groundwater Supply Models

Groundwater supply modeling for regional planning is typically performed with the TWDB GAMs. As discussed in Section 2.1 the GAM is integral to defining the amount of groundwater that will available in the future, and thus the potential supply of groundwater. Managed available groundwater is calculated based on a set of DFCs. Once a set of DFCs has been established, the GAM (where available) is run to estimate the maximum amount of pumping that can occur while maintaining conditions that satisfy the DFCs.

GAMs, like most groundwater models, are calibrated to historical data, and are required to meet certain industry-standard measures of calibration. During calibration, basic hydrogeologic parameters, such as hydraulic conductivity or storativity, are adjusted within reasonable ranges in order that the model’s simulated results closely match measured results. Because a numerical model always represents a simplification of reality, the simulated results will never perfectly match the measured results. However, a well-calibrated groundwater model will produce realistic estimates of hydrogeologic responses to a given set of conditions as long as the model is appropriately conceptualized and well-constrained.

One potential source of uncertainty in GAMs is the set of conceptual assumptions made for basic processes that control the hydrogeologic response of the modeled aquifer. As an example, many aquifers discharge in riparian regions, either through seeps, groundwater evapotranspiration, or discharge to streams through baseflow. During model calibration, it is often difficult to determine the proportional impact of each of these discharge mechanisms due to the lack of direct measurements for most of them. While the relative proportion of each discharge may not be too important while predicting water levels, they do become important when using the groundwater model to predict change in baseflow, thus leading to uncertainty in the prediction of future baseflow.

Furthermore, a groundwater model makes most accurate predictions when the values for input parameters or stresses fall inside the range used in calibration. For example, if a region has historically had very little pumping, and has very little change in water levels, the model will not typically be well-constrained with respect to predicting responses under heavy pumping conditions. The lack of constraint occurs because the parameters that govern the response to pumping (especially storativity) may be varied over a considerable range without affecting calibration.

Climate, too, can impact GAM inputs (as discussed in Section 2.3.2), especially inputs such as recharge and evapotranspiration that may be sensitive to climate conditions. In such cases, uncertainty in the future climate conditions will lead to uncertainty in these inputs. Pumping, typically one of the most significant drivers of future groundwater conditions, is also dependent on both climate conditions (in times of drought, groundwater use will typically increase) and various anthropogenic factors, such as population change and the growth or decline of industry or agriculture in an area. Thus, uncertainty in model predictions will be affected by uncertainty in future pumping estimates.

Finally, there can be uncertainty in the pumping numbers derived to satisfy the DFCs for the aquifer. When GAM runs are made to determine managed available groundwater, certain simplifying assumptions need to be made about the spatial distribution of future pumping. In addition, DFCs that are based on water levels or drawdown are often expressed in terms of an average statistic which does not constrain the spatial variability of the metric. For example, it may be assumed that the current spatial distribution of pumping will remain constant for the next 50 years. One can intuitively see that if the assumption is relaxed, then countless different pumping scenarios could be conceived that could result in the same average drawdown. For example, a particular GCD that is coincident with a single county boundary sets a DFC that the average drawdown in the county cannot exceed 20 ft in 50 years. This condition could be met with one-quarter of the county having an average of 80 ft of drawdown with the remainder with no drawdown or with one half of the county averaging 30 ft of drawdown with the other half averaging 10 ft drawdown. This non-uniqueness leads to uncertainty in the actual distribution of pumping and drawdown that will occur even if the DFC is maintained.

2.2.3 Uncertainty in Water Demand Projections

Water demand projections are typically calculated separately for different use-types such as municipal, industrial, irrigation, livestock, and steam-electric. Each of these water demands depend on a number of factors – projections for population and per-capita usage for municipal demands; economic growth and energy prices for industrial demands; agricultural growth, farming practices, crop types, and energy prices for irrigation demand.

This study addresses the two most significant demand categories for the State of Texas – municipal and irrigation water demand. Other categories for water demand, including industrial (manufacturing and mining), steam-electric, and livestock, are not explicitly discussed in this study. However, the techniques outlined for the other demand categories can easily be extended to these, if needed.

Uncertainty in Municipal Demands

Estimates of municipal demands depend on population projections and estimates of per-capita water usage. The most commonly used method for developing population projections is called the 'cohort component method'[2]. This method starts with current population numbers and uses estimates of birth, death, and migration rates (per year) for different age, gender, and ethnic groups (cohorts) within the population to project the population into future years. Birth and

[2] For details see the methodology described for Texas population projections on the Texas State Data Center website http://txsdc.utsa.edu/tpepp/2008projections/2008_txpopprj_txtotnum.php

death estimates are typically obtained through surveys and other data-collection methods. Migration rates – rates at which people move in or out of a region – are more difficult to obtain and are, arguably, most prone to uncertainty. Typically, migration rates are not directly measured, but are indirectly determined by first taking into account birth and death rates and then comparing the resulting estimate with the actual census data for a given year (the difference between the actual census population and the population estimate using only births/death rates can be assumed to be due to migration in/out of the region). Migration rates are also the most susceptible to future socio-economic conditions. A region with a growing economy can attract surrounding populace with new jobs. On the other hand regions with slowing economies may have negative migration rates thereby reducing their populations. Climate conditions can also play a role in migration, especially for agricultural and coastal communities. All these factors make it difficult to predict the migration rates to use for population projections.

Water usage rates are the other key component for municipal demand. Water usage rates are highly variable, even within a short period, and depend on prevalent water use practices of consumers - something that is difficult to predict for the future. Moreover, climate conditions as well as existing water policy can also impact water usage rates. During a drought, for example, a drought contingency plan may be imposed that limits the amount of water that can be legally used by water users for various purposes.

Uncertainty in Irrigation Demand

Agricultural irrigation has historically been the largest water use in the state of Texas. Current irrigation water use is typically based on surveys that assess how much of a particular crop is being grown in a region and the amount of water being used for irrigating that crop. The process of projecting irrigation demand into the future is considerably more complicated depending on multiple factors such as future crop prices, energy prices, land and water availability, changes in agricultural practices, and changes in government incentives, among other things. For example, TWDB calculates ‘individual crop water needs’ or irrigation rates for the different TWDB crop categories. Evapotranspiration (ET) based estimates using methods set forth in Borrelli et al. (1998) are used as a starting point, along with data collected and reported by the Texas ET Network and the Texas High Plains ET Network. The Farm Service Agency (FSA) is also used as a source for irrigated acreage data. Lastly, surface water data supplied by the TCEQ, Texas

Water Masters, and comments from GCDs are taken into account. The rate of future change in irrigation water demand is based on TWDB research that uses mathematical optimization models to determine the most profitable distribution of crops, taking into account factors such as crop profitability, overall rate of water use, land availability, improved technology, local acreage history, and conversion of irrigation water rights to municipal use. Many of these factors are not very well known. For example, agricultural technology in the future are highly volatile (crop and energy prices) and may be sensitive to future climate change (water availability and crop yields).

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3.0 Methodology - Incorporating Uncertainty into the Planning Process

This section presents the methodology to incorporate some of the important sources of uncertainties (discussed in Section 2.2) into the existing framework for water resources planning (discussed in Section 2.1). It is important to note, that the methodology discussed here is based on an incremental approach that proposes adding levels of uncertainty in the decision-making process while preserving the fundamental elements of the well-established planning process.

Figure 3-1 shows the overall methodology for uncertainty analysis. The figure closely follows the planning framework presented in Figure 2.1 (existing framework for water resources planning in the State of Texas). As can be seen from the figure, the methodology to assess the impact of uncertainty in a water plan can be broken down into two main parts. The first part, which can be classified as 'uncertainty quantification, consists of selecting, analyzing, and quantifying uncertainties inherent in the water plan. Uncertainties in demand and supplies can either be represented using **discrete probabilistic scenarios** or **continuous probability distributions**. The uncertainty in projected needs can be computed by combining the scenarios and/or distributions of demand and supply. Depending on the method chosen to represent uncertainty, the process of 'uncertainty quantification' yields either a set of discrete scenarios a probability distribution for projected needs. Thus, instead of relying on a single projection for future needs (as is the case with the current Texas water management plan), uncertainty-based water planning process takes into consideration multiple scenarios or a range of water-need projections.

Discrete Probabilities*: Used where several distinct outcomes are possible with given likelihoods. For example, a coin toss can result in two (discrete) outcomes – heads or tails – each with 50% probability.*

Continuous Probabilities*: Used where a continuous range of outcomes are possible with given likelihoods. For example, a survey of heights of men in a certain district may range from 5 to 7 feet, with the extremes having low probabilities and the middle range having higher probabilities.*

The second part of this process, which can be classified as 'planning under uncertainty', can be broken down into two sub-components: a) assessing the reliability of a set of water management strategies to meet the range of water-need scenarios, and b) adding to or modifying water management strategies to improve the reliability of meeting projected water needs.

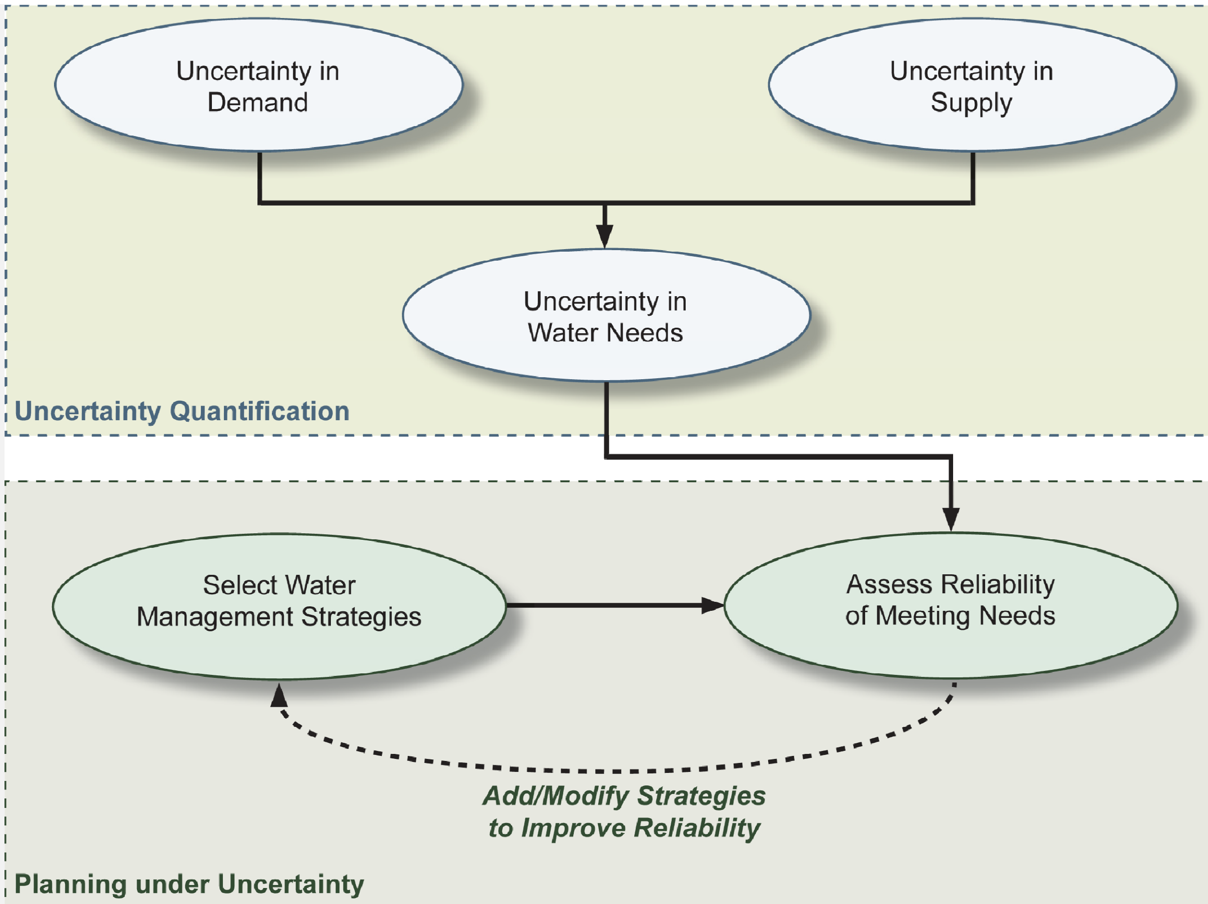

Figure 3-1 Overview of uncertainty analysis methodology for water resources planning.

Reliability of Water Management Strategies*: The likelihood that the yield from the set of water management strategies is sufficient to meet a range of plausible water need projections for a given time horizon.*

The **reliability** for a given set of water management strategies is defined as the *likelihood that the total additional supply from the water management strategies would be sufficient to meet a range of plausible water need projections for a given time horizon*. Note that these reliabilities are relative to the scenarios used for uncertain factors. Moreover, it is possible that certain strategies have high reliabilities for near-term needs but may show lower reliabilities for long-term needs (in part due to the higher uncertainty in projections for long-term needs). If the given set of water management strategies is seen to have low reliability, there may be a need to add to or modify the strategies until they meet the range of projected water needs with a certain desired level of reliability (shown by the dashed arrow in Figure 3-1). As can be seen from the figure, strategy selection, reliability assessment, and adding/modifying water management strategies to meet target reliability are iterative steps that may need to be repeated until a satisfactory water management plan is reached. Various other factors, in addition to reliability, would need to be considered in the selection process. These include cost, socio-economic factors, and environmental impacts, among others. This process of 'planning under uncertainty' can be compared with the existing methodology where the water management strategies are designed to meet a single water-need projection (not a range of water needs with given likelihoods).

The following sub-sections describe these two steps in more detail. Section 3.1 presents approaches for quantifying uncertainty as it pertains to demand and supply. Section 3.2 describes the methodology to assess the reliability of a given water plan. Section 3.3 discusses the framework to optimize the water management plan to meet a certain desired level of reliability.

3.1 Uncertainty Quantification

Prior to analyzing the impact of uncertainty on the water planning process, it is necessary to quantify the main sources of uncertainty as related to the water plan. The main goal in water supply planning is to propose a group of water management strategies that can collectively meet a certain projected water need in the future. As discussed earlier, there are three main drivers in the selection of these strategies: future demand for water, future supply (the difference of these two gives the water need – when demand is more than supply), and the additional supply that is expected from the water management strategies considered. The process of uncertainty quantification consists of defining and quantifying the main uncertainties in these components.

> ***Uncertain Variable**: A quantity whose value is not known with certainty. For example, future population may be considered an uncertain variable as it is not known exactly what the population will be in the future.*

The approach followed here is to define discrete alternative scenarios for **uncertain variables** that are used as inputs in predicting demand or supply (such as future climate, population, water usage, etc.). The scenarios are considered **mutually exclusive** (i.e., it is not possible for two scenarios of a given event to occur simultaneously) and **independent** (i.e., the occurrence of one scenario does not influence the occurrence of another scenario). Combining and aggregating the scenarios for different inputs allow one to develop alternative scenarios for demands, supplies, and needs. Where possible, probabilities may be assigned to these scenarios to reflect the relative likelihood of occurrence of one scenario over another. As mentioned earlier, another way to characterize uncertainty would be to use ‘continuous probability distributions’ for the uncertain variables. Continuous probability distributions represent the probabilities across the entire range of the uncertain variable in a functional form instead of as discrete outcomes. For the purposes of this study, it was determined that using discrete scenarios would be more conducive and intuitive for the water planning process, and thus this technique is used in this methodology section.

Broadly speaking, three ways of quantifying uncertainty have been proposed in this report:

- Develop multiple scenarios with different assumptions for underlying factors and use these to quantify uncertainty in future projections. This is a useful approach when one or a few underlying factors (such as climate trends for supply or migration rates for municipal demands) are known to contribute most significantly to the uncertainty. This is the approach used for characterizing the uncertainty in water supply (due to climate change) and in the population projections used for estimating municipal demand.
- Compare past projections to actual data, and use the ‘misfit’ to bound the uncertainty of future projections. This is a useful approach when it is difficult to separate the underlying uncertain factors in projections. This is the approach used for characterizing uncertainty in irrigation demands.
- Assess the historic variability for a particular demand factor and use this to quantify the uncertainty in the future projections. This approach is appropriate for factors that: a) display inherent variability in time or space, and b) are based on surveys or historical data instead of depending on a mathematical model. This is the approach used for characterizing the uncertainty in per-capita usage rates (used for municipal demand).

Each of these approaches has been highlighted in different sub-sections below. It is important to note that these are not the *only* techniques for quantifying uncertainty (many other very sophisticated techniques, such as Monte Carlo simulation, exist), but are rather those that were thought to be the most easily applicable to the current water planning framework.

The following sub-sections give further details on the process for quantifying uncertainty in supply, demand, and strategy yields, respectively.

3.1.1 Quantifying Uncertainty in Supply

The current process for water planning relies on estimates of water supplies over time. The overall supply to an entity may encompass supplies from groundwater, streamflow, and other surface water sources.

Depending on the assumptions made about the future state of the water supply sources, there can be multiple sources of uncertainty that may need to be accounted for. It is important to acknowledge upfront that in most cases, it is infeasible to try to quantify all possible sources of uncertainties. The focus should be on the areas of uncertainty which would create the largest impact on the forecasted outcome and/or which typically dominate the other (less significant) uncertainties in the forecast model for water supply. For example, with surface water supply estimates, consideration of the possible range of future states of climate conditions such as temperature, precipitation, and wind may have a greater impact on the estimates of future supply than the uncertainty due to the mathematical representations of weather in any particular climate model. On the other hand, groundwater resources may be impacted less significantly by future climate uncertainty than by the uncertainty for quantifying the model's parameters of the physical characteristics of the aquifer. The onus is on the expert(s) undertaking the analysis to make the selection of uncertain factors in a relevant and meaningful manner.

As discussed in Section 2.2, the most significant uncertainties in water supply predictions are related to: a) assumptions regarding future climate conditions, and b) approximations and parameters in the mathematical model used for predicting water supply. The following chapters outline the approach to quantify each of these two types of uncertainty.

3.1.1.1 Uncertainty in Future Climate Conditions

As discussed in Section 2.2.1, there are two major sources of uncertainty in predicting future climate conditions: a) uncertainty in the models used to predict climate change; and b) uncertainty in the factors (especially carbon emissions) that will likely impact future climate. Figure 3-2 shows one way to incorporate these uncertainties into projections for future surface water supplies. The first step is to select a suite of appropriate models that can be used to

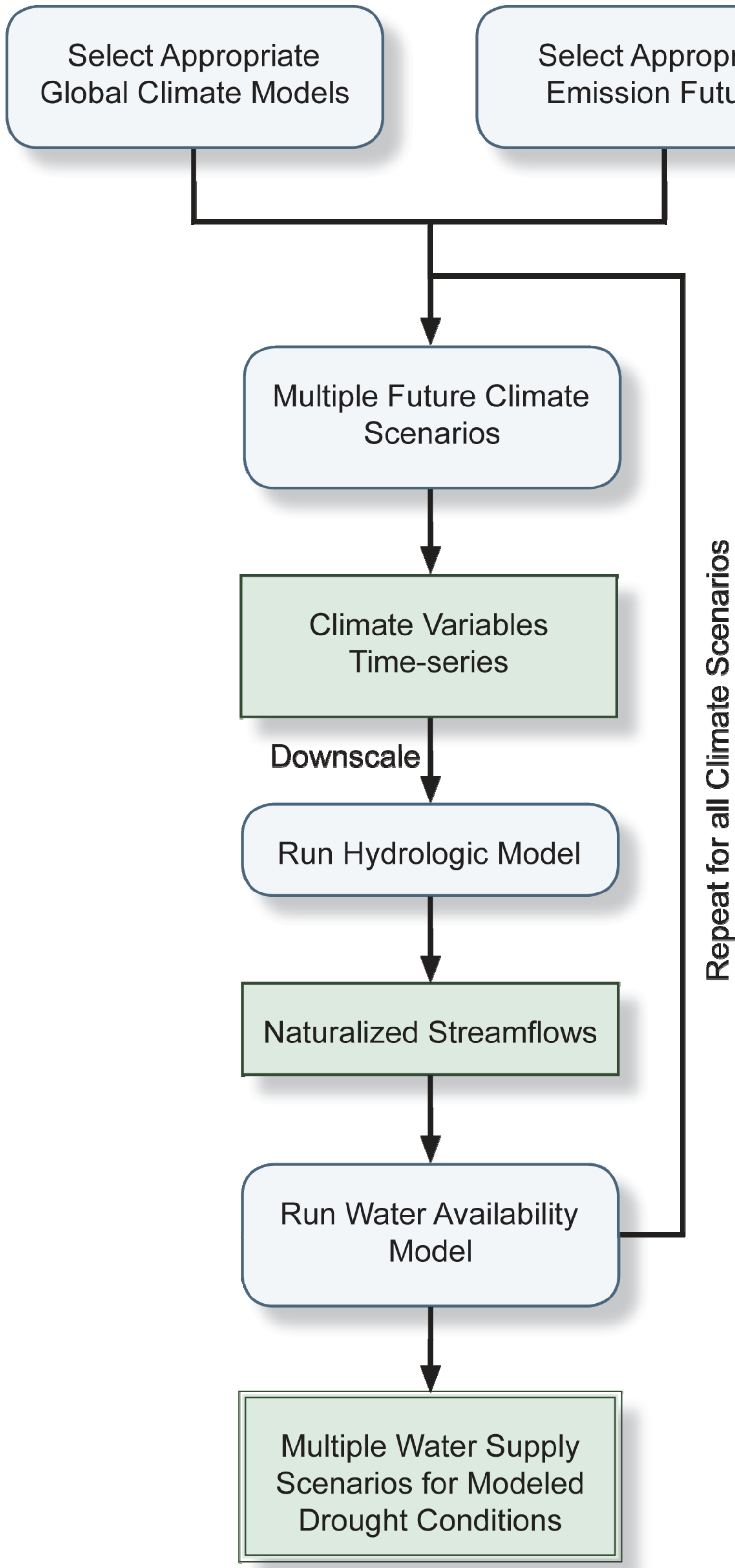

Figure 3-2 Framework for quantifying climate uncertainty.

provide a range of plausible predictions for climate change. Models should be chosen so that they represent the best knowledge about pertinent climate trends while adequately representing the variability in the predictions of interest (such as precipitation and temperatures). Next, multiple 'emission futures' need to be selected (assuming carbon emissions are the main driver of climate change) to feed into the global climate models. These emission futures depend on assumptions of how society, at large, will respond to climate change.

These multiple emission futures can then be run with multiple global climate models to come up with an ensemble of 'climate scenarios' that can be assumed to represent the uncertainty in future climate conditions. Note that the more 'climate scenarios' that are used, the better the characterization of uncertainty will be. Thus, it is recommended that *all* available information be utilized in coming up with these climate scenarios.

It is possible to ascribe likelihoods to each of the climate models typically by assuming that climate scenarios that show large discrepancies with existing data may be deemed less likely than those that are most consistent. However, it is not recommended to assign quantitative likelihoods without strong scientific justification as this may lead to biased results. It is preferable (and more conservative, from a decision-making perspective) that each model and scenario be treated as equally plausible and be given equal likelihood – this is the approach followed in this report.

Once climate models and emission futures have been combined to yield multiple climate scenarios, they may be used to predict future water supplies. Each climate scenario typically includes time-series projections of monthly mean climate variables, such as temperature, precipitation, wind, etc. In cases where the time or space scale of these predictions is too large for the water management area, they may need to be **downscaled** to a desired scale. Once future climate related time-series (temperature, precipitation, wind, etc.) have been obtained at the desired scale, a hydrologic model can be run to assess the response of water resources to the climate conditions.

> ***Downscaling**: The process of extracting information at a finer resolution – in space or time – from large-scale dataset. For example, downscaling could involve estimating monthly rainfalls from annual rainfall projections.*

The hydrologic model takes the climate variables (rainfall, temperature, wind, etc.) and routes and balances water across different water resources and hydrologic processes, taking into account factors such as rainfall runoff, stream routing, evapotranspiration, surface water evaporation, interception, infiltration, soil moisture, among others. The hydrologic model can be used to predict naturalized streamflows (similar to those used in the current planning framework discussed in Section 2.1) for different climate scenarios. These naturalized streamflows can then be used as inputs into the WAM, along with the respective data on net evaporation-precipitation, to estimate available water supplies (under various physical and legal constraints). To mirror the 'drought of record' standard that is used in the current planning framework, water availability predicted by the WAM should be based on a 'firm yield' analysis, which estimates the maximum water that can be supplied consistently across the modeled period of record. The limiting water supply will typically correspond to the driest conditions (drought) in the modeled period. This process repeated for all climate scenarios yields multiple projections of water supplies in a protracted 'drought period' under different future climate conditions. Note that these projected droughts may or may not be worse than the drought of record.

While, the methodology detailed above is for surface water supplies, it can be easily extended for groundwater supplies. Climate can have an important impact on recharge and evapotranspiration for groundwater aquifers (especially shallow aquifers). Thus to develop groundwater supplies for different climate scenarios, the climate variable time-series (with precipitation and temperatures) would need to be converted into inputs (such as recharge and potential evapotranspiration rates) for the groundwater availability model being used. Multiple groundwater supplies could then be estimated for the DFCs (see Section 2.1 for details) for a range of future climate conditions in a similar manner as for surface water supplies.

The framework described in Figure 3-2 depends on multiple climate models and carbon emissions. Much of this data can be obtained from work done by researchers and scientists across the world. The following paragraphs provide references and resources for procuring this information.

The Intergovernmental Panel on Climate Change[3] (IPCC) has evaluated and archived models developed by multiple research agencies across the world and used to produce hundreds of

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[3] The IPCC was established by the World Meteorological Organization and the United Nations Environmental Program to assess scientific information on climate change. The IPCC publishes reports that summarize the state of the science.

simulations of past and future climates. The World Climate Research Program's (WCRP's) Working Group on Coupled Modeling (WGCM) has helped to coordinate these activities through the Coupled Model Inter-comparison Project (CMIP) initiative (see Meehl and others 2007). This collection of (constantly updated) models, officially known as the *WCRP CMIP multi-model dataset*, has been archived by the Lawrence Livermore National Laboratory's PCMDI and is available for free and non-commercial use.

To deal with uncertainty in future emissions the IPCC has developed a number of alternate futures such as was presented in a Special Report on Emission Scenarios (SRES) for the Third Assessment Report (AR3) (PICC, 2000; IPCC, 2001). This report presented multiple (40) emission scenarios each based on different assumptions for greenhouse gas pollution, land-use, and other driving forces from future technological and economic development. An overview of these scenarios can be obtained from http://sedac.ciesin.columbia.edu/ddc/sres/.

These two sources of uncertainty have been combined in the IPCC's Fourth Assessment Report (AR4) (Meehl et al., 2007) which presents results for multiple models with different emission scenarios. Among other things, the AR4 includes all environmental variables, including precipitation and temperature changes computed for 112 projections using 16 different AOGCMs (atmospheric-ocean general circulation models – another term for global climate models), 3 different carbon emission scenarios developed by IPCC, and multiple 'initial conditions' for the models. In addition, to make their use more conducive for regional decision making, a subset of these projections have been downscaled to a $^{1}/_{8}$ degree (approximately 12 km) resolution and are available for public access at http://gdo-dcp.ucllnl.org/ downscaled_cmip3 _projections/ #Welcome.

The dataset of downscaled predictions for temperature and precipitation changes for multiple models and different carbon emission scenarios can be assumed to encapsulate the uncertainty in future climate conditions. In keeping with the methodology outlined in Figure 3-2, analysts will need to select scenarios for their region of interest. Typically, it is computationally infeasible to select all 112 scenarios. However, a subset of these scenarios can probably be chosen such that they bound the variability in temperature and precipitation predictions while realistically representing the potential for economic and social growth for the region of interest.

3.1.1.2 Uncertainty in Water Supply Modeling

Water supply projections typically rely on numerical models that predict water supply for given sets of management, climatic, and hydrologic conditions. Surface water and groundwater models have both shared and distinct sources of uncertainty. The key to incorporating uncertainty in water supply models into the regional planning process is to first identify the source of uncertainty and then to define a range of inputs/parameters or different models (with different reasonable modeling assumptions) that result in multiple estimates of water supply. These multiple water supply estimates can be assigned a weight or likelihood factor based on subjective or objective criteria. This overall methodology is similar to the one discussed for climate change in Section 3.1.1.1.

The important sources of uncertainty in surface WAMs and GAMs used as part of Texas planning were introduced in Section 2.2.2. The two major sources of uncertainty in water supply models are: a) assumptions and approximations made in the supply model, and b) inputs and parameters used with the supply models.

If the conceptual model (consisting of underlying assumptions and approximations) is thought to be uncertain, multiple models with a range of plausible conceptual assumptions may be used – for example, multiple groundwater models with varying hydrologic boundary conditions. The water availability predictions would then be made for this ensemble of models.

The uncertainty in model inputs and parameters can often be reduced by using external data to constrain the range of the values that these may take. The process of model calibration is essentially a means to reduce uncertainty in model parameters by matching model predictions with known data about the behavior of the modeled system. For example, the hydraulic conductivity used in GAMs can be 'calibrated' by matching measured hydraulic heads with those that the model predicts. The pumping distributions used in GAMs are similarly derived based on of the specified DFCs for the given groundwater aquifer. Uncertainty in model inputs and parameters can also be reduced by using direct information about these inputs and parameters. This process is often referred to as 'conditioning' inputs and parameters to data. For example, available literature values of sedimentation rates for certain types of reservoirs can be used to come up reasonable estimates for sedimentation rates to use with the WAM.

While uncertainty in inputs and parameters may be reduced by the above measures, it cannot be completely eliminated. For example, there still remains some uncertainty in calibrated models due to insensitive input/parameters and errors in field observations. The non-uniqueness in pumping distributions for GAMs has already been discussed in Section 2.2.2. In such cases the model can be run with different plausible input/parameter values producing a range of predictions within some acceptable performance threshold. Examples include using multiple hydraulic conductivity fields for GAMs within a maximum calibration error or using a range of plausible pumping distributions all of which meet the DFC for a given GAM. Where possible, these input/parameter combinations can be weighted by giving a higher weight (likelihood) to the scenarios that better match available historical records.

These different layers of uncertainty may be combined by using a nested approach – multiple conceptual models run with multiple inputs/parameters. Obviously, such an approach imposes a significant computational burden and may not be feasible in many cases. In such cases, it is recommended that only the more significant sources of uncertainty be characterized. As an example, a particular groundwater availability model may have a reasonably well-defined conceptualization (boundary conditions, aquifer structure, etc.), while hydraulic conductivity (an important hydrogeologic parameter) is ill-defined due to lack of data. In this case, it would be recommended to assess the uncertainty in aquifer parameters only by using a single groundwater model with multiple aquifer conductivity fields and weighting the predictions based on the fit with measured groundwater heads.

3.1.2 Quantifying Uncertainty in Demand

The current model for water planning is based on projected demand for water. Water demand projections are typically calculated separately for different use-types such as municipal, industrial, irrigation, livestock, and steam-electric. Each of these water demands depend on a number of factors: projections for population and per-capita usage of water for municipal demands; economic growth and energy prices for industrial demands; agricultural growth, farming practices, crop types, and energy prices for irrigation demand. A lot of thought and work go into calculating demand projections. However, even the best of projections are not guarantees of what the future holds. Thus, there is a need to assess and quantify the uncertainty in these projections.

The rest of this chapter is organized into two sub-sections that address uncertainty in the two most significant demand categories for the state of Texas – municipal and irrigation water demand. Other categories for water demand include industrial (manufacturing and mining), steam-electric, and livestock. In most cases, these do not form a significant proportion of a region's demands, and it can be argued that the uncertainty in municipal and irrigation demand would overshadow the uncertainty in these other demand categories.

3.1.2.1 Uncertainty in Municipal Demand

Municipal demand is dependent on two major factors – population and per-capita usage (total municipal water use divided by the total population). The methodology to come up with a projection for municipal demand is to first select an appropriate population projection for the region of interest and then estimate future per-capita usage in the area. Multiplying population with per-capita usage gives the total municipal demand. Since both the population projection and per-capita usage are estimates, they are inherently uncertain.

Uncertainty in population projections may be quantified following an approach similar to the one proposed for quantifying climate uncertainty. Multiple scenarios with different birth, death, and migration rates are selected, and different population projections are calculated using these rates. As discussed in Section 2.2.3, migration rates are most susceptible to uncertainty, and thus, can be assumed to be the only uncertain factor in population projections. Thus, birth and death rates could be assumed to be known, and a range of plausible migration rates can be used to come up with multiple population projections. Another approach would be to compare past population projections with actual population data and use the difference to characterize the uncertainty in future projections. The latter approach is the one used to characterize irrigation demand uncertainty and is not discussed in this section to reduce redundancy. The interested reader is referred to the section on irrigation demand (Section 3.1.2.2) for further details.

The Texas State Data Center (TxSDC) publishes population projections of the state and all counties in the state by age, sex, and race/ethnicity. The 2008 methodology for coming up with the population projections can be obtained at http://txsdc.utsa.edu/tpepp/2008projections/. The TxSDC also publishes different scenarios of population growth. These scenarios are based on different assumptions of migration rates since this is the dominant source of uncertainty for population projections in Texas. In the 2008 TxSDC data, for example, four migration scenarios are considered – no migration, migration at half the 1990-2000 migration rate estimate, migration at the 1990-200 migration rate estimate, migration at the 2000-2004 migration rate estimate, and migration at the 2000-2007 migration rate estimate. There were years of extensive growth from 1990 to 2000 in most counties in Texas and is thus likely to be an upper bound on migration rates. The 2000-2004 migration estimate is meant to be indicative of more recent trends in population growth (after the period of rapid growth from 1990 to 2000). The 2000-2007 record is also an updated migration record, except that it includes substantially elevated migration into most counties after hurricane Katrina struck the Central Gulf Coast in 2005. Apart from the TxSDC, other planning groups may have more locally specific population projections available. It is the onus of the analyst to select population projections that best reflect the potential for growth in the region of interest.

Once population scenarios have been decided upon, they can be ascribed probabilities if there is reason to believe that certain scenarios are more likely than the others. In most cases, the probabilities will be based on subjective judgment about future birth, death, and migration trends in the region of interest.

Uncertainty in per-capita usage rates has to be quantified using a slightly different approach than above. This is because per-capita usage rates are typically obtained from surveys and data-collection efforts (by local agencies such as water utilities, river authorities, etc.) and are not based on mathematical models. In this case, the variability in historic water usage data may be used to develop usage scenarios for the below-average rainfall years (recall that for planning purposes, the water supply corresponds to a protracted drought period, thus, the demand, too, should correspond to low water availability conditions). One way to come up with these usage scenarios is to look at the distribution of per-capita usage only for low rainfall years and estimate reasonable scenarios consisting of the expected, low, and high usage rates. These scenarios can then be used to characterize the uncertainty in per-capita usage rates. As for population projections, it is possible to ascribe likelihood to these usage scenarios – either based on expert judgment or using statistical methods on the dataset used to come up with the scenarios. As an example, Figure 3-3 below shows the water usage rates in gallons per capita per day (GPCD) for a hypothetical water user entity for the last 25 years. Years with above-average water use (175 GPCD) are shown in red, and years with below-average water use are shown in blue. The average usage rate is used as a threshold to separate the low-rainfall usages from the rest of the dataset. Assuming that above-average water usage corresponded to low rainfall years (one could also compare the water use data with rainfall records for this purpose), the water usage rates shown in red can be used to assess uncertainty in water demand for drought conditions. In this case, the upper bound for this subset (water usage for low-rainfall conditions) is given by 220 GPCD, the lower bound is given by 180 GPCD, and the average is given by 188 GPCD. These levels are shown by the red, blue, and green dashed lines respectively.

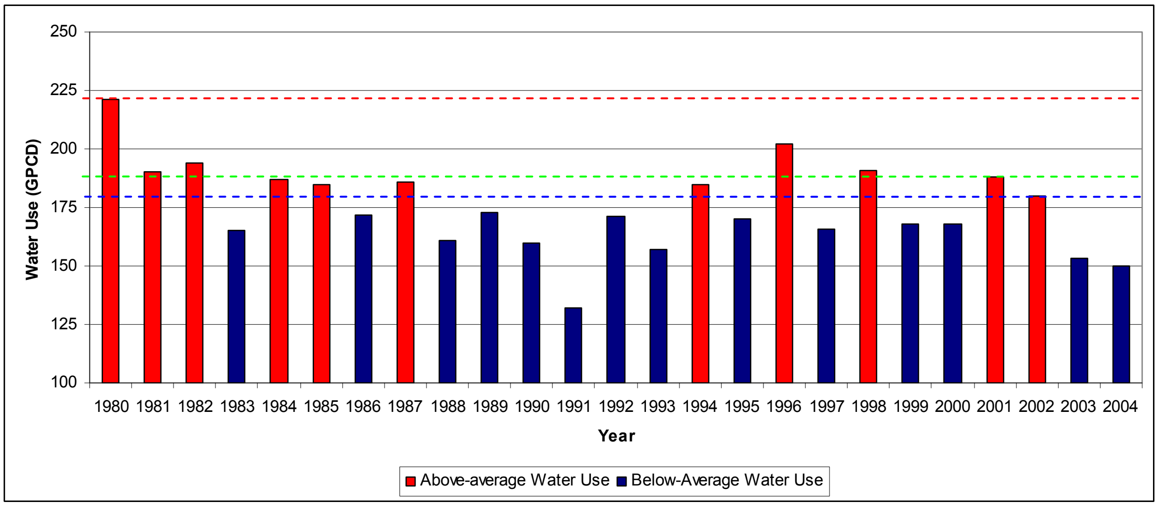


Figure 3-3 Assessing uncertainty in water usage rates for low-rainfall years.

Once the population and usage scenarios have been selected, these can be combined by multiplying each population estimate with the different usage rates to come up with an ensemble of demand scenarios. The probability for a particular demand scenario is given by multiplying the probabilities of the corresponding population and usage rate. This process is shown in Figure 3-4 below, where three population scenarios (using different migration rates) and three usage rates (minimum, average, and maximum) are used to yield a total of nine (3x3) demand scenarios. The three population scenarios have probabilities 0.2, 0.6, and 0.2, respectively, while the usage rates have probabilities 0.1, 0.8, and 0.1 (note that the sum of all probabilities for a set of scenarios should be equal to 1). These probabilities are multiplied to give the demand scenario probabilities showed at the bottom of Figure 3-4 (these probabilities should also sum to one over all demand scenarios).

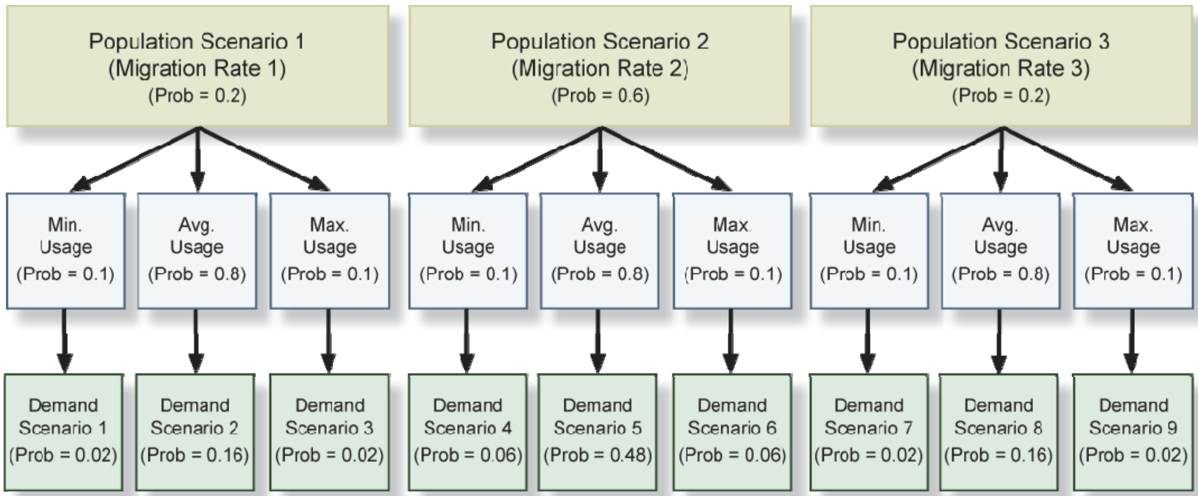


Figure 3-4 Calculating demand scenarios from population and usage rates.

3.1.2.2 Uncertainty in Irrigation Demand

The process of projecting irrigation demand (see Section 2.2.3 for details) for the future depends on multiple factors such as future crop prices, energy prices, land and water availability, and changes in agricultural practices, among other things. Many of these factors are highly volatile and thus subject to large uncertainties in the future. Due to the complexity of the approach using a piece-wise uncertainty quantification approach similar to that used for municipal demands (wherein the uncertainty in each contributing factor would be individually assessed and then combined with others), it would be very difficult to address irrigation demand projections. One way to address the uncertainty in irrigation water demand projections is to compare past projections with actual water use. This gives a measure of the discrepancy between projected estimates and actual water use. In the past, water plans have predicted irrigation water demands based on optimistic or pessimistic market conditions. For example, Figure 3-5 shows irrigation demand projections and actual irrigation water usage for 20 years for a hypothetical region. As can be seen, the projections are sometimes above and sometimes below the true irrigation usage. For each year, the difference in the projected and actual water usage can be calculated and is shown in the second graph in the figure. For this example, reasonable upper and lower bounds for the difference would be 5000 acre-feet/year (ac-ft/yr). Using the bounds on the difference between projected and actual water use, low, medium, and high scenarios can be developed and are shown on the third graph in the figure. The medium scenario is the default projection, the low scenario is the default projection minus 5000 ac-ft/yr (the lower bound on the difference),

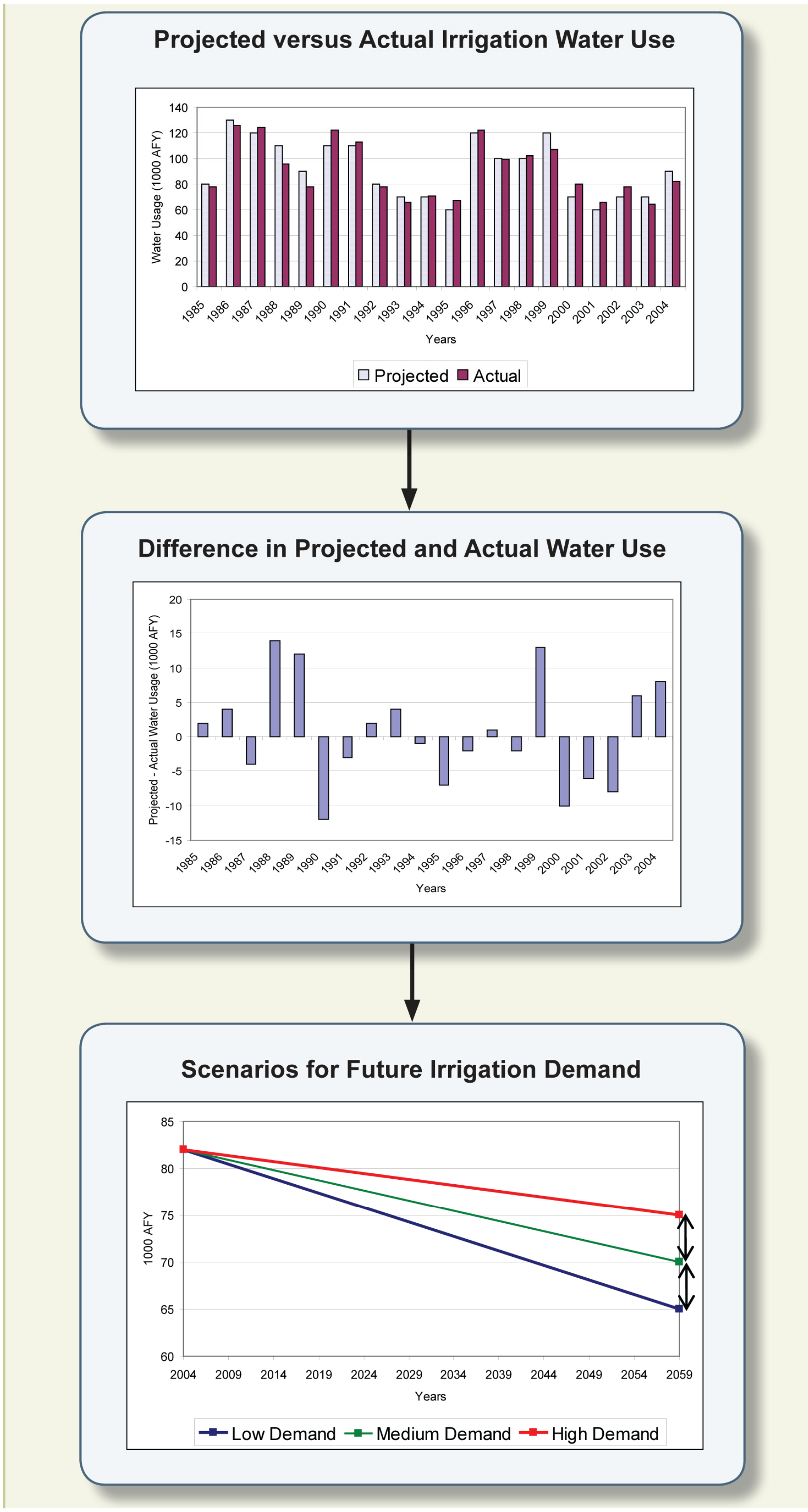


Figure 3-5 Quantifying demand uncertainty using past projections and usage data.

and the upper scenario is the default projection plus 5000 ac-ft/yr (the upper bound on the difference). As before, likelihoods can be ascribed to these scenarios using either subjective judgment or information from the data. For example, for 5 out of the 20 years, the difference between projected and actual use was 5000 ac-ft/yr or more, for 5 out of the 20 years, the difference was -5000 ac-ft/yr or less, while for the other 10 years the difference was within 5000 ac-ft/yr. Thus, reasonable likelihoods would be 5/20 (0.25) for the upper demand scenario, 5/20 (0.25) for the lower demand bound, and 10/20 (0.5) for the medium demand scenario.

A word of caution, the methodology described above is best applied when there is not a wide discrepancy in projected and actual water usages. In cases where these differences are very large, it may be best to either: a) improve the projection methodology, or b) use the default projection and update it frequently as more data becomes available. As an example, the irrigation projections for the 1984 water plan assumed highly favorable market conditions and projected irrigation demand in 2000 to be 16 million acre-feet, about 60 percent more than the actual 2000 irrigation water use (10 million acre-feet). Conversely, the 1990 state water plan assumed pessimistic conditions and projected the 2000 irrigation water use to be 7 million acre-feet about 30 percent less than the actual 2000 irrigation water use. Given the wide discrepancy seen between irrigation demand projections and actual irrigation use, the 2007 state water plan recommended using the status quo rather than projections based on optimistic or pessimistic market assumptions and adjusting the projections (if need be) in every 5 year water-planning cycle.

3.1.3 Quantifying Uncertainty in Future Water Needs

Water needs arise when demand is more than supply and is defined as the difference between the demand and the supply for water. A water surplus arises when supply is more than demand. Projected water needs are essential to the water planning process as planners come up with different water management strategies to fulfill these needs. The approach discussed in the previous sections characterizes the uncertainty in future demands and supplies by developing alternative scenarios for demand and supply. Since there are multiple scenarios for demand and supply, there are bound to be multiple water-need/surplus scenarios. Each need/surplus scenario corresponds to a combination of demand and supply. A useful representation of these multiple possibilities is through a 'probability tree' which is shown in Figure 3-6.

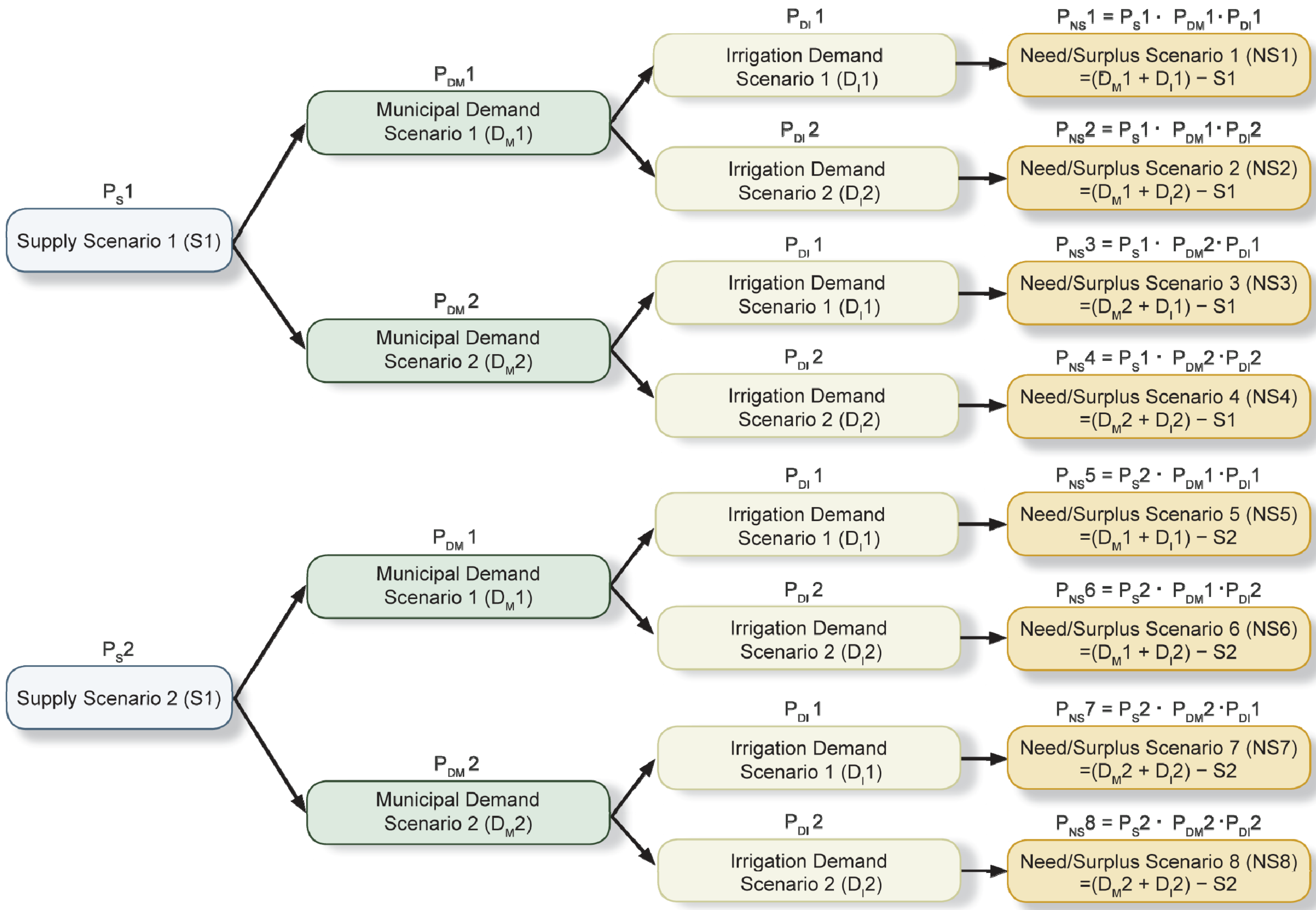


Figure 3-6 **Probability tree to show combinations of supply and demand scenarios leading to multiple water-need/-surplus scenarios.**

This simple example uses two supply scenarios, two municipal demand scenarios, and two irrigation demand scenarios. For each demand and supply, a corresponding probability is shown in grey above it. Each 'path' down the tree represents one possible future outcome for water need/surplus. As can be seen, the need/surplus for each outcome is the total demand (sum of municipal and irrigation demand) minus the total supply (positive numbers represent need, while negative numbers indicate surplus). Since there are two supply scenarios, two municipal demand scenarios, and two irrigation demand scenarios, there are a total of eight (2×2×2) need/surplus scenarios possible. The probability for a particular need/surplus scenario is the product of all the corresponding demand and supply probabilities that lead to that need/surplus. The sum of the probabilities for all the need/surplus scenarios should also equal to one.

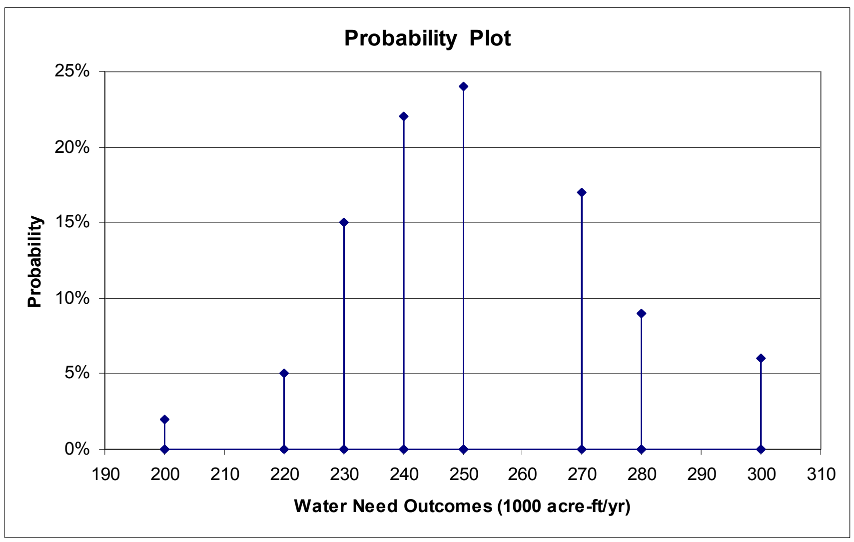
Once all the need/surplus scenarios have been calculated with their corresponding probabilities, they can be aggregated into a 'discrete probability' plot. The probability plot shows the relative likelihoods of different (discrete) need/surplus outcomes. Another useful tool to visualize the uncertainty in the projected needs/surplus is the '**cumulative probability**' plot. The cumulative probability plot is constructed by first sorting all need/surplus outcomes by magnitude (low to high) and then successively adding the probabilities from low to high values. The cumulative probability for a given need or surplus value denotes the probability that the need/surplus will be less than or equal to that particular value. Cumulative probabilities at intermediate points are calculated by interpolating between the two nearest sample points. As an example, consider the water needs (for the sake of simplification only needs, not surplus, are shown here) and probabilities shown in Table 3-1 below.

> ***Cumulative Probability**: The probability that an uncertain variable is less than or equal to a specified value.*

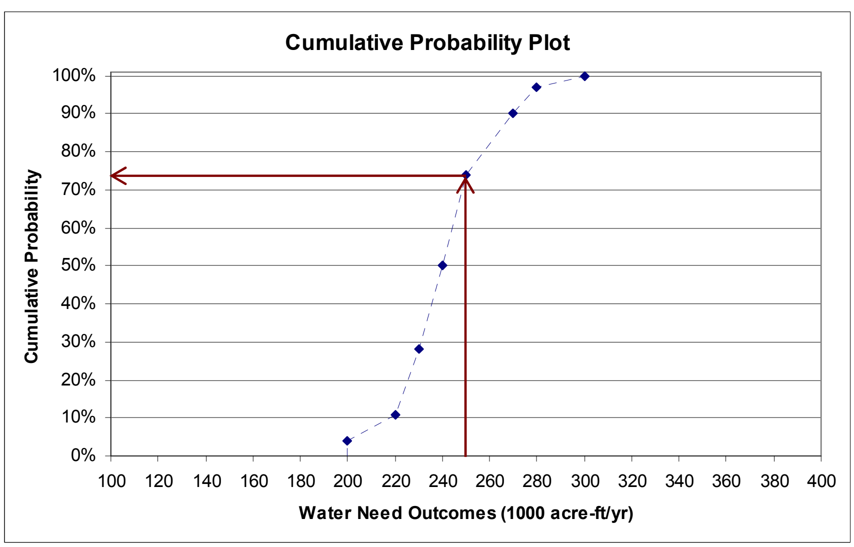
Table 3-1 Example water-need scenarios and probabilities.

Scenario #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Water Need (1000 ac-ft/yr)	200	220	230	240	260	270	280	300
Probability	0.02	0.05	0.15	0.22	0.24	0.17	0.09	0.06

The two kinds of probability visualization tools for this example are shown in Figure 3-7. The first graph in the figure is a probability plot and the second graph is the cumulative probability plot for the 8 hypothetical need scenarios (the dashed line shows the linear interpolation line between the 8 scenarios). The cumulative probability plot is particularly useful in decision making, as it can be used to assess the probability that projected water need is less than or equal to some given amount. For example, in the cumulative probability plot in Figure 3-7, there is a 74 percent probability (based on all the demand and supply scenarios and associated probabilities) that the water needs will be less than or equal to 250,000 ac-ft/yr.



(a)



(b)

Figure 3-7 Plotting (a) probabilities and (b) cumulative probabilities for water need outcomes.

3.2 Planning Under Uncertainty

Once the uncertainties in demand, supply, and water needs have been characterized and quantified, this information can be used in the water planning process in various ways. This chapter discusses some ways that the quantified uncertainty can be incorporated into the water planning process for the state of Texas.

> ***Deterministic Planning**: Planning without the consideration of randomness or uncertainty. Strategies are proposed to meet goals for a fixed outcome.*

> ***Planning Under Uncertainty**: Planning that considers randomness or uncertainty in the decision-making framework. Strategies are proposed to achieve an acceptable level of reliability for meeting goals for a range of possible outcomes*

Figure 3-8 compares the (existing) '**deterministic planning'** framework (described in Section 2.1) with '**planning under uncertainty**'. The deterministic paradigm assumes that the information used in the planning process is certain and complete and thus starts with a deterministic estimate for future water need. Sets of strategies are then assessed to see if their combined yield meets the projected water need, while also satisfying criteria related to costs, socio-economic concerns, environmental impacts, political feasibility, among others. Planning under uncertainty can mirror this process closely. A key difference in the methodology for planning under uncertainty, however, is that it considers multiple alternatives for future water needs rather than the single water-need projected used in deterministic planning. With uncertainty in the planning framework, it becomes necessary to acknowledge that there may be certain scenarios when projected water needs may not be met by the proposed set of strategies. Different water management strategies can then be assessed for their '**reliability**' with respect to the uncertainty in the demand and supply projections. Here reliability is defined as the probability that a certain strategy (or set of strategies) meets the range of water-need projections. The goal of the planning process then is to identify strategies that have an acceptable level of reliability (i.e., there is a sufficiently high likelihood of meeting projected water needs) while also accounting for other important criteria like cost, yield, impact to the state's water, agriculture, and natural resources.

As discussed in the earlier section, the uncertainty in future water needs can be visualized using the cumulative probability plot. Once this has been developed, the combined yield for a set of strategies can be assessed for its reliability of meeting projected water needs. If the reliability is

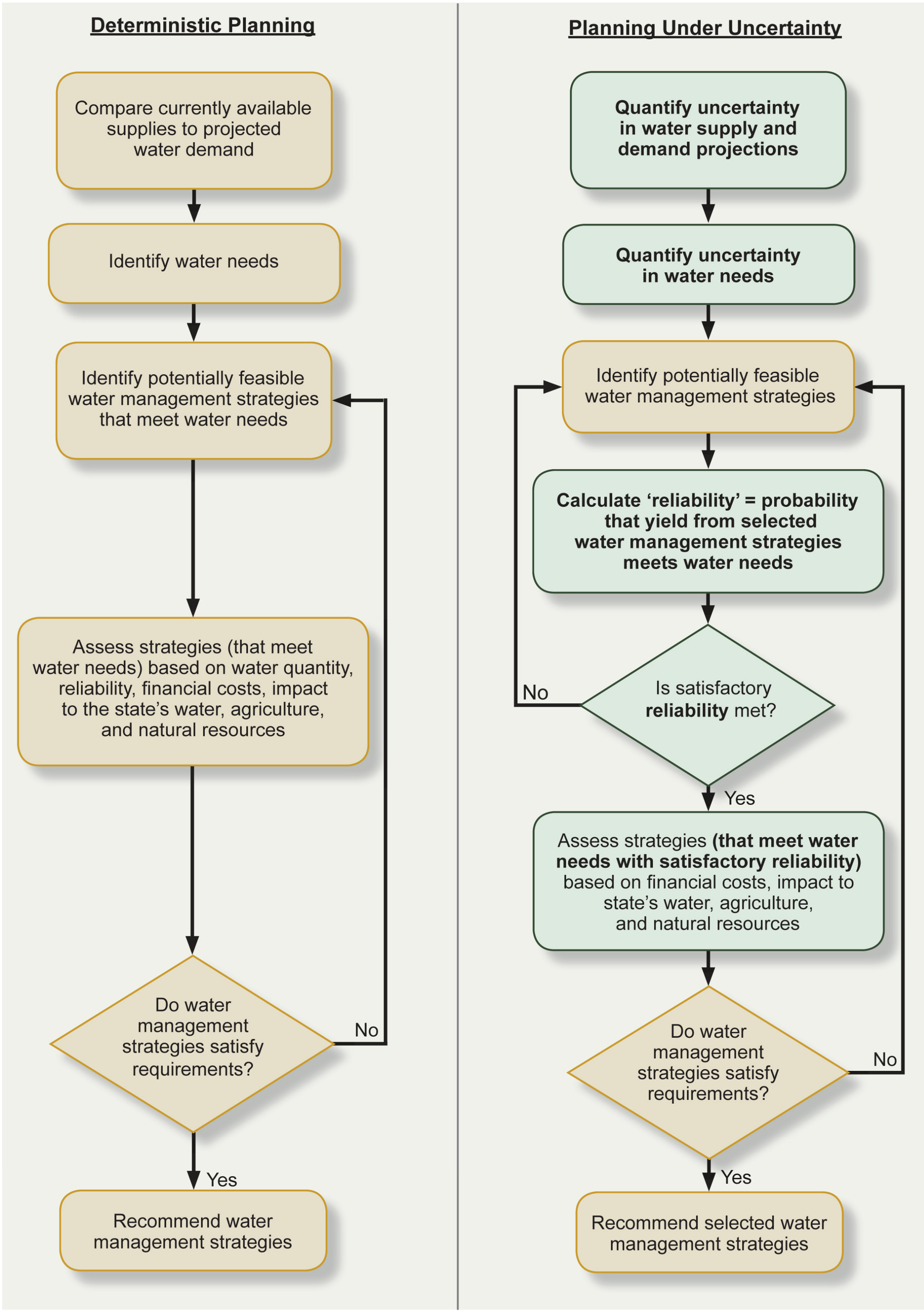


Figure 3-8 Deterministic versus uncertainty-based water planning frameworks.

deemed too low then other sets of strategies with higher yields, which lead to better reliability, may need to be considered. Finally, trade-offs in the various factors such as costs, yields, reliabilities, project feasibility, socio-economic and environmental impacts, among other considerations will need to be considered before proposing a set of strategies. In conclusion, the fundamental difference between planning under uncertainty with the deterministic planning framework is that the driver in the planning process is the reliability of meeting projected water needs instead of a single deterministic water need projection.

It is important to note that the choice of an acceptable reliability level is a decision that can depend on various factors including the risk-averseness of decision-makers, confidence in the uncertainty quantification process, and other subjective considerations.

The following sub-sections address two key components of planning under uncertainty in more detail: a) assessing reliability of strategies, and b) selecting strategies to improve reliability..

3.2.1 Assessing Reliability of Water Management Strategies

As mentioned earlier, the cumulative probability plot for projected water needs/surplus can be a useful tool for assessing the reliability of water management strategies. The probabilities, displayed in the cumulative probability plot, represent the probability that the uncertain variable (need/surplus in this case) is less than or equal to a certain value. Using this information, the reliability of a set of water management strategies can be assessed by comparing the combined yield with the water need (strategies would rarely be proposed for surpluses) cumulative probability function This is done by reading the cumulative probability of the yield (for the water management plan) from the water-need cumulative probability plot. Using the example shown in Figure 3-7, if the yield of a water management plan was calculated to be 250,000 ac-ft/yr, the probability that projected water need would be less than or equal to this yield (or conversely, that the yield would be more than or equal to that water need) is 74 percent as shown in Figure 3-7. Thus, there is a 74 percent likelihood (based on the alternative scenarios and probabilities used to characterize demands and supplies) that the water management strategies would meet projected water needs. In other words, the water management strategies have an 74 percent *reliability* of meeting projected water needs. Using this approach, the reliability of the yield from any collection of water management strategies can be assessed vis-à-vis the water-needs distribution.

Note that this reliability is *strictly* with respect to the defined scenarios and ascribed likelihoods. If one were to change the scenarios or the associated likelihoods, the reliability may change. This is especially true when only a few scenarios are used. In general, as more scenarios with better defined probabilities are used, the reliabilities become less dependent on the individual scenarios.

3.2.2 Selecting Water Management Strategies under Uncertainty

In cases where the assessed reliability for a set of water management strategies is deemed too low, additional or alternative strategies can be added to increase the yield and improve the reliability. Strategy selection is a complex and subjective process that takes into account multiple factors – strategy costs, strategy yields, environmental impacts, feasibility of proposed strategies, political and policy constraints, and impacts on multiple (often conflicting) stakeholders. The goal is to satisfy the different criteria while meeting projected water need.

One way to incorporate uncertainty in the selection process is to first list a number of alternative sets of feasible strategies. The reliabilities for each set of strategy can then be assessed from the cumulative probability plot, and these reliabilities can then become a factor (in addition to other factors such as cost, environmental impacts, socio-economic concerns, political feasibility, etc.) in the decision-making process. Figure 3-9 shows an example of calculating the reliability for a given yield from a set of strategies. In this example, the yield from the set of strategies is 260,000 ac-ft/yr. The reliability that this yield will meet projected water needs as characterized in the cumulative probability plot is read off as (approximately) 82 percent.

Conversely, decision-makers may also first decide on a reasonable reliability level for meeting projected needs. Once this reliability level has been decided upon, the cumulative probability plot can be used to find the associated water need that must be met by water management strategies to obtain that reliability level. Figure 3-10 shows the same cumulative probability plot as Figure 3-9 but this time with a reliability target of 90 percent, which corresponds to a water need of 270,000 ac-ft/yr.

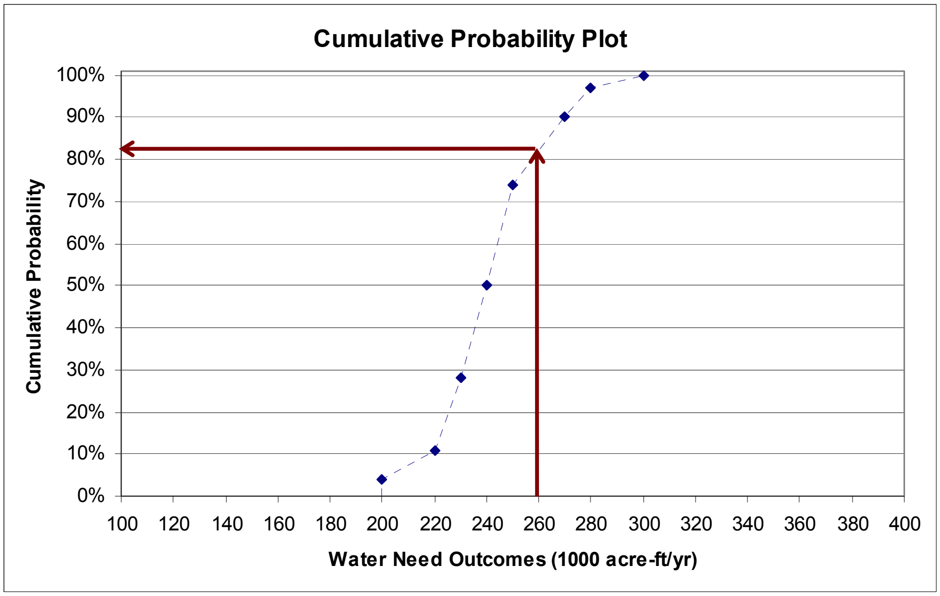


Figure 3-9 **Reading reliability for a given yield from the water-need cumulative probability plot.**

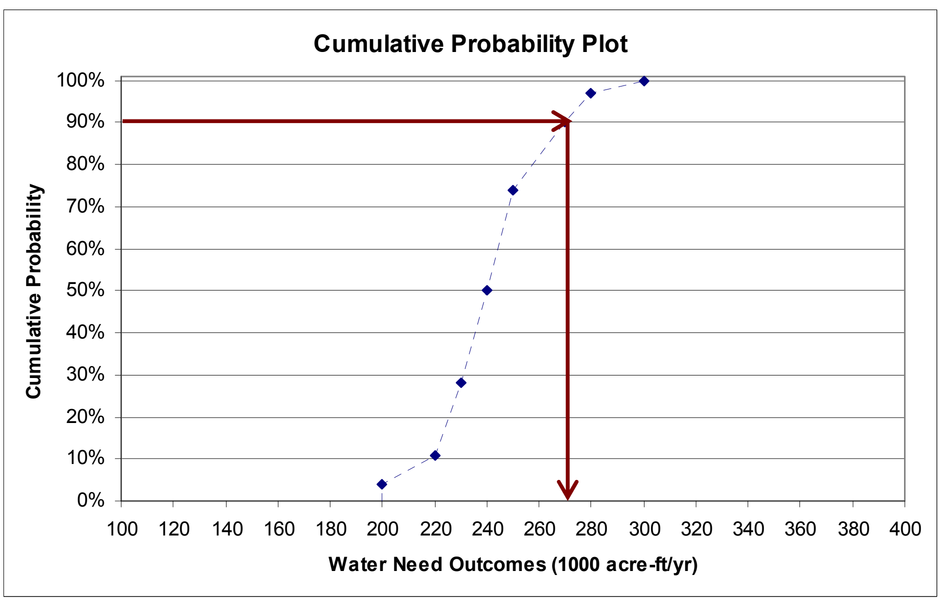


Figure 3-10 **Reading the water need that must be met by water management strategies for a given reliability level.**

Any set of water management strategies that yield 270,000 ac-ft/yr or more of water or more will ensure at least 90 percent reliability (based on the demand and supply scenarios and associated likelihoods). This water need associated with the target reliability level can then be used as the target yield for water planning purposes, and strategies can be selected to meet this water need while also considering the other multiple factors that inform the decision making process. In the process of going through the strategy selection process, it may be necessary to update the target reliability level to accommodate for the other factors considered in the decision-making process.

When comparing alternative strategies, a useful tool to assess the relative value of one set of strategies versus another is the 'trade-off curve'. A Trade-off curve, as the name implies, displays the trade-off between competing objectives for multiple solutions (a solution corresponds to some combination of water management strategies in this case). Solutions that are part of the optimal trade-off curve are such that it is impossible to improve on any one objective without worsening another objective. In the simplest case, if the objective is to minimize cost while maximizing reliability (or yield), the trade-off curve can be constructed by stepping through multiple reliability levels and finding the lowest cost solution that meet the associated water need (for a given reliability level). A graph of these optimal costs and reliabilities is the trade-off curve for cost and reliability. Consider a very simple example that involves only two objectives in the strategy selection process – costs and reliability with three strategies and the same water-need cumulative probability plots as shown in Figures 3-7 to 3-10. The costs and yields from each strategy are given in Table 3-2 below.

Table 3-2 Example Strategies with Cost and Yields.

Strategy	Cost ($M)	Yield (1000 ac-ft/yr)
A	1	120
B	1.5	130
C	2.5	140

As can be seen from this table, no single strategy can meet even the minimum projected water need (200,000 ac-ft/yr). Since this is a simple example, all possible combinations of the strategies can be listed. The costs, yields, and reliabilities of different strategy combinations are shown in Table 3-3. The reliability for each of the yields for meeting projected water needs are calculated from the cumulative probability plot as shown in Figure 3-11.

Table 3-3 Sets of Strategies with Associated Costs, Yields, and Reliabilities.

Sets of Strategies	Cost ($M)	Yield (1000 ac-ft/yr)	Reliability
∅ (Do Nothing)	0	0	0
A	1	120	0
B	1.5	130	0
C	2.5	140	0
A+B	2.5	250	74%
A+C	3.5	260	82%
B+C	4	270	90%
A+B+C	5	390	100%

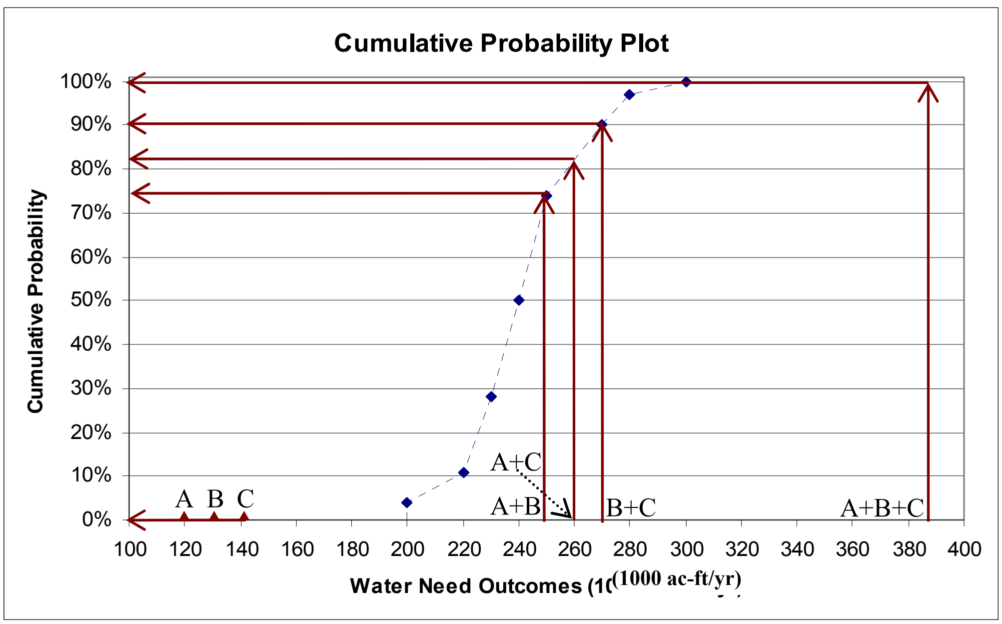


Figure 3-11 Assessing reliabilities of competing sets of strategies from the cumulative probability plot.

Figure 3-11 shows the yields and the associated reliabilities for all sets of strategies on the cumulative probability plot. As can be seen from the figure doing nothing, A, B, or C all have a 0 percent reliability (the three strategies all provide water less than the minimum expected water need, thus there is still unmet water need with either of the reliabilities). A+B gives a yield of 250,000 ac-ft/yr and this is expected to satisfy projected needs with a 74 percent likelihood. Similarly A+C has an 82 percent reliability, B+C has a 90 percent reliability, and A+B+C have a 100 percent reliability of meeting water-need projections (all three strategies together yield more water than the maximum projected water need). These costs and reliabilities can be displayed with a 'trade-off graph' as shown in Figure 3-12. From this graph, the set of strategies with the most favorable trade-offs can be identified. A strategy set can be considered having an optimal trade-off if there exist no other combinations of strategies that are better in both cost and reliability. The solutions representing the optimal trade-off for this case (considering only cost and reliability) are 'do nothing' (0 cost, 0 yield, 0 reliability), A+B ($2.5M cost, 250,000 ac-ft/yr yield, 74 percent reliability), A+C ($3.5M cost, 260,000 ac-ft/yr yield, 82 percent reliability), B+C ($4M cost, 270,000 ac-ft/yr yield, 90 percent reliability), and A+B+C ($5M cost, 390,000 ac-ft/yr yield, and 100 percent reliability). A, B, or C are not optimal from a cost and reliability perspective since they cost more than doing nothing yet do not improve the reliability.

Figure 3-12 also shows the incremental increase in reliability with more expensive strategies. The dashed lines connecting one solution to another are a visual indicator for the ratio of the increase in reliability and the increase in cost. A line with a steep slope indicates a relatively high increase in reliability for a given increase in cost, while a line with a flat slope indicates a relatively low increase in reliability while going from the cheaper solution to the more expensive one. Note, that connecting the lines would have a slope of zero or negative when the non-optimal solutions (such as A, B, and C for Figure 3-12) are connected. Traversing across these trade-off lines (from cheapest to most expensive sets of strategies), the decision maker could stop at a point where the incremental increase in cost does not correspond with an associated increase in reliability. It could be argued that for this example, the A+B solution represents a 'sweet spot' which has the most efficient trade-off between cost and reliability. The solutions A+C, B+C, and A+B+C while more expensive do not have a commensurate increase in the reliability (the rate of increase in cost is more than the rate of increase in the reliability). Of course, cost and reliability are only two of three factors for this problem. A complementary cost versus yield trade-off curve can also be constructed in the same way and is shown in Figure 3-13. This figure shows the incremental increase in yields and this time A and B do appear as part of the optimal trade-off set. Solution C, however, is still sub-optimal since there exists another solution (A+B) that has the same cost and higher yield. Solutions, such as C, that are sub-optimal in both trade-off curves can, arguably, be taken out of consideration in the planning process. Other solutions, such as A and B, that are unfavorable with respect to one trade-off while optimal for another may be considered based on the priorities of the decision-makers.

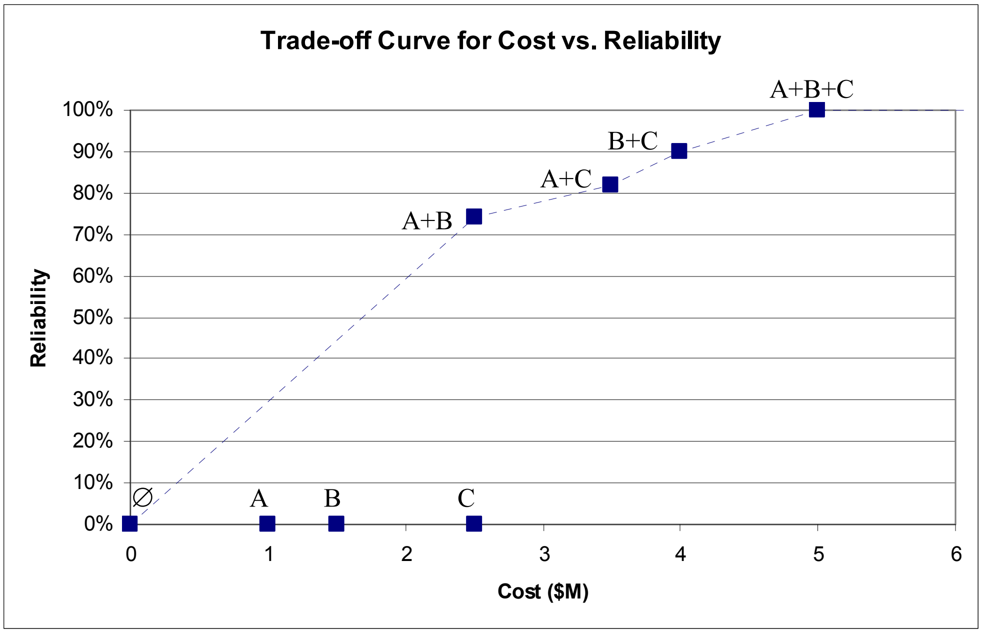


Figure 3-12 Trade-off in cost and reliability for competing sets of strategies (optimal trade-off in cost and reliability is identified with dashed line).

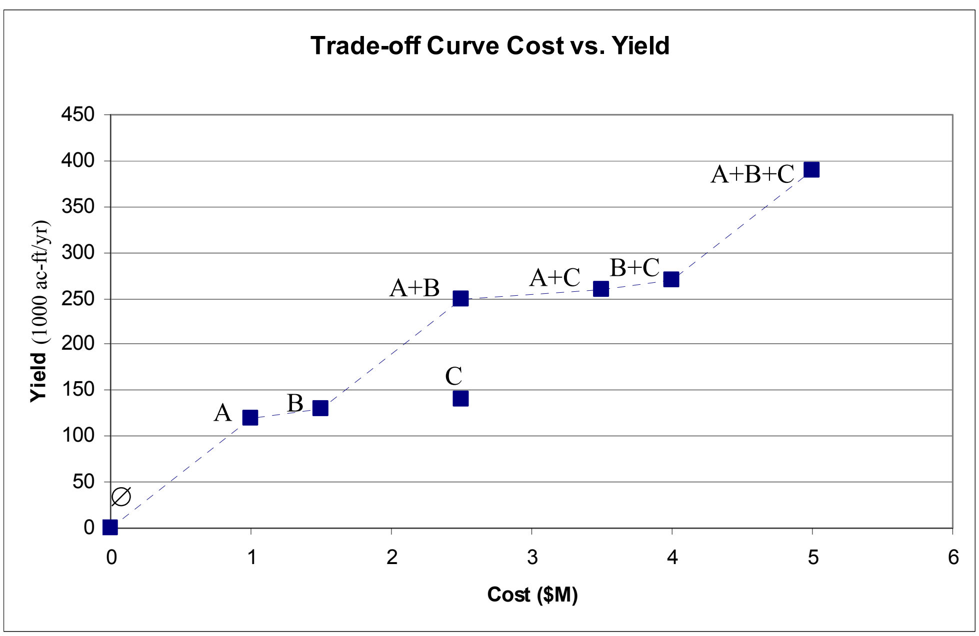


Figure 3-13 Trade-off in cost and yield for competing sets of strategies (optimal trade-off in cost and yield is identified with dashed line).

The example presented above demonstrates how reliability can be incorporated in the decision-making process while selecting alternative strategies. However, it is relatively simple compared to the actual water planning process. In reality, water management strategies are proposed to meet water shortages across multiple time horizons. Multiple objectives and constraints, such as environmental impacts, socio-economic factors, and political feasibility need to be considered while choosing between competing sets of strategies. Finally, the above methodology is based on the assumption that proposed water management strategies will provide the expected yield in the future. In reality, there are uncertainties regarding the implementation of the strategies as well as the yield from the strategy in the future.

The proposed methodology may be extended to address some of these concerns. Multiple planning horizons can be included in the analysis by calculating water-need scenarios for different time periods in the future. The reliabilities of promising sets of water management strategies would then be assessed with respect to water-need scenarios for different time horizons. Water management strategies may then be selected by considering the combined reliabilities across the planning horizon as well as other factors such as cost, yields, etc. Note that in most cases, the uncertainty in supply and demand projections tends to increase with time, thus the reliabilities for a set of water management strategies would in general decrease with time. Thus, the reliabilities for the furthest planning horizon can be taken as a limiting case (as reliabilities for shorter planning periods would tend to be higher) in the decision-making process.

Addressing the uncertainty in water management strategy implementation and yields is a more difficult process as it complicates the calculation of reliabilities. One way to include these uncertainties is to assess the resulting reliability with certain strategies excluded from the set of strategies considered. The excluded strategy would correspond to the outcome that the strategy is not implemented in the future. Thus, in the example above (Table 3-3), if strategy C is thought to have uncertainties in future implementation, the strategy set A+B+C can have two outcomes: a) C is implemented, giving a total yield of 390,000 ac-ft/yr; and b) C is not implemented, giving a total yield of 250 ac-ft/yr (this is the yield for only A+B). The corresponding reliabilities for these two outcomes are 100 percent and 74 percent reliability. Thus, it can be concluded that the reliability of meeting projected water needs for the strategy set A+B+C varies from 74 percent to 100 percent depending on whether C is implemented or not. These reliabilities can be combined to calculate an average reliability, which can be used when evaluating the proposed strategy. Alternatively, the range of reliabilities can be an additional factor, so that strategy combinations that display a large variance in reliabilities can be given a lower priority than others that are more robust with respect to implementation uncertainties.

Finally, different water management strategies can take different amounts of time to implement. Thus, water management strategies need to be prioritized such that there is sufficient time for the strategy to be implemented to meet projected water needs. The prioritization of water management strategies in time would, thus, need to consider various competing factors including: a) time of implementation, b) water-need projections for different time periods, c) budget considerations (the decision-makers may find it appropriate to wait longer to implement some of the more expensive strategies), and d) environmental as well as socio-economic factors.

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4.0 Example Application

A hypothetical case study has been developed to demonstrate the concepts presented in the previous section. While the case study is hypothetical, care has been taken to build a representative and realistic case-study. Where possible, data are taken from existing databases to better reflect the relative scales of the supplies, costs, demands, and yields involved in the water planning process. However, to simplify the analysis certain assumptions had to be made for this case study: a) the water planning process was considered for only one time horizon (2050); b) demand was assumed to consist only of municipal demand; c) supply was assumed to come only from an upstream reservoir; and d) strategy selection was based on only cost, yield, and reliabilities.

The case study steps through the process of quantifying the uncertainty in supply (primarily due to climate change), demand (primarily municipal demand), and water need. Multiple scenarios for future demand, supply, and water needs are developed. Next the process of planning under uncertainty is addressed. To establish a baseline, the deterministic water need (using the most likely water demand and supply projections) is addressed first. A water management strategy (conservation and reuse) is assumed to meet the deterministic water need projection. This represents the status-quo or the 'deterministic' water plan. To demonstrate the importance of uncertainty, the reliability of this deterministic water plan is assessed with respect to the different water need scenarios. Next, a number of water management strategies are defined with associated costs and yields. Reliabilities of promising sets of the water management strategies are assessed and the trade-offs between cost, yield, and reliability are analyzed. Information from these trade-off curves is used to recommend favorable sets of strategies. Finally, the impact of different sources of uncertainty on the reliabilities and the strategy-selection process is investigated.

4.1 Case Study Description

The case study chosen represents a hypothetical water user – the city of 'Texasville' – located in the Colorado River basin. Texasville derives its water supply from an upstream surface water reservoir located on the Colorado River. Texasville has estimated its projected water demand (primarily municipal demand) to be 270,000 ac-ft/yr in the year 2050. This demand is based on a population projection of 1.5 M people and a per-capita usage rate of 0.18 ac-ft/yr (equivalent to approximately 160 gallons/day). The reservoir serves nearby cities as well as agricultural and industrial customers downstream of Texasville. It is assumed that if the reservoir experiences a drought worse than the drought in the historical record, the customers of the reservoir will be required to share proportionally in the water supply shortage according to a use weighted basis. Texasville has projected available supply from the reservoir as 260,000 ac-ft/yr for the year 2050 (based on the worst drought of record in the past 50 years).

With these demands and supply, the projected water need for 2050 is found to be 10,000 ac-ft/yr. A 'water reuse and conservation' strategy with an associated cost of $1M and expected yield of 12,000 ac-ft/yr has been proposed to address this water need in the future. The city is interested in assessing the impact of uncertainty related to: a) climate change, b) population projections, and c) per-capita usage rates on the proposed water plan.

4.2 Uncertainty Quantification

This section presents details on how uncertainty can be quantified for the case-study. The section is divided into two sub-sections that discuss the uncertainty quantification process for supply and demand, respectively.

4.2.1 Uncertainty in Supply

Climate was assumed to be the main driver for uncertainty in supply. A recent study sponsored by the Lower Colorado River Authority (LCRA) and San Antonio Water Supply (SAWS) (CH2M Hill, 2008) was used as the basis for quantifying uncertainty in water supplies due to climate change. This study investigated the impact of climate change on water resources for the lower Colorado River basin. The LCRA-SAWS study presented an approach for selecting multiple scenarios for future climate conditions. In this study, two IPCC carbon emission futures – SRES A2 and SRES B1 - were chosen to represent reasonable pessimistic and optimistic outlooks for future carbon emissions. The pessimistic outlook - SRES A2 - corresponds to a '*higher emissions path with technological change and economic growth more fragmented, and slower, higher population growth*', while the optimistic outlook - SRES B1 - corresponds to '*lower emissions path with rapid change in economic structures toward service and information, with an emphasis on clean, sustainable technology, reduced material intensity and improved social* *equity'*. The LCRA-SAWS study then analyzed predictions from a suite of GCM models for these two emission scenarios.

Two models – NCAR CCSM3[4] and GFDL CM2.1[5] (henceforth referred to as CCSM and GFDL) – were seen to provide temperature and precipitation predictions close to the upper and lower ranges of predictions from all scenarios and were assumed to bound the uncertainty in climate change for future water supplies. The two carbon emission futures were combined with the two climate models to yield a total of four climate scenarios. For each of the four scenarios, downscaled global projections for average changes in precipitation and temperature were obtained from the Lawrence Livermore National Laboratory (LLNL) under the WCRP's Coupled Model Intercomparison Project Phase 3 (CMIP3). The LCRA-SAWS study then mapped the climate change statistics from the various scenarios on to historical climate variability records to generate a time-varying series of temperature and precipitations. These were, in turn, used in conjunction with a hydrologic model – the Variable Infiltration Capacity (VIC) hydrologic model (Liang, 1994) – to estimate naturalized streamflows and net evaporation-precipitation for each of the scenarios. Results from this hydrologic modeling indicated that the annual streamflow in the Colorado River was projected to decrease under all climate change scenarios by 2050. This was despite the fact that certain climate change scenarios predicted a small *increase* in the precipitation indicating that evapotranspiration was the dominant hydrologic process affecting runoff and streamflow for this river basin. Further details of this methodology can be obtained from (CH2M Hill, 2008).

The four scenarios from the LCRA-SAWS study were combined with a 'baseline' scenario, representing unaltered historical records (this is the scenario without any climate change). All future climatic scenarios were treated as equally likely.

The naturalized streamflows and net evaporation-precipitation for these five scenarios were assumed to represent the alternative hydrologic scenarios for Texasville. These were used within a WAM to calculate the total available surface water supply for the city. The cumulative naturalized inflow and cumulative net evaporation-precipitation during the drought of record

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[4] Community Climate System Model, version 3.0 from the National Center for Atmospheric Research, USA.

[5] Geophysical Fluid Dynamics Laboratory Coupled Model, version 2.1 from the U.S. Department of Commerce/ National Oceanic and Atmospheric Administration/Geophysical Fluid Dynamics Laboratory, USA.

(spanning 11 years for this case) for the water supply reservoir serving Texasville are given in Figures 4-1 and 4-2. The figures illustrate the broad range of possible effects of future climate conditions on hydrology. Of particular interest is the GFDL-A2 future climate scenario which resulted in not only the lowest stream flow but also the highest net evaporation-precipitation of all the scenarios being considered in this case-study. The GFDL-A2 scenario may, therefore, be considered as a candidate for expressing the worst possible conditions during a future drought of record.

Figure 4-3 shows the WAM simulated storage time series for the reservoir which supplies Texasville and other reservoir customers. The eleven years shown in Figure 4-3 correspond to the worst reservoir draw down during the period of record in the baseline scenario. For each of the four future climate change scenarios, Texasville and the other reservoir customers were simulated as attempting to divert an amount equal to the supply provided in the baseline scenario. Without reducing diversions of reservoir storage in the future climate scenario simulations, storage contents would reach zero in multiple months during the drought of record. Zero reservoir storage represents months in which some or all customers are unable to divert any water from the reservoir. Therefore, customer diversions must be curtailed to allow access to some amount of stored water in all months of the drought to all customers. For this study, the diversions of stored water allowed for Texasville and the other customers were curtailed on a use-weighted proportional basis in order to raise reservoir storage contents above zero during the simulated drought period. For example, rather than Texasville having access to its full baseline 260,000 ac-ft/yr diversion, the diversion was reduced below 260,000 ac-ft/yr based on Texasville's proportion of the overall reservoir customer allocation.

Table 4-1 shows the reservoir supplies for Texasville after diversion curtailment. Note, that all climate scenarios show reservoir supplies *less* than the baseline case, thus a shortage more severe than the baseline case is to be expected for all climate scenarios. The five supplies shown in Table 4-1 represent five future water supply scenarios for the city of Texasville. Since all future climatic scenarios were assumed to be equally likely, all future water supply scenarios for Texasville were also assigned equal likelihood. Therefore, the 260,000 ac-ft/yr water supply under the baseline climate scenario carries the same likelihood as the 180,000 ac-ft/yr water supply under the GFDL-A2 climate scenario.

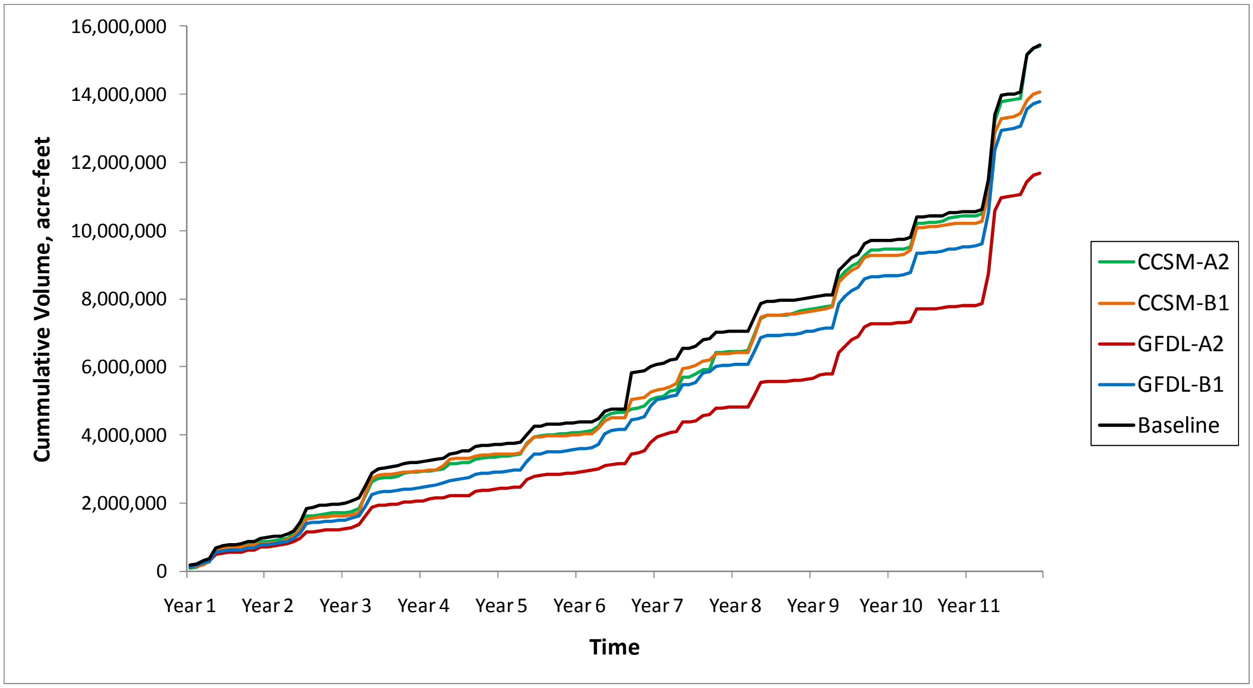

Figure 4-1 **Cumulative naturalized inflow at the location of Texasville's reservoir during the drought of record period.**

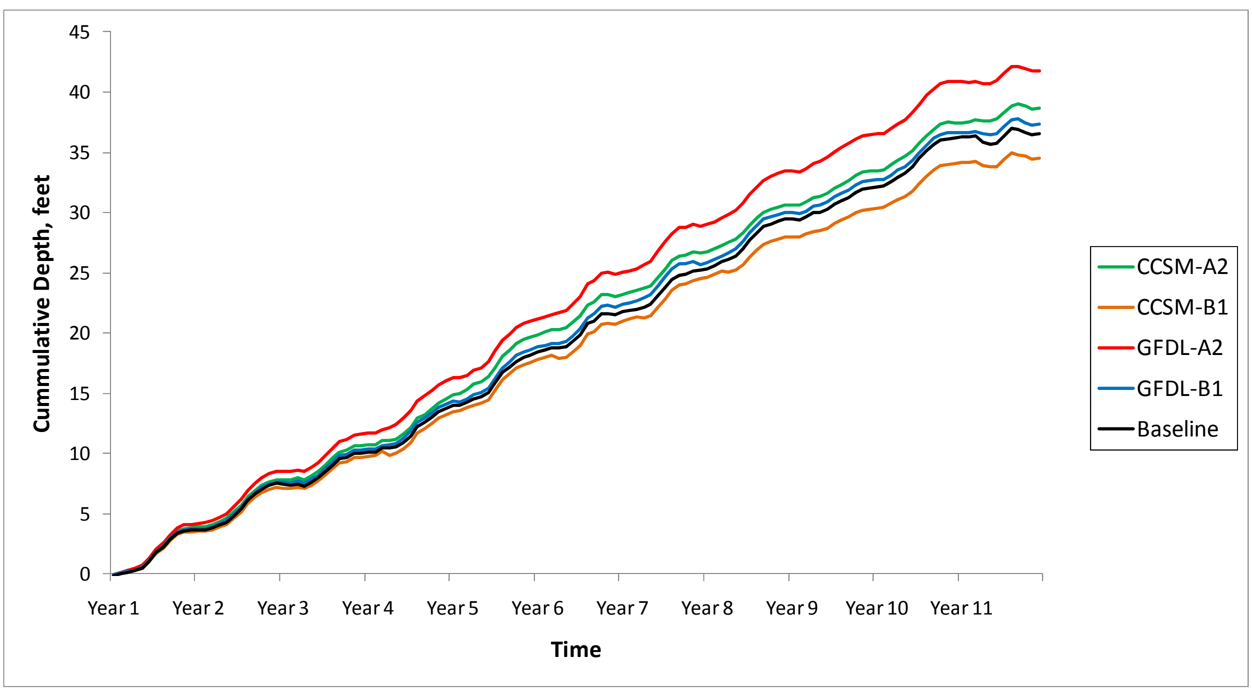

Figure 4-2 **Cumulative net evaporation-precipitation at the location of Texasville's reservoir during the drought of record period.**

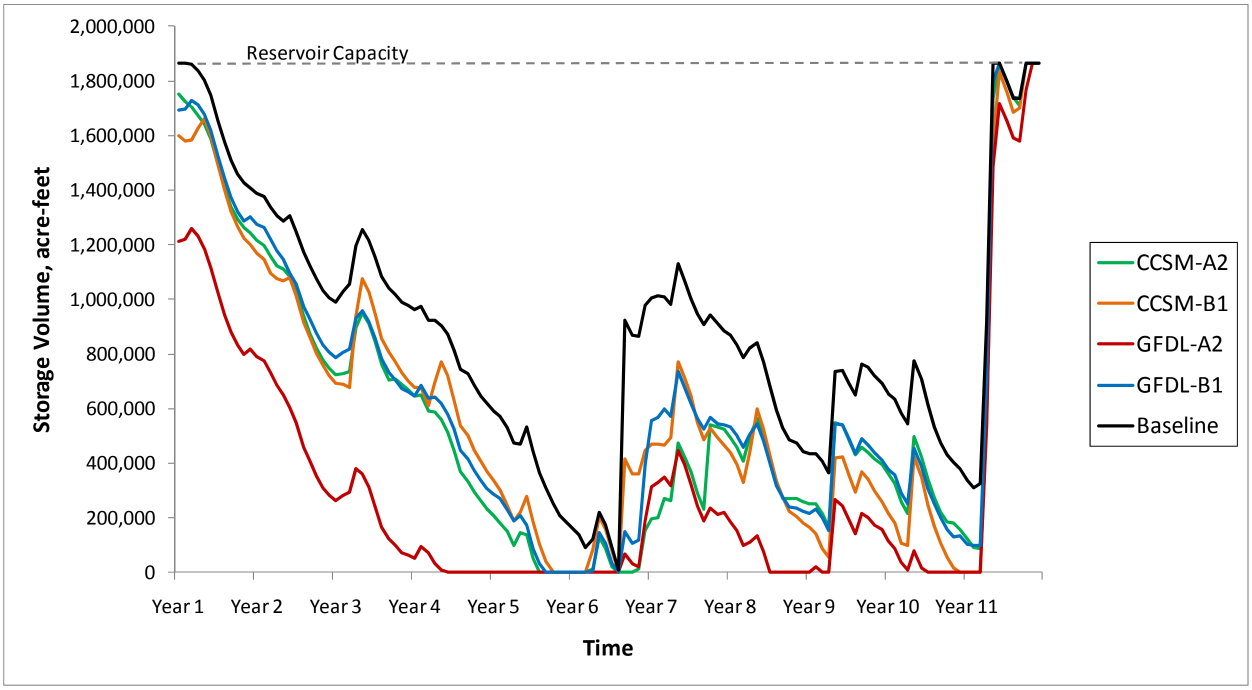

Figure 4-3 **Reservoir storage while allowing full baseline diversion rates during the drought of record period.**

Table 4-1 **Available municipal water supplies for Texasville for different climate scenarios.**

Climate scenario	Baseline	CCSM-A2	CCSM-B1	GFDL-A2	GFDL-B1
Available Municipal Water Supply, ac-ft/yr	260,000	235,000	250,000	180,000	240,000
Relative Likelihood	20%	20%	20%	20%	20%

4.2.2 Uncertainty in Demand

Demand for Texasville consists primarily of municipal demand. Municipal demand is calculated by multiplying population projection with the per-capita usage rate for a certain year. Both these factors - population projections and per-capita usage rates – are considered uncertain factors for Texasville's demand estimates. Population projections for Texasville were derived based on birth, death, and migration rates obtained from the Texas State Data Center. The main driver of uncertainty in population projections is the migration rate, thus only migration rate was varied from one scenario to another. The Texas State Data Center defines alternative migration scenarios (see discussion in Section 3.1.2.1). Six representative population projections were created to correspond to different migration scenarios. The scenarios range from no migration

(Scenario 1) to high migration (Scenario 6), with intermediate migration rates chosen between these two extremes. Scenario 3 is the population scenario with 50 percent migration rate and is considered the 'baseline projection' used for the deterministic water plans. Consequently this scenario was deemed to be the most likely among all population scenarios. Scenarios 4 and 5 were considered the next most likely, followed by scenario 2. The 'no migration' and 'high migration' scenarios (scenarios 1 and 6) were considered the 'bounding' cases for population projections (representing the minimum and maximum population growth for Texasville) and were given the lowest probability. The probabilities were assigned such that the baseline scenario was considered twice as likely as scenarios 4 and 5, each of which were considered twice as likely as scenario 2, which in turn was considered twice as likely as the no migration and high migration scenarios (scenarios 1 and 6). These probabilities were ascribed based on how plausible different migration rates seemed for the city of Texasville.

The different scenarios for population growth along with the corresponding likelihoods are shown in Table 4-2 (the baseline scenario is shown in bold). Additionally, the population projections for the year 2050 are shown with their probabilities in Figure 4-4 below. Note, that unlike the supply scenarios (Table 4-1) where all scenarios predicted lower supplies, the baseline population projection falls somewhere in between the distribution of population projections. Thus, for some scenarios, demand is expected to be less while for others it is expected to be more than the baseline demand.

Table 4-2 Texasville population projections.

Year	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
2000	650,000	650,000	**650,000**	650,000	650,000	650,000
2010	740,000	780,000	**800,000**	820,000	830,000	860,000
2020	850,000	950,000	**1,000,000**	1,050,000	1,080,000	1,150,000
2030	920,000	1,080,000	**1,200,000**	1,300,000	1,400,000	1,500,000
2040	940,000	1,200,000	**1,350,000**	1,500,000	1,620,000	1,800,000
2050	960,000	1,300,000	**1,500,000**	1,700,000	1,800,000	2,100,000
Relative Likelihood	5%	10%	**40%**	20%	20%	5%

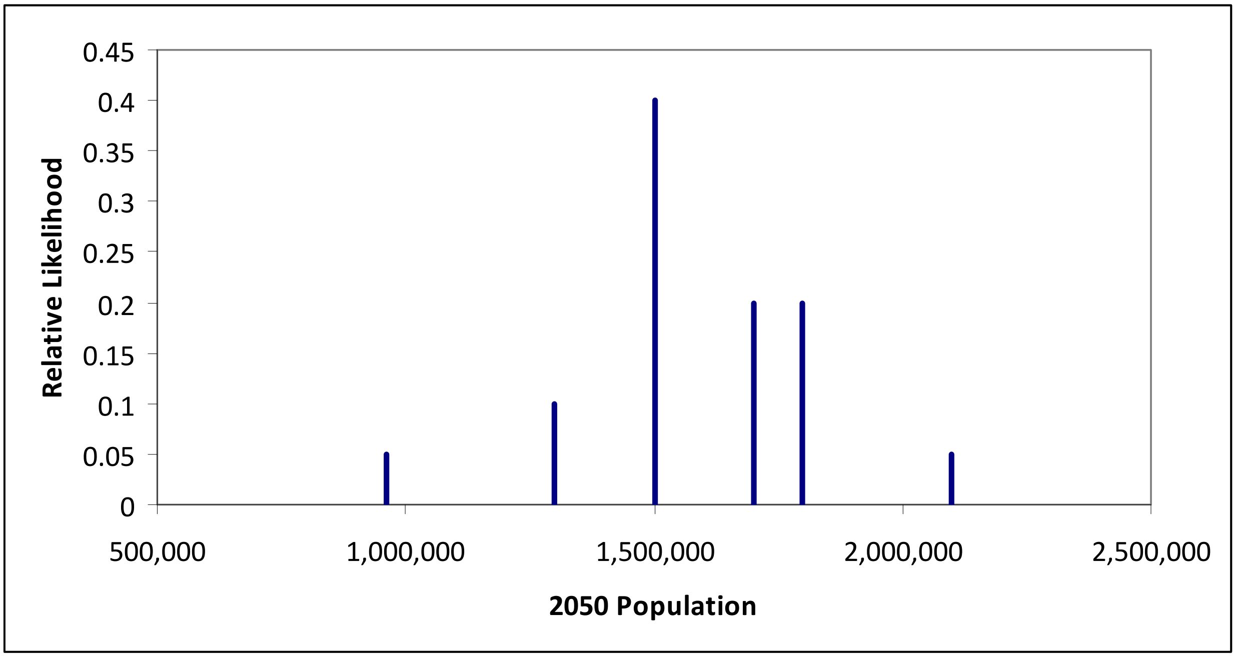

Figure 4-4 2050 population scenarios for Texasville.

The other demand factor considered uncertain is the per-capita usage rate. The city estimates its water usage-rate from survey data that is collected every year. The historical per-capita usage rates for the city are compared with the annual rainfall (for the last 25 years) in Figure 4-5 below. As can be seen from the figure, lower than average rainfall years correspond to high per-capita usage rates. The average usage rate (0.18 ac-ft/yr per person) is shown by the dashed line in Figure 4-5. The city bases its water plan on drought conditions, thus per-capita usage should also correspond to low rainfall years. Figure 4-6 shows the usage-rates that have been filtered by taking all higher than average per-capita usage rates. These rates are assumed to correspond to low-rainfall conditions. The variability seen in this filtered dataset can be assumed to represent the variability in usage rates (for low rainfall conditions) and scenarios were developed for low, average, and high water usage rates (for low rainfall conditions). From the data, these were calculated to be 0.17, 0.18, and 0.19 ac-ft/yr and are shown by the blue, green, and red dashed lines in Figure 4-6, respectively. The high and low usage rates were given likelihoods of 20 percent and the average usage rate a likelihood of 60 percent.

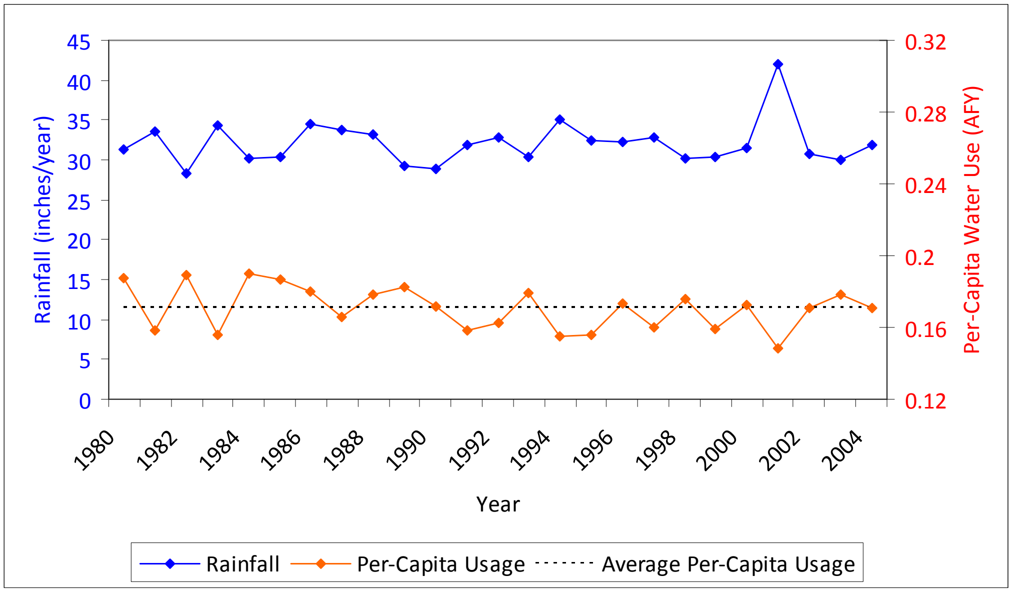

Figure 4-5 Per-capita water usage rate and rainfall for the last 25 years for Texasville.

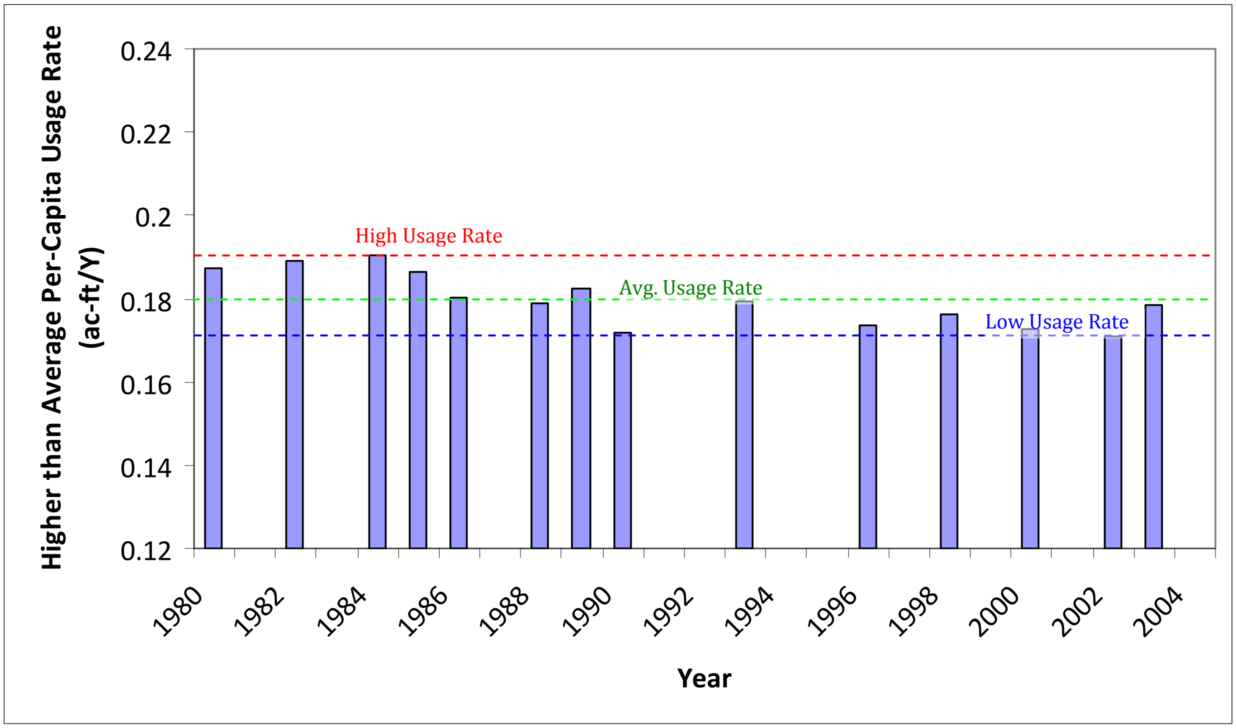

Figure 4-6 Higher than average water usage rates for Texasville.

The six population scenarios (Figure 4-4) are combined with the three usage rates (Figure 4-6) to yield a total of 18 demand scenarios with different combinations of population and usage rate estimates. The likelihood for each demand scenario is the product of the likelihoods for the population and usage rate scenarios. The 18 demand scenarios and corresponding likelihoods are shown in Table 4-3 (for each scenario the contributing population and usage scenarios are also indicated) and plotted in Figure 4-7.

Table 4-3 Demand scenarios derived from population and usage scenarios.

Population scenario	Usage rate	2050 demand (ac-ft/yr)	Relative likelihood
Scenario 1	Low	163200	1%
Scenario 1	Medium	172800	4%
Scenario 1	High	182400	1%
Scenario 2	Low	221000	2%
Scenario 2	Medium	234000	7%
Scenario 2	High	247000	1%
Scenario 3	Low	255000	8%
Scenario 3	Medium	270000	28%
Scenario 3	High	285000	4%
Scenario 4	Low	289000	4%
Scenario 4	Medium	306000	14%
Scenario 4	High	323000	2%
Scenario 5	Low	306000	4%
Scenario 5	Medium	324000	14%
Scenario 5	High	342000	2%
Scenario 6	Low	357000	1%
Scenario 6	Medium	378000	4%
Scenario 6	High	399000	1%

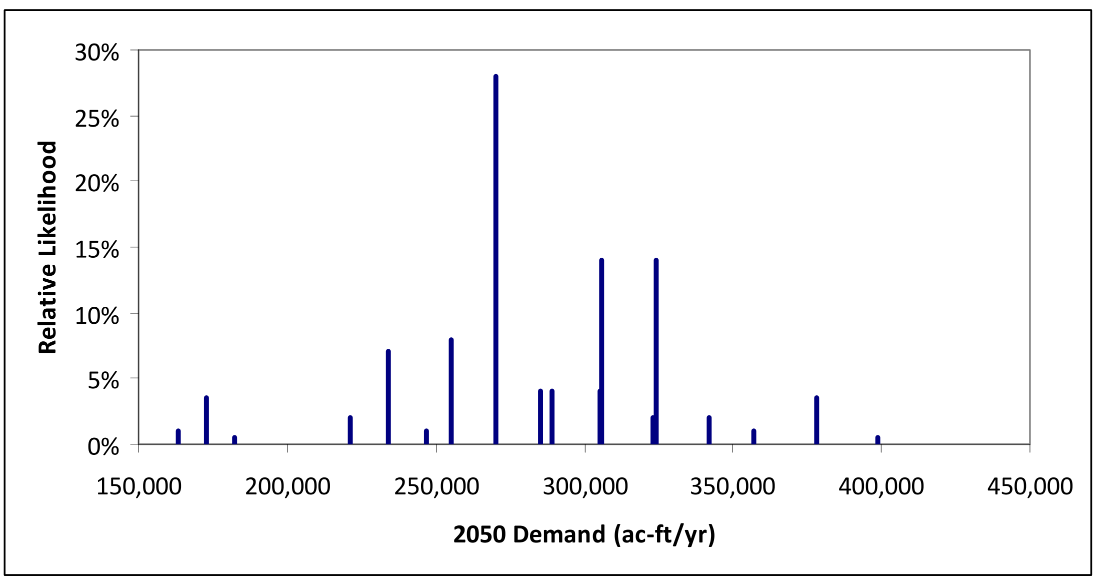

Figure 4-7 2050 demand scenarios for Texasville.

4.2.3 Uncertainty in Future Water Needs

Water needs can be calculated for every combination of the demand and supply scenarios by subtracting the corresponding supply from the demand. Note that it is possible for projected supply to be more than projected demand in which case there will be a surplus – indicated by a negative value for need. The 5 supply scenarios (Table 4-1) combined with the 18 demand scenarios (Table 4-3) give a total of 90 water-need scenarios. These water-need scenarios with the associated likelihoods are shown in Figure 4-8. Note that there are multiple scenarios that have negative water needs. These indicate cases where the projected supply is more than the projected demand.

The individual scenarios and likelihoods can be aggregated into a cumulative probability plot as discussed in Section 3.1.3. The cumulative probability plot for all the 90 scenarios is shown in Figure 4-9. The cumulative probability for a particular water-need value indicates the likelihood that the water need will be *less than or equal to* that value.

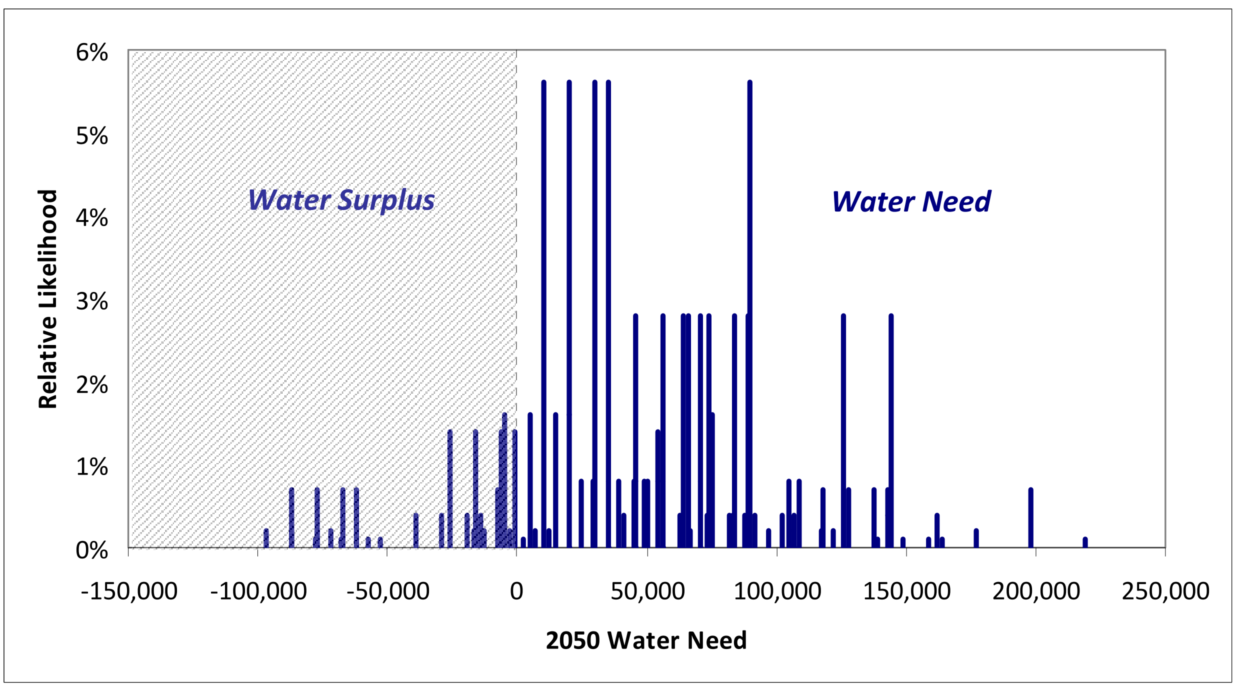

Figure 4-8 2050 water-need scenarios for Texasville.

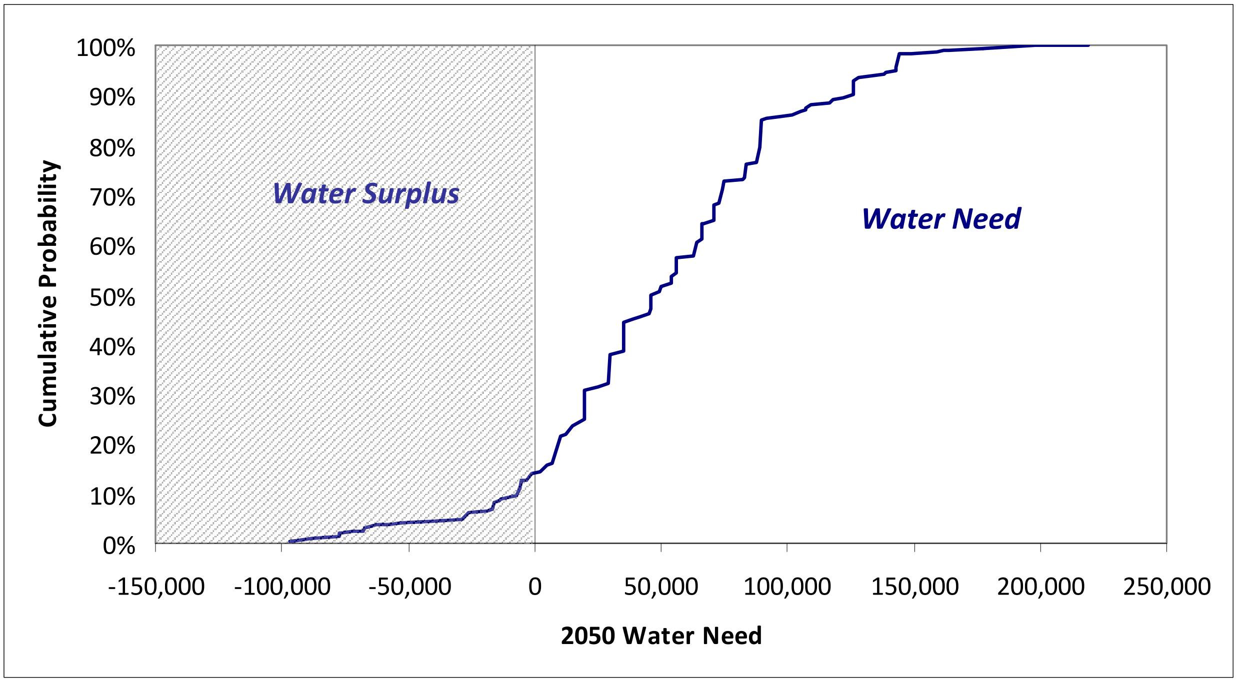

Figure 4-9 Cumulative probability plot for 2050 water needs for Texasville.

4.3 Planning under Uncertainty

As mentioned earlier, using deterministic projections, the city has estimated future water demand to be 270,000 ac-ft/yr and future water supplies to be 260,000 ac-ft/yr, leading to a water need of 10,000 ac-ft/yr in the year 2050. A 'water reuse and conservation' strategy with an expected yield of 12,000 ac-ft/yr has been proposed to address this water need in the future. In addition to conservation and reuse, five other candidate strategies are also under consideration. These are: building an additional reservoir, developing local groundwater resources, a wastewater reuse program, opening a brackish groundwater desalination plant, and constructing a pipeline to transport water from another water supply facility. The strategies along with the associated capital cost (in current dollar value) and expected yields are given in Table 4-4 below. The baseline strategy (conservation and reuse) is shown in bold.

Table 4-4 Water management strategies to be considered for Texasville.

Strategy ID	Strategy	Capital cost ($ million)	Expected yield (ac-ft/yr)
S0	**Conservation and Reuse**	**1**	**12,000**
S1	Reservoir	150	75,000
S2	GW Development	30	30,000
S3	Wastewater Reuse	20	50,000
S4	Desalination	90	40,000
S5	Pipeline	60	50,000

To make the analysis simpler for this example, cost, yields, and reliabilities are the only factors considered. In actuality multiple other criteria would need to be considered (in addition to the three listed above) when evaluating water management strategies.

4.3.1 Assessing Reliability of Water Management Strategies

The first step in planning under uncertainty is to assess the reliability of the initial set of water management strategies. In this case, the 'baseline' water management strategy is conservation and reuse with an additional yield of 10,000 ac-ft/yr. This yield is shown on the cumulative probability plot (calculated earlier) in Figure 4-10. For visualization purposes only positive water needs (shortages) are shown henceforth.

Figure 4-10 shows that the likelihood that projected water needs will be less than or equal to 12,000 ac-ft/yr is approximately 22 percent. In other words, the reliability of the water conservation and reuse strategy *alone* is 22 percent. This reliability is based on all the sources of uncertainty (climate, population, and usage rates) considered for this case.

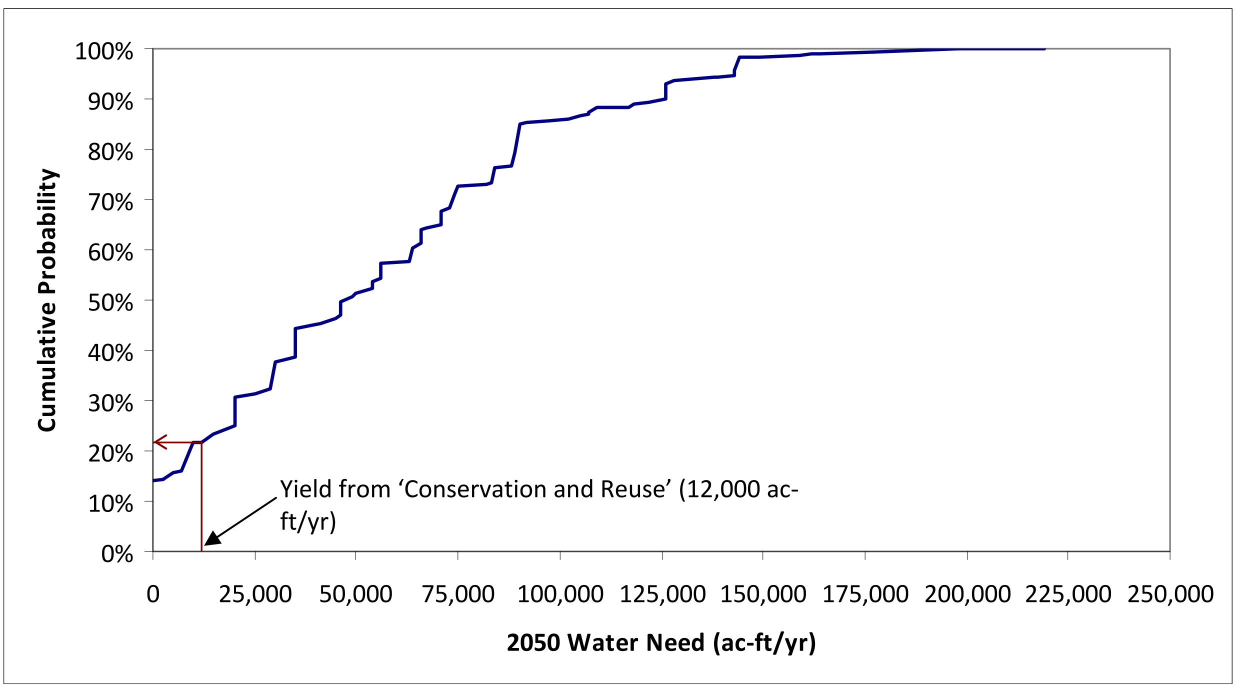

Figure 4-10 Calculating reliability of 'conservation and reuse' strategy using the cumulative probability plot for 2050 water needs for Texasville.

4.3.2 Selecting Strategies under Uncertainty

Conservation and reuse alone is not sufficient to meet projected water needs with sufficient reliability. Thus, additional sets of strategies need to be considered to improve the reliability while also taking into account cost and yield considerations. Table 4-5 shows the additional cost, yield, and reliabilities (rounded to a whole number) for some select set of strategies under consideration (there are other combinations of strategies that are not shown here). Figures 4-11 and 4-12 show the cost-reliability and cost-yield trade-off graphs for these sets of strategies.

The trade-off information reveals the interplay between cost, yield, and reliability for the various sets of strategies. Strategy sets A and B can be deemed to have lower than desirable reliability (both lower than 50 percent). Of the remaining sets of strategies D and E are not optimal from a trade-off perspective. This means that there are other sets of strategies that are better both in terms of reliability and/or yield while having the same or lower costs than these sets of strategies. For example, strategy set D (conservation and reuse + pipeline) has a cost of $61M dollars with a yield of 62,000 ac-ft/yr and a reliability of 57 percent. However, there exists another strategy set (C – conservation and reuse + wastewater reuse) with a lower cost ($21M dollars), same yield (62,000 ac-ft/yr), and same reliability (57 percent).

Similarly strategy set E (conservation and reuse + reservoir) is not optimal from a trade-off perspective compared to F (conservation and reuse + wastewater reuse + GW development). In this case, the non-optimal solutions are the same for both the cost versus reliability and cost versus yield trade-offs. Unless there are other significant other factors for the consideration of these sets of strategies, they can be discarded from further consideration. The trade-off lines for the remaining set of strategies (C, F, G, H, I, J, K, and L) reveal that both reliabilities and yields tend to increase for higher costs. However, beyond a certain point, the relative increase in reliability is not proportional to the increase in cost. This is seen by the relatively flat trade-off lines for the more expensive solutions. While going from C to F, G, and H, the reliability does increase substantially with increasing costs; but for strategy sets I, J, K, and L, the incremental increase in reliability is much less than the incremental increase in costs. It could be argued that these very high cost, high reliability strategy sets do not provide adequate ‘bang for the buck’. From a decision-making perspective, strategy set H (conservation and reuse + wastewater reuse + GW development + pipeline) seems to have a good balance between cost ($111M), yield

(142,000 ac-ft/yr), and reliability (94 percent) with respect to the sources of uncertainty considered for this case.

Table 4-5 Sets of strategies with associated costs, yields, and reliabilities.

Strategy Sets	Strategies considered	Capital cost ($M)	Expected total yield (ac-ft/yr)	Reliability
A	• Conservation and reuse	1	12,000	22%
B	• Conservation and reuse • GW development	31	42,000	45%
C	• Conservation and reuse • Wastewater reuse	21	62,000	57%
D	• Conservation and reuse • Pipeline	61	62,000	57%
E	• Conservation and reuse • Reservoir	151	87,000	76%
F	• Conservation and reuse • Wastewater reuse • GW development	51	92,000	85%
G	• Conservation and reuse • Wastewater reuse • Pipeline	81	112,000	88%
H	• Conservation and reuse • Wastewater reuse • GW development • Pipeline	111	142,000	94%
I	• Conservation and reuse • Wastewater reuse • Desalination • Pipeline	171	152,000	98%
J	• Conservation and reuse • Wastewater reuse • GW development • Reservoir	201	167,000	99%
K	• Conservation and reuse • Wastewater reuse • GW development • Pipeline • Reservoir	261	217,000	100%
L	(ALL) • Conservation and reuse • Wastewater reuse • GW development • Desalination • Pipeline • Reservoir	351	257,000	100%

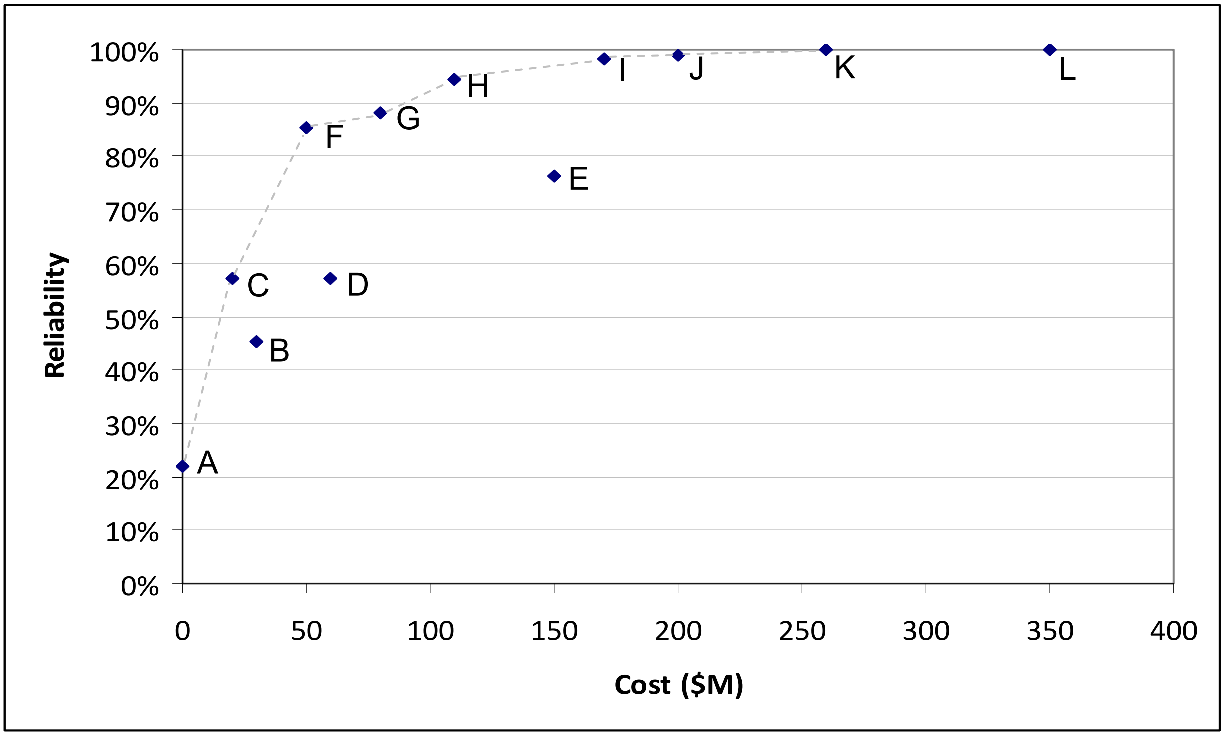

Figure 4-11 Trade-off between cost and reliability for select sets of strategies.

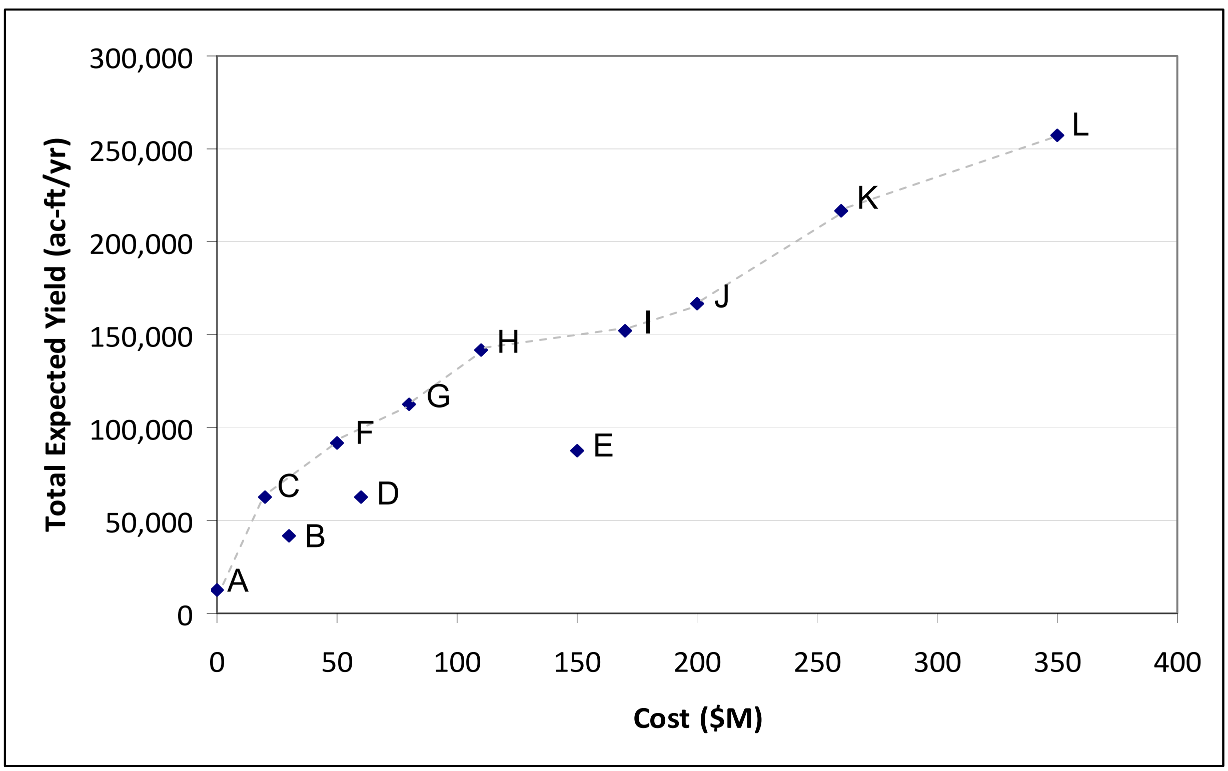

Figure 4-12 Trade-off between cost and total expected yield for select sets of strategies.

4.3.3 Assessing Sensitivity to Sources of Uncertainty

Selection of the different sources of uncertainty is an important step in the uncertainty quantification process. Reliabilities are assessed based on the different scenarios defined for the quantified sources of uncertainties. Thus, it is useful to assess the impact different sources of uncertainty have on the assessment of reliability as well as on the overall planning process. An easy way to accomplish this is to fix certain factors while considering uncertainty in the other factors. With this assumption, cumulative probability plots and trade-off graphs can be generated (as discussed above) for different sources of uncertainty.

For this example, three cases are considered: a) uncertainty in population and climate (with deterministic usage rate), b) uncertainty in climate only (with deterministic usage rate and population), and c) uncertainty in population projections only (with deterministic usage rate and climate conditions). Each of these cases is described below.

For the first case, the usage rate was assumed deterministic (equal to the current average = 0.18 ac-ft/yr) leading to a total of 6 demand scenarios (one for each population scenario) and 5 supply scenarios (one for each climate scenario). These demand and supply scenarios can be combined to generate 30 scenarios for future water needs with associated likelihoods (the likelihood for a scenario in this case would be the product of the likelihoods for the corresponding population and climate scenarios). Aggregating these scenarios produces a cumulative probability plot that only considers uncertainty in supply due to climate change and population projections.

For the second case – uncertainty in climate only – demand and usage rates were assumed to be deterministic (270,000 ac-ft/yr and 0.18 ac-ft/yr, respectively) with the uncertainty in supply represented by the five climate scenarios. Finally, for the third case – uncertainty in population only – a single (deterministic) supply estimate (260,000 ac-ft/yr) was used with 6 population scenarios. Cumulative probability plots were constructed for each of these cases and are shown in Figure 4-13. The figure compares the cumulative probability plots for projected water needs with different sources of uncertainty – uncertainty in climate, population, and water usage rates (henceforth referred to as the 'full cumulative probability'); uncertainty in climate and population; uncertainty in climate only; and uncertainty in population only. It also shows the water need with no uncertainty (shown by the dashed line in green), i.e., the water need that is used for current deterministic planning. It is interesting to note that the cumulative probability with deterministic usage rate (uncertainty in climate and population) is very similar to the 'full cumulative probability'. It could thus be concluded that uncertainty in usage rate has very little impact on water needs compared to climate or population uncertainty. Comparing the 'Uncertainty in Climate Only' case with the 'Uncertainty in Climate and Population' shows the impact ignoring uncertainty in population has on the water need probability distribution. Similarly comparing the 'Uncertainty in Population Only' case with the 'Uncertainty in Climate and Population' shows the impact uncertainty in climate has on the water need probabilities. The fact that both these distributions are significantly different from the 'Uncertainty in Climate and Population' and the 'full cumulative probability' indicates that both climate and population are important drivers of uncertainty (in future water needs) for this case. It is also worth noting that as additional sources of uncertainty are accounted for, the cumulative probability tends to shift towards higher water needs, indicating that more water would be needed to meet the same level of reliability.

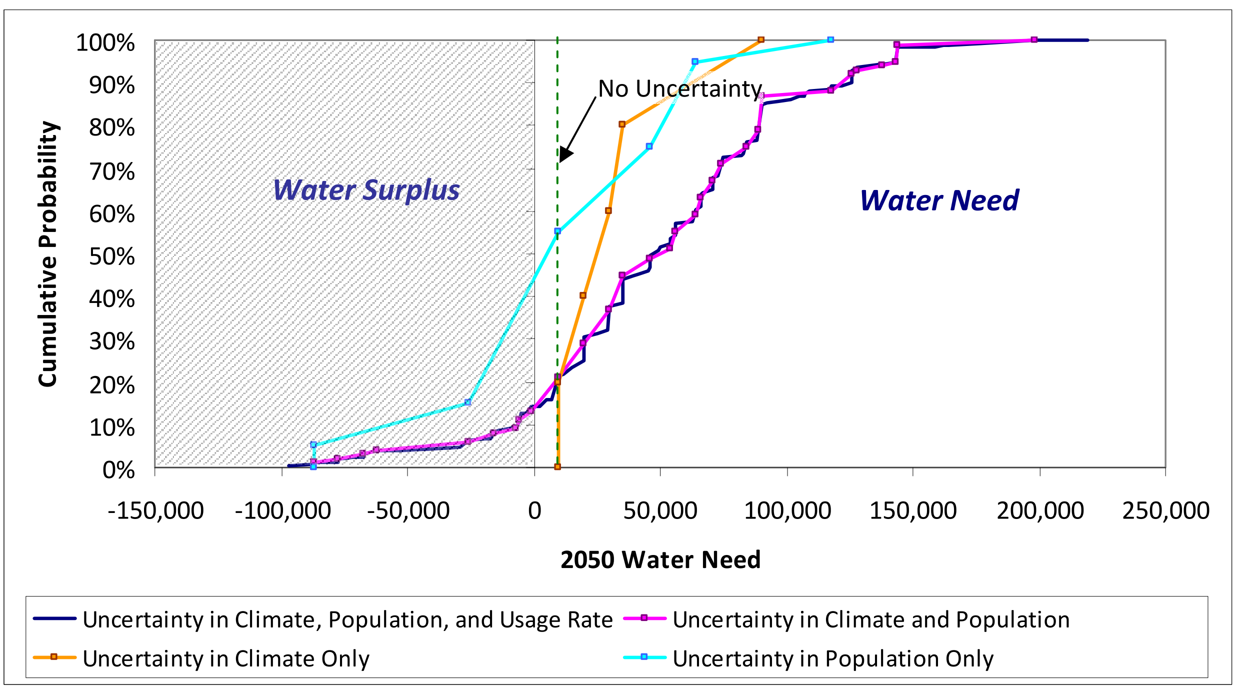

Figure 4-13 Cumulative probabilities for different sources of uncertainty.

Figure 4-14 shows the reliability for the water conservation and reuse strategy, but in this case for different sources of uncertainty. From Figure 4-14, it can be seen that the reliability of the strategy is in relation to the underlying sources of uncertainty considered. When not considering uncertainty at all, a yield of 12,000 ac-ft/yr will always satisfy the projected water need of 10,000 ac-ft/yr, i.e., the reliability of the strategy is 100 percent. When considering uncertainty in population projections, this strategy will satisfy projected water needs approximately 56 percent of the time (the reliability with respect to uncertainty in population projections is 56 percent). Similarly the strategy has a reliability of approximately 24 percent with respect to climate uncertainty, 22.5 percent with respect to population and climate uncertainty, and 22 percent with respect to uncertainty in climate, population, and usage rates.

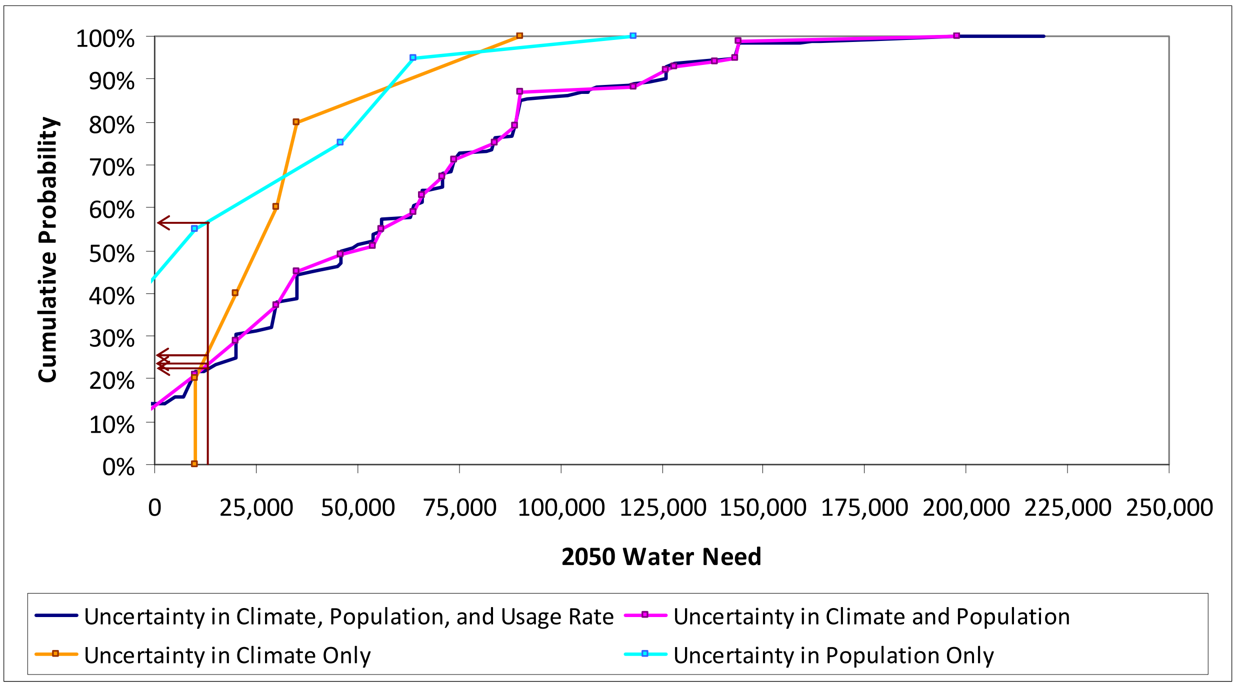

Figure 4-14 Calculating reliability of 'conservation and reuse' strategy using cumulative probabilities with different sources of uncertainty.

To calculate the impact different sources of uncertainty have on the decision-making process, Table 4-6 shows the cost, yields, and reliabilities for the same strategy sets for different sources of uncertainties (climate, population, and climate + population + usage rate[6]). The trade-off graph (Figure 4-15) is seen to change significantly for different uncertainty sources. In general, the reliabilities with respect to only climate uncertainty or only population uncertainty were higher than the reliabilities with respect to climate, population, and usage rate uncertainty. B, D,

[6] Since the cumulative probability for climate+population+usage was shown to be very similar to climate+population, the latter is not considered in this analysis.

and E could still be considered sub-optimal with respect to the cost versus reliability trade-off. However, the incremental increase in reliability with the increase in cost was less pronounced for the first two cases (only climate or population uncertainty). In fact, for these two cases, strategy set C (conservation and reuse + wastewater reuse) seems to present the best trade-off in terms of cost ($20 M) and reliability (approximately 90 percent).

Table 4-6 Sets of strategies with associated costs, yields, and reliabilities.

Strategy ID	Capital cost ($M)	Expected total yield (ac-ft/yr)	Reliability w.r.t. uncertainty in climate	Reliability w.r.t. uncertainty in population	Reliability w.r.t. uncertainty in climate, population, and usage rate
A	1	12,000	24%	56%	22%
B	31	42,000	73%	83%	45%
C	21	62,000	90%	92%	57%
D	61	62,000	90%	92%	57%
E	151	87,000	99%	97%	76%
F	51	92,000	100%	98%	85%
G	81	112,000	100%	99%	88%
H	111	142,000	100%	100%	94%
I	171	152,000	100%	100%	98%
J	201	167,000	100%	100%	99%
K	261	217,000	100%	100%	100%
L	351	257,000	100%	100%	100%

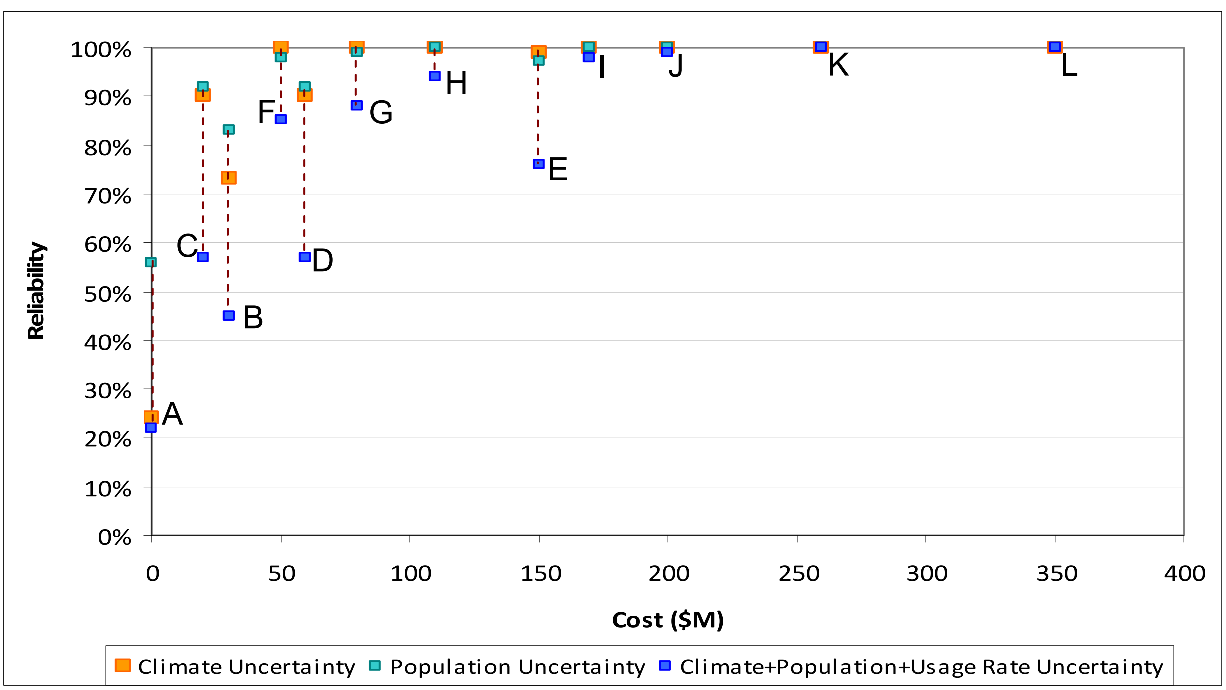

Figure 4-15 Trade-off between cost and reliability with different sources of uncertainty.

4.4 Discussion

The Texasville case-study demonstrates some of the important concepts in uncertainty quantification and planning under uncertainty. This case-study selected three important sources of uncertainty – climate, population projections, and water usage-rate. Climate uncertainty was characterized by using multiple scenarios for climate change (in addition to a baseline scenario, representing no systematic change in climate conditions) derived from the LCRA-SAWS study (CH2M Hill, 2008). It was seen that accounting for climate change led to a reduction of projected supply for all climate scenarios. Thus, the baseline supply projection (based on historic records) could be considered overly optimistic for this case. Demand uncertainty was characterized by using six population scenarios (with different migration rates) and three usage-rates (low, average, and high). Unlike the climate scenarios, the baseline case for demand was found to be in the middle of the range of all scenarios. The cumulative probability plot for water-need projections was constructed using the combination of demand and supply scenarios. The plot showed a skew towards higher water shortages than the baseline case. This can be attributed to the optimistic supply projection for the baseline case which led a majority of the water-need scenarios to have higher water needs than the baseline. This highlights one of the key benefits of quantifying uncertainty – reducing the reliance of the planning process on overly optimistic (as is this case) or overly pessimistic estimates.

The importance of uncertainty in the planning process was demonstrated by first proposing a water management strategy to meet the 'deterministic need' (i.e., the water need calculated using only baseline projections for demand and supply). When uncertainty was included in the analysis, it was found that the reliability of this water management strategy alone was not sufficiently high. This indicated that additional water management strategies would need to be proposed to meet projected water needs with higher reliabilities. Reliabilities for various sets of strategies were assessed and then compared with cost and yields to find sets of strategies with favorable trade-offs in these three factors. It was seen that certain strategies were clearly not optimal since other sets of strategies existed that were cheaper yet provided better reliabilities. Others, while not sub-optimal in terms of the trade-off, did not display a corresponding increase in reliabilities for an increase in costs.

Finally, this process was repeated with different sources of uncertainty. It was seen that uncertainty in usage-rates did not make much difference in the reliabilities or the trade-offs for the various strategies. On the other hand, climate uncertainty and uncertainty in population projections were both important drivers in the ‘planning under uncertainty’ process. This indicates that the city of Texasville should be cognizant of the uncertainties in climate and population projections, and plan ahead for changes in both these underlying factors. This also indicates that future planning cycles may need to reassess and refine assumptions regarding climate and population growth, thus allowing the city to better adapt to changes in the future.

5.0 Summary and Conclusions

This study presents a methodology to quantitatively address some of the important elements of uncertainty in the water planning process for the State of Texas. The approach proposed is incremental and builds on the existing planning framework. This report first summarizes the current planning process, highlighting some of the important sources of uncertainty (as identified in the 2007 State Water Plan) therein. The quantifiable sources of uncertainty considered in this study are: a) uncertainty due to climate change, b) uncertainty in water supply models, and c) uncertainty in demand projections.

The methodology to incorporate uncertainty in water resources planning can be divided into two steps: a) uncertainty quantification, and b) planning under uncertainty. To keep the analysis simple and easy to understand, a 'scenario-based' approach is proposed for uncertainty characterization. In this approach, alternative scenarios for demand and supply projections are developed by either: a) varying the underlying assumptions and models used for the projections; b) comparing past projections with actual data and using the misfit to bound the uncertainty in projections; and c) assessing historic variability to calculate feasible upper, lower, or average values for uncertain factors. The report discusses techniques and references different data-sources that can be used to quantify uncertainty in climate, water supply models, population projections, usage-rates, and irrigation demands. Once multiple demand and supply scenarios have been developed, they can be combined to yield multiple water need/surplus scenarios. These water need scenarios form the basis for the proposed planning under uncertainty methodology which is driven by the reliability of meeting future water needs instead of a single deterministic future water need. The ensemble of water-needs projections can be aggregated in the form of a probability distribution plot that displays the probability that the projected water need is less than or equal to a certain value. This cumulative probability plot is a very useful decision-making tool as it can be used to assess the reliability of various water management strategies for meeting a given water-need value. Using the cumulative probability plot, the reliabilities for promising sets of water management strategies can be calculated and compared with costs and yields to find the most efficient and reliable water management strategies. A trade-off plot is a useful visual tool in this process as it displays the relative importance of different objectives for various strategies considered in the decision-making process.

The report demonstrates these concepts for a hypothetical case-study, stepping through the process of uncertainty quantification and planning under uncertainty for a hypothetical water user. The results for the case study highlight the importance of considering uncertainty in the water planning process. Inclusion of uncertainty in the planning framework allows strategies to be selected that are more robust with respect to the uncertainties in supply and demand projections. The case study also assesses the relative importance of different sources of uncertainty for the reliabilities and trade-offs for different water management strategies. For the case study, results indicate that climate and population projections are the two most significant uncertain factors, while uncertainty in usage rates has a negligible impact on the reliability calculation (and thus the planning process).

Based on the proposed framework, some of the salient conclusions and recommendations of this study are given below:

- The methodology to incorporate uncertainty into the water planning process should be incremental and build on the existing planning framework.
- The approach proposed in this study is to use a set of alternative scenarios to represent the uncertainty in different elements of the water planning process. This is an intuitive and easy to understand approach that fits in seamlessly with the existing planning framework.
- It is infeasible to try to quantify *all* possible sources of uncertainties. Thus, the focus should be on the areas of uncertainty which are of most importance to stakeholders and would create the largest impact on the projections of demand and supply. The methodologies proposed in this report are generalized enough to be adapted to other demand and supply factors.
- The choice of which uncertain factors to quantify and which methodology to use for quantification depends on the stakeholders and available data sources. Uncertainty may be characterized using alternative model assumptions or by assessing historic variability.
- Consideration of uncertainty adds value to the planning process by allowing the reliabilities of water management strategies to be assessed and incorporated into the decision-making framework allowing for a more robust water management plan.

- Instead of a single deterministic water need projection, the driver for planning under uncertainty is the reliability of meeting a range of projected water needs.
- Using this approach, the trade-offs in cost, benefits, and reliabilities of alternative sets of strategies may be assessed. This trade-off information can be useful in selecting the final set of strategies.
- It is useful to assess the importance of different sources of uncertainty. This can be achieved by assessing the reliabilities and trade-offs with only a subset of the various sources of uncertainty. This process allows one to identify those uncertain factors that the decision-making process is most sensitive to. It can also help prioritize future efforts in data-collection and model refinements, thereby reducing uncertainty in the most important factors in the planning process.

Finally, it is to be noted that this study represents a 'first step' in the incorporation of uncertainty in the planning framework. Thus, it is important to acknowledge the caveats and limitations of the proposed approach, which would be addressed in future studies. Some important limitations of the study are:

- A simple scenario-based approach has been used in this study. Other more sophisticated uncertainty quantification approaches exist and can be addressed in future work.
- The study assumes that demand and supply uncertainty are independent. However, factors that influence supply uncertainty (such as climate change) can also influence demand. This link can be made explicit in future studies.
- The study considers uncertainty only in demands and supplies. In many cases, the yields from water management strategies can also be uncertain. Furthermore, there in uncertainty in the implementation of certain water management strategies. This study has proposed handling this uncertainty in a qualitative manner. Future work should address the quantification and incorporation of these uncertainties in the planning framework.
- Future work should also consider more sources of uncertainty. These may include: a) approximations and assumptions in WAMs and GAMs, b) scaling issues related to inputs and outputs of the WAMs and GAMs, and c) uncertainty in other (apart from municipal and irrigation) demand types, among others.

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6.0 References

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APPENDIX A

Draft Report
Comments and Responses

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Appendix A
TWDB Comments Contract 090483057
"*Analyzing Risk and Uncertainty in the Management of Texas Water Resources*"

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1) Overall, the report on uncertainty and risk in water resources planning in Texas is very well written and comprehensible. The authors are to be commended for making this potentially difficult topic easy to read and to understand.

2) Please provide a MS Word file of the final report in addition to a PDF file.

   This has been provided in the CD submitted.

3) The TWDB formal review process does not allow reviewer comments on typographical or editorial issues; the Board considers proofreading and editing the sole responsibility of the contractor. Please review the report for editorial and typographical errors.

   The report has been proof-read and edited for typographical/editorial issues.

4) Page xi. Please label figures on page.

   Completed

5) Page xi, figure. The process depicting key steps in "deterministic" regional planning is misleading. There are five fundamental steps in the process: 1) compare currently available supplies to projected future demands, 2) identify water needs, 3) identify potentially feasible strategies to meet water needs, 4) select strategies for evaluation based on water quantity and reliability, financial costs, impacts to the state's water, agricultural, and natural resources, and 5) based on the evaluation recommend strategies for implementation. Boxes 3 through 5 are not specified requirements for regional water planning in administrative rules. Please consider modifying the diagram to reflect this here and in the main body of the report (Figure 3-8).

   Both Figures have been modified.

6) Executive Summary, page xii, 1st paragraph, 3rd sentence states: "*this introduces a key concept - reliability…*" Administrative rules currently require planning groups to evaluate strategies based on costs, quantity of water supplied and reliability of supply. Thus, reliability is not a novel concept in regional water planning. Please consider rewriting to reflect that the uncertainty analysis in this report extends or further develops the concept of reliability.

   The statement has been rewritten. Reliability is defined specifically in terms of the probability of meeting projected water needs for the different water need scenarios.

7) Page 2-2, 2nd paragraph. Add “mining” to the categories of water demands.

Completed

8) Page 2-2, top paragraph, 2nd sentence states: “*Regional water planners are responsible for…*” This implies that regional water planning groups develop future demands and supplies on their own. The TWDB develops most demand and supply projections for the planning groups, and present them to planning groups for review and comment. In some cases, projections are revised if planning groups provide adequate supporting information. Please consider rewriting as: “*The TWDB and regional water planners…*”

Completed

9) Page 2-4, final sentence of first paragraph: Not all regions were required to use the results of the Desired Future Conditions process in the current round of planning, but it will be a requirement in the next round. In addition, Managed Available Groundwater values will not be the sole factor in determining annual groundwater availability as used in the planning process. Please revise this sentence and other areas of the report to reflect this. We suggest rewriting this sentence as "*The regional planning groups will incorporate these Managed Available Groundwater values as part of the annual groundwater supplies that go into the regional planning process.*"

Completed

10) Page 2-4, 2nd paragraph. Please consider adding another section to distinguish total supply from groundwater supply, and please consider recognizing that wastewater reuse is a component of total supply in regional water planning.

Completed

11) Page 2-4, next to last sentence states: “*Planning groups also assess the financing of these strategies, in addition to their social, economic and environmental impacts*.” Please rewrite as: “*Planning groups also estimate the financial costs of strategies and assess how strategies impact the state’s water, agricultural, and natural resources*.”

Completed

12) Page 2-4, last sentence states: “*Based on all these factors water management strategies are proposed for different times in the planning horizon such that all projected water needs are met by the proposed set of water management strategie*s.” This is not correct. In some cases, water user groups have unmet needs. Please rewrite as: “*Based on all these factors water management strategies are proposed for different times in the planning horizon depending upon timing of need* ~~*such that all projected water needs are met by the proposed set of water management strategie*~~s.”

Completed

13) Page 2-5, final paragraph, 1st sentence states: "*…to develop conservative projections*…" Please strike the word "~~*conservative*~~." The word conservative implies a value judgment.

Completed

14) Page 2-5, final paragraph, 2nd sentence states: "*These projections and strategies may be updated every five years thus improving their accuracy and reliability*." Rewrite as: "*...projections and strategies are reviewed every five years and updated based on new data and information*."

Completed

15) Page 2-8, last paragraph: Please consider striking the parenthetical phrase: "(~~*especially due to carbon emissions from anthropogenic sources*~~)." The report does not substantiate this statement.

Completed

16) Page 2-9, last paragraph, 1st sentence: Rewrite as: "…CO2 *emissions* ~~*are likely*~~ *may have a major role…"*

Completed

17) Page 2-8, "Climate Forcings" inset. Please clarify what is meant by "*fluctuations in the Earth's orbit*" and provide a time scale for these fluctuations. If this refers to the earth's 18.6-year nutation period, please explain if this period is considered long enough for its effects to be considered climate change.

The discussion on fluctuations in the Earth's orbit is superfluous to the intent and purpose of this report. Therefore, this text has been removed to focus on the main uncertainties that are considered in this report.

18) Page 2-11, paragraph 1. Please add a brief description of hydrologic stationarity.

Completed

19) Page 2-12, last paragraph – Please change "GAM predictions" to "GAM inputs"

Completed

20) Page 2-13, last paragraph states: "*In most cases, these other [manufacturing, mining, livestock, and steam-electric] do not form a significant proportion of a region's demand…"* In many cases, these categories do make up a large percentage of regional demands*."* Please strike the last two sentences of this paragraph, and other areas of the report where this statement appears.

Completed

21) Page 2-14, first paragraph, 3rd to last sentence. Hurricanes (e.g., Katrina) are not climatic phenomena; they are weather events. Please consider using another example of climatic phenomena.

Reference to hurricane Katrina has been removed as this is (as the reviewer pointed out) on a climate phenomenon. We have, instead, mentioned migration in agricultural and coastal communities that may be more impacted by long term climate trends.

22) Page 2-15. "*For example, the irrigation water use in the Texas State Water Plan is calculated by multiplying the total acreage (within a county) for a given crop with the individual crop water needs (supplied by the National Resources Conservation Service* – NRCS)." This statement is incorrect. Since 2003, TWDB staff have calculated "individual crop water needs" or irrigation rates for the different TWDB crop categories. These are evapotranspiration (ET) based estimates that are calculated using methods set forth in "*Mean Crop Consumptive Use and Free-Water Evaporation for Texas*" (John Borrelli, Clifford B. Fedler, and James M. Gregory) as a starting point, along with data collected and reported by the Texas ET Network and the Texas High Plains ET Network. In addition, the Farm Service Agency (FSA) is the source for irrigated acreage data. Lastly, surface water data supplied by TCEQ, Texas Water Masters, and comments from Groundwater Conservation Districts are taken into account. Please revise the draft report to reflect this.

Completed

23) Page 3-5, Section 3.1.1.1. The report cites two major sources of uncertainty in predicting climate conditions – model uncertainty and uncertainty in carbon emissions. Please comment on whether other sources identified in page 2-8 that lead to climate uncertainty (solar radiation, fluctuations in Earth's orbit, …) have been identified as less uncertain, and on the time-scales associated with variation in each of these factors.

Please see response to comment #15.

24) Page 3-12, first paragraph of Section 3.1.2.1: The reports states that per capita use is: "*The average amount of water that a person uses in a year*" This is incorrect. Per capita usage as defined in the regional planning process represents total water use in the municipal category (residential plus commercial and institutional use) divided by population. It represents the amount of water necessary for a city to meet the needs of its people and its businesses, expressed on a per resident basis. Please revise accordingly.

Completed

25) Page 3-13. The sentence beginning with "*No migration is obviously the least conservative ...*" is incorrect. In counties where out-migration has occurred, the no migration scenario often results in the highest population and demand projections. Please revise this sentence to reflect this possibility.

Completed

26) Page 3-15, 2nd paragraph, 3rd sentence. See comment number 13.

Completed

27) Page 3-22, "*Planning Under Uncertainty*" inset. It is unclear that maximization of likelihoods is proposed in this report. Please identify where in the process this maximization occurs, or please reword to say "… *Strategies are proposed to achieve a particular level of reliability for meeting goals for a range of possible outcomes*."

Completed

28) Page 3-29, paragraph 1. Option A+C is missing in the discussion. Please include.

Completed

29) Page 4-3, paragraph 2. Please provide references for the VIC model.

Completed

30) Pages 4-18, 4-19, Figure 4-13. The cumulative probability for the "*Uncertainty in Climate Only*" shows the impact of uncertainty in combined population and usage when compared to the "full cumulative probability", not just of population as is suggested in the discussion. Similarly, the cumulative probability for the "*Uncertainty in Population Only*" shows the impact of combined climate and usage, not just of climate. Please change the discussion to reflect this or present the cases of "*Uncertainty in Climate and Usage*" and "*Uncertainty in Population and Usage*" to show the impacts of population and climate, respectively.

'Uncertainty in Climate Only' has deterministic population and usage rate; 'Uncertainty in Population Only' has deterministic supply and usage rate. Comparing these distributions to the 'Uncertainty in Climate and Population' shows the impact population uncertainty and climate uncertainty have on the water need distribution, respectively. The cases of 'Uncertainty in Climate and Usage' and 'Uncertainty in Population and Usage' have not been considered here because usage rates were demonstrated to have very little impact on the water need distribution. The discussion has been modified to emphasize and clarify this.

31) Page 4-19, footnote. Please change "… for climate+population …" to "… for *climate+population+usage rate*…"

Completed