How Do North American Water Agencies Define Water Supply Level of Service?

A Report Prepared For The Water Utility Climate Alliance

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Executive Summary

The concept of Level of Service (LOS) is widely used in water supply planning to define system-wide performance goals and evaluate the need for new infrastructure investment. In principle, water supply LOS defines quantitative performance criteria and specific risk tolerance thresholds to guide infrastructure decision-making. However, in practice, there is no accepted industry-wide guidance on how water managers should define and evaluate LOS. In this report, we present a framework for water supply LOS evaluation using five core elements – system dynamics, future scenarios, performance indicators, risk tolerance, and equity. System dynamics refers to the approaches that water managers employ to understand the distinct components and interdependencies within their water supply systems and inform decisions (e.g., water supply and financial modeling). Future scenarios refer to the uncertainties water managers consider when evaluating LOS and how these uncertainties are sampled or explored in the context of understanding and modeling the system dynamics. Performance indicators represent the choices that water managers make to translate model output across future scenarios into decision-relevant metrics. Risk tolerance defines performance levels or thresholds that specify acceptable performance indicators to be achieved. Finally, equity relates to how water managers employ performance goals across water users, incorporating important historical and demographic context into water planning and management decisions.

Through structured interviews with representatives from water agencies serving 12 major metropolitan areas across North America, we summarize how each aspect of water supply LOS is at present incorporated into water systems' decision-making. Our findings reveal diverse definitions and applications of LOS in water supply decision-making across water agencies. The interviews highlight several general trends and gaps in current practice regarding LOS, including:

- All surveyed water agencies had sufficient capacity to utilize sophisticated computational models to represent water supply system dynamics. However, the majority of the agencies model water supply risk independent of financial risk, potentially hiding trade-offs between supply reliability and financial stability when defining specific LOS requirements.
- Exploratory modeling with plausible scenario ensembles is gaining popularity with water managers, though currently only used by a minority of the surveyed water agencies.
- Water agencies utilize a diverse array of performance indicators, the most popular of which represent the reliability of water storage.

- Few water agencies have clear policies regarding risk tolerance, and water managers could benefit from recent literature regarding robustness and Decision Making Under Deep Uncertainty.
- Equity is an element of LOS with growing importance and is recognized as a core part of system LOS by most surveyed water agencies and an area that warrants further study and guidance.

Introduction

Planning and timing water supply infrastructure investments is a core challenge for urban water supply managers (AWWA, 2023). Effective infrastructure investment portfolios must carefully balance water supply risks from drought and other climate-related risks with financial risks stemming from new debt to finance investments (Kane et al., 2016; Boyle, 2014). Striking this balance is complicated by large uncertainties regarding how global climate change will impact local water resources, the direction and speed of future water demand changes, and evolving regulations regarding water quality and management (e.g., the recent changes to federal standards regarding PFAS; Wang et al., 2022; Rachunok & Fletcher, 2023; Hoa et al., 2025; EPA, 2024). Traditionally, many North American water utilities have used a deterministic approach to determine the timing and volume of new water supply sources (i.e., no formal accounting for uncertainties; Asefa et al., 2015). Commonly applied "firm yield" approaches, illustrated in Figure 1a, utilize a conservative estimate of available supply (the "firm yield") and a deterministic projection of future demand. Under Firm yield approaches, the timing of infrastructure investments is based on when and by how much water demand is projected to exceed available supply (illustrated by point A in Figure 1a). The volume of new supply needed from the new infrastructure investment is determined by the rate of growth in the demand projection.

While the firm yield approaches are simple and intuitive for water managers, their reliance on deterministic projections makes them prone to inadequately characterizing both water supply needs and financial risk (Asefa et al., 2015). In major metropolitan areas in North America, water managers have largely moved beyond deterministic analysis by acknowledging uncertainty in demand projections, which are notoriously difficult to project accurately (House-Peters et al., 2011). Figure 1b illustrates a planning framework incorporating uncertainty into demand projections while maintaining a deterministic estimate of firm yield. Demand projections used in this style of analysis can either take the form of a probabilistic demand forecast or a set of discrete scenarios that describe differing levels of growth. Under the most extreme demand scenario shown in Figure 1b, water demand exceeds available supply at point B, ten years earlier than point A, estimated using the deterministic projection. However, in low-growth demand projections, the demand never exceeds available supplies, and new supply infrastructure is not required. The approach shown in Figure 1b represents a shift in emphasis in the decision-making process, from a need to precisely project future demand growth to a question of risk tolerance by decision-makers. Evaluating multiple scenarios of demand growth can also inform decision-makers about the value of adaptive measures, such as demand curtailment, that may prevent the most extreme demand growth scenarios.

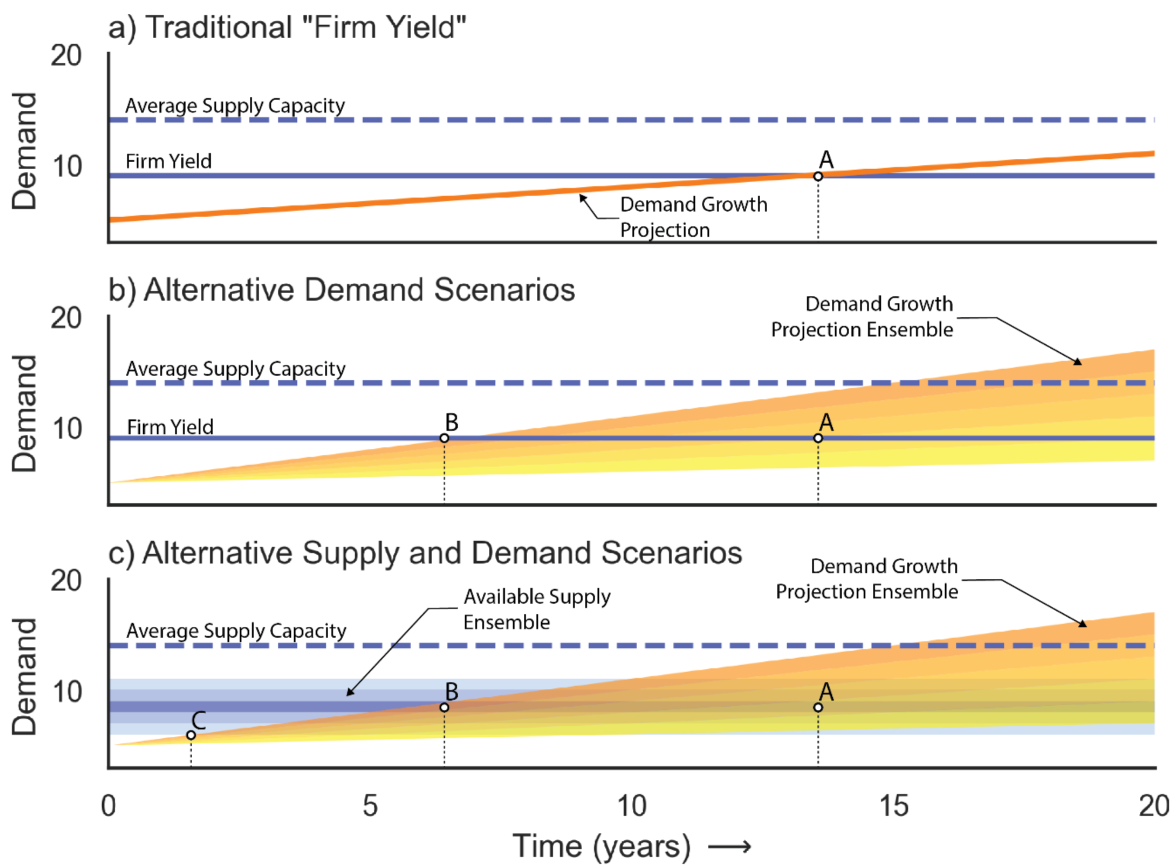


Figure 1: The evolution of water supply planning from traditional deterministic analysis to ensemble modeling of supply availability and water demand growth. a) A traditional firm yield approach that estimates the timing of new infrastructure using deterministic projections of supply (the "Firm Yield"), blue solid line, and demand growth, orange line. b) An approach that utilizes multiple demand growth projections, shown in the orange shading. c) An approach that acknowledges uncertainty in both supply, blue shading, and demand, orange shading.

While incorporating uncertainty in demand projections represents a step forward in water supply planning, it still assumes a reliable and deterministic estimate of available water supply. Figure 1c illustrates a planning framework that recognizes uncertainty in both demand growth and available water supply. It includes a range of available supply estimates, shown in blue shading, rather than a single estimate of firm yield. The planning framework shown in Figure 1c is less reliant on assumptions about future supply and demand. It provides decision-makers with a range of scenarios regarding the timing of new infrastructure. Under a “worst-case” scenario, illustrated by point C, new infrastructure must be developed and brought online with the utmost urgency, among all the trigger points shown in Figure 1. Conversely, under a “favorable” future scenario, where demand grows slowly and available supply exceeds expected estimates, new infrastructure may not be required during the planning horizon. The time it takes to bring new supply sources online is an additional consideration that can be evaluated with the methodology illustrated in Figure 1c. Project completion depends on both project and regulatory requirements and may take several years and, in some cases, more than a decade.

The uncertainty represented within Figure 1c provides a more holistic representation of plausible future conditions and allows decision-makers to examine trade-offs between water supply and financial risks explicitly. However, including additional uncertainty also requires a more direct engagement with risk tolerances in infrastructure investment planning. To fully utilize the information illustrated in Figure 1c, water utilities must have a clearly defined "Level of Service" (LOS) that defines acceptable system performance and articulates the water utility's risk tolerance. Since no utility can afford to invest in supply sources at a level that can withstand all future scenarios stemming from both demand and supply extremes, understanding the level of investment through careful systems-wide LOS exploration is crucial. Although utilities vary significantly in how they operationalize LOS requirements, as shown in this report, their processes on major infrastructure decisions directly connect to these LOS concepts.

A unified framework for water supply Level of Service

Water supply LOS is a commonly used concept in water supply planning (Khan et al., 2009; Borgomeo et al., 2014; Asefa et al., 2015; Han et al., 2017); however, to date, it has no widely accepted industry-wide definition. In Figure 2, we address this gap by presenting a conceptual framework that defines LOS using five primary components – system dynamics, performance indicators, future scenarios, risk tolerance, and equity. System dynamics refers to the models and methods that water managers use to explore relationships within the physical water supply system and the financial implications of future water supply investments. Future scenarios incorporate plausible projections about system uncertainties, such as demand growth or available supply. Performance indicators are the measures that water managers use to transform information about the water supply system dynamics (observations and/or model output) into meaningful evaluation metrics when assessing different candidate infrastructure investment decisions. Risk tolerance refers to the limits of acceptable risks within a water supply system. Risk tolerance encompasses attitudes regarding the risks of water supply shortfalls and financial risks stemming from new infrastructure investments. Equity refers to the distributional outcomes of performance across water users and how water agencies incorporate historical and demographic context into water planning and management decisions (Osman & Faust, 2021; Fletcher et al., 2022).

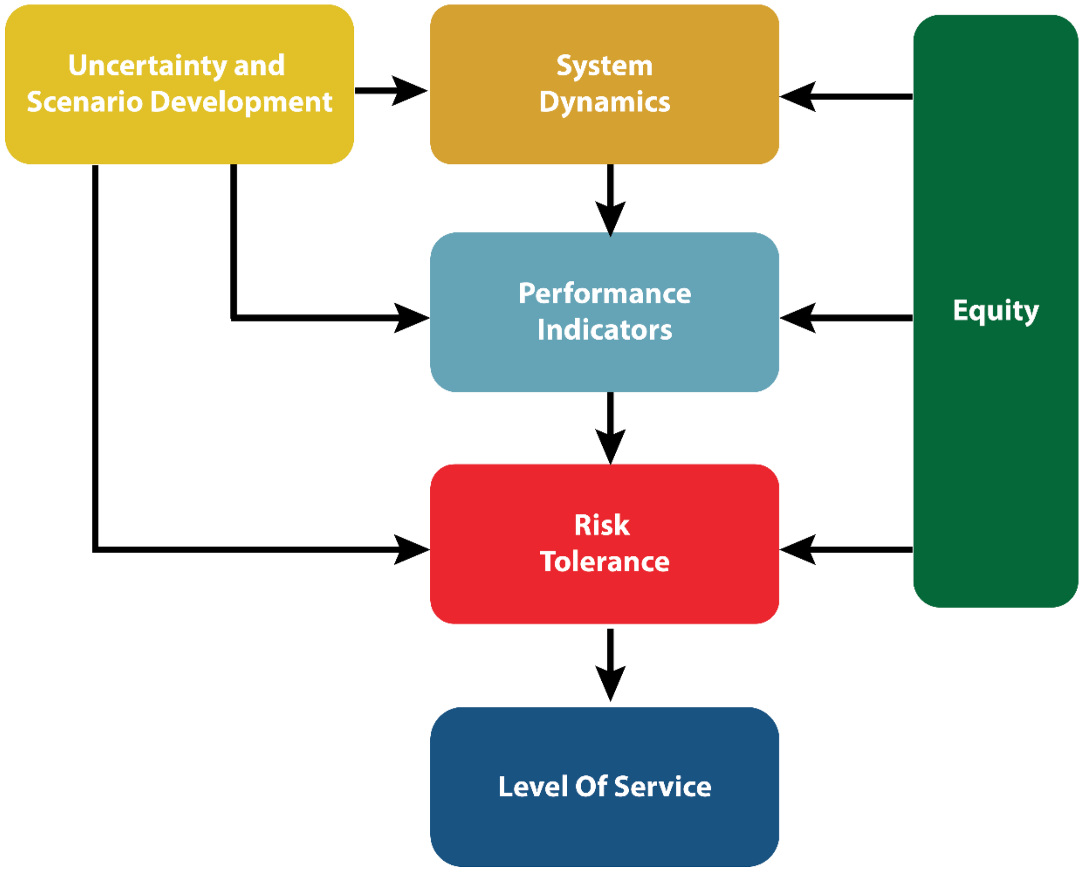


Figure 2: A conceptual framework for water supply Level of Service (LOS)

While water managers recognize each component of the LOS framework illustrated in Figure 2, no industry-wide standards currently exist to guide them in addressing each component of LOS or integrating these concepts into future planning efforts. To understand how water managers approach water supply LOS, we conducted a series of structured conversations with 12 water agencies from major metropolitan areas across North America (Figure 3). Through our discussions, we sought to 1) provide a baseline for how water managers currently utilize the concept of LOS to inform water supply planning efforts, 2) identify common challenges for evaluating LOS in urban water supply systems, and 3) highlight opportunities for future innovation in this area. This report summarizes the responses of the 12 water agencies and contextualizes them within the LOS framework introduced in Figure 2. The interview questions can be found in Appendix A of this report.

Figure 3: Water agencies surveyed for this report

The remainder of this report uses the framework presented in Figure 2 to summarize how the 12 water utilities surveyed in this study incorporate LOS concepts into decision-making for water supply infrastructure investments. Section 2 summarizes how the twelve water agencies model system dynamics and explores how modeling choices may influence perceived LOS. Section 3 discusses the treatment of uncertainty and the development of future scenarios for LOS evaluation and summarizes the types of uncertainties incorporated by the 12 surveyed agencies. Section 4 presents an overview of common performance indicators and reviews how surveyed water agencies incorporate performance indicators into LOS evaluations. Section 5 discusses risk tolerance in the context of infrastructure investment planning. Section 6 explores how water agencies incorporate equity considerations into water supply LOS. Finally, Section 7 summarizes opportunities and challenges facing water agencies across North America and provides a set of best practices for effectively incorporating LOS into infrastructure planning.

2. Systems dynamics

Water supply infrastructure investment decisions are fundamentally shaped by the choices water managers make regarding how to model system dynamics. In the context of water supply LOS, systems dynamics may include physical processes that influence the water supply system (e.g. climate, hydrology, reservoir storage, groundwater levels, water distribution systems), operational decisions (e.g., reservoir releases, short-term drought mitigation measures, source dispatch), and finances (e.g., debt service, revenues, water rates, reserve fund balances). A helpful notion when exploring how water utilities model system dynamics is a control volume, a concept from thermodynamics that has been used to conceptualize human-natural systems modeling (Srikrishnan et al., 2022). In the context of water supply LOS, a control volume refers to the portion of the system whose dynamics are explicitly modeled during LOS evaluation. Early in the planning process, water managers must decide what system components are included in the control volume and which elements will be treated as external model inputs or outputs. In this section, we explore how the control volume concept can be used to frame water supply LOS evaluations and summarize how the 12 water agencies surveyed in this study capture system dynamics through quantitative modeling.

Figure 4 illustrates two frameworks for modeling LOS systems dynamics using control volumes. In Figure 4a, the LOS control volume includes representations of the physical system and operational decisions. Candidate policy alternatives (i.e., infrastructure investment options, short-term drought mitigation policies) and supply uncertainties (i.e., demand growth and hydroclimate scenarios) are inputs to the control volume. The output of the control volume is an estimate of water supply LOS. The financial implications of measures needed to maintain water supply LOS are modeled in an independent control volume, with the water supply policy, financial actions (i.e., water rate and bond structures), and financial uncertainties treated as control volume inputs. The LOS evaluation illustrated in Figure 4a represents a sequential approach to infrastructure decision-making, where water managers first explore how future infrastructure decisions influence water supply LOS and then pass this information to an independent financial team to evaluate the financial implications of candidate investment decisions. This process resembles traditional modeling frameworks utilized by utilities in North America and most water agencies surveyed in this study (Figure 5).

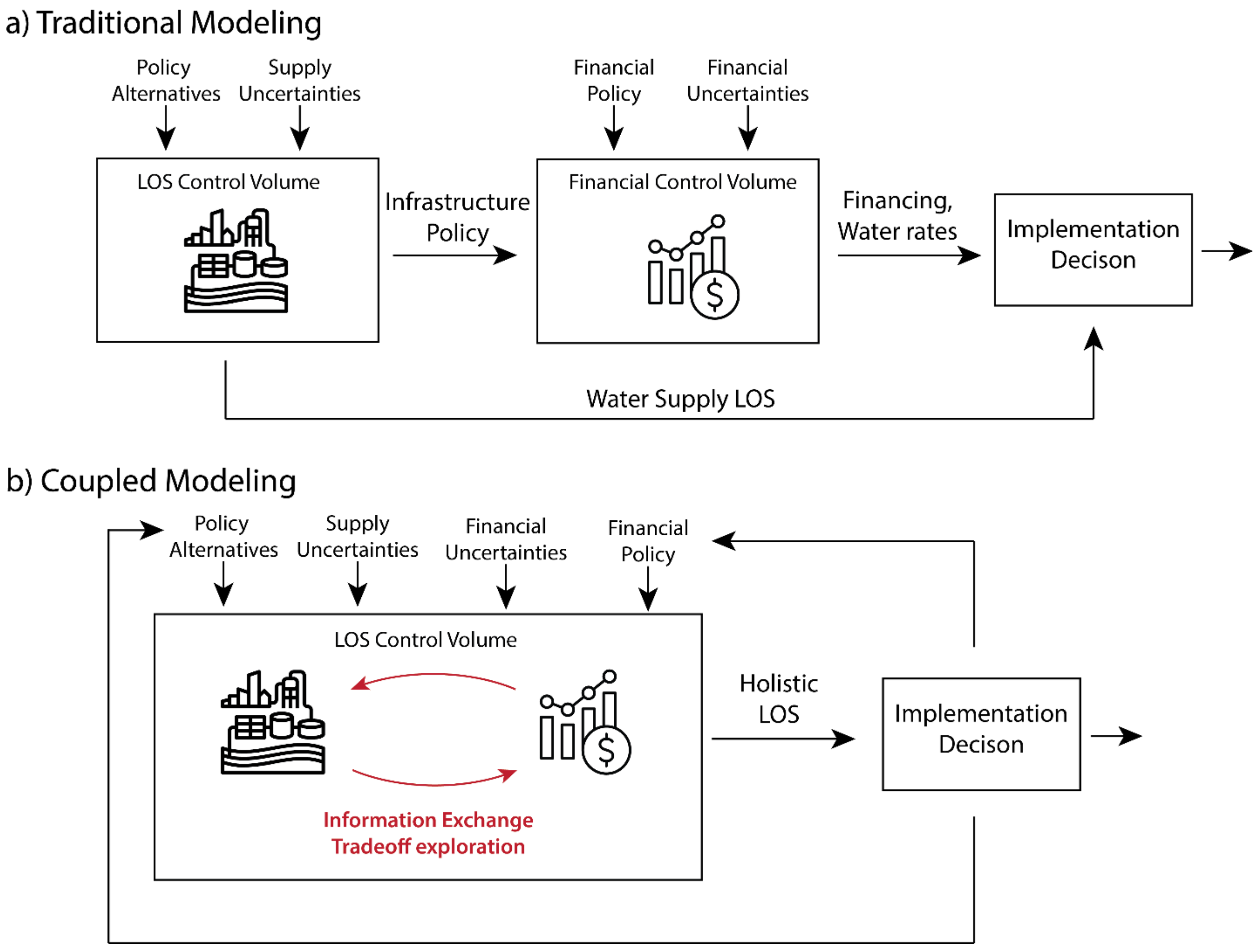


Figure 4: Control volume representation of LOS evaluation. a) A traditional approach where water supply modeling and financial analysis are conducted using independent control volumes. Infrastructure alternatives are evaluated using the results from modeling the water supply system, and results are passed to financial modelers to assess the impact of investments on future finances. b) A coupled modeling approach, where water supply and financial modeling are conducted in a single control volume. This approach allows water utilities to explore trade-offs and interdependencies between water supply and financial risk.

There is a growing awareness among water managers that treating water supply and financial considerations independently increases risks to both water supply reliability and utility budgets (Hughes et al., 2014; Dickinson et al., 2015; Smull et al., 2022; Gorelick et al., 2023). Debt burden from infrastructure investment impacts water agencies' ability to manage water rates, respond to drought crises, and ability to finance future infrastructure projects (AWWA, 2011). Credit rating agencies (e.g., Moody's, Fitch) assign credit ratings – which strongly influence utilities' ability to finance future infrastructure – with structural assessments of financial health and robust long-term planning that evaluate metrics such as debt covenant ratios (the ratio between annual revenues and debt service payments; Tsagarakis, 2013; AWWA, 2011). LOS evaluations that utilize independent control volumes for LOS evaluation and financial analysis do not explicitly capture the important feedbacks between water supply investments and financial risk. Recent work has proposed coupled modeling frameworks, illustrated in Figure 4b, that evaluate water supply and financial risks within a single control volume (Zeff et al., 2016; Trindade et al., 2020; Gorelick et al., 2023). The coupled analysis of water supply and financial stability in Figure 4b allows water managers to capture feedbacks between supply and financial risks, evaluate trade-offs between supply reliability and financial stability, and adaptively explore investment options (Sahin et al., 2018; Gorelick et al., 2023). While coupled water supply and financial modeling has been a growing subject of academic research, our conversations with North American water agencies indicate that water management practitioners have not widely adopted these ideas (Figure 5). However, it is important to note that current and projected water availability and population growth vary between these agencies; in some cases, availability remains greater than projected needs, and therefore, future needs can likely be met without augmentation, through measures including optimization, efficiency, and reuse.

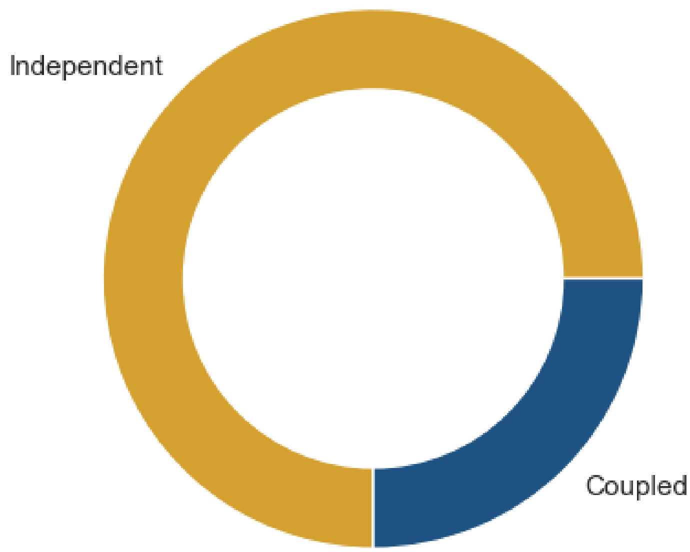
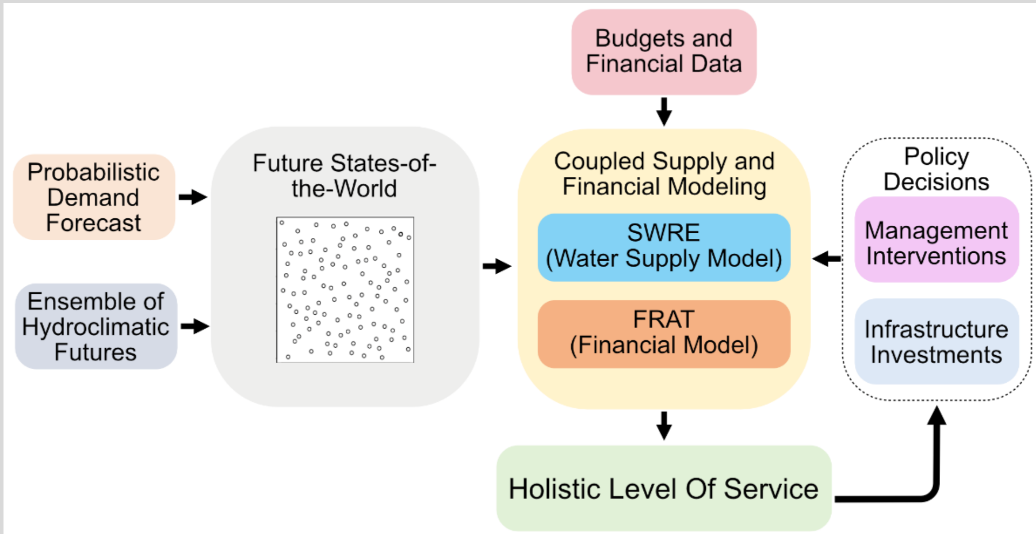


Figure 5: Coupled financial modeling by surveyed water utilities. Only three of the twelve utilities in this study explicitly couple water supply and financial modeling during LOS evaluation.

Box 1: Coupled Water Supply and Financial Risk Assessment at Tampa Bay Water



Tampa Bay Water (TBW), a regional water wholesaler serving about 2.6 million residents in Southwest Florida, uses a coupled water supply and financial modeling framework to evaluate future infrastructure investment decisions (shown in the figure above). TBW's LOS evaluation procedure couples two modeling systems - the System-Wide Reliability (SWRE), which models water supply, and the Financial Risk Assessment Tool (FRAT), which models utility finances. TBW uses these models to explore the impacts of new infrastructure investments on water supply risk. SWRE modeling output is passed to FRAT to evaluate the financial risk associated with candidate investment portfolios. FRAT uses historical budgetary data and future projections to explore the financial implications of new infrastructure investments, returning covenant ratios and projected changes in water rates. Results from SWRE and FRAT are utilized by a team of engineers and financial analysts to develop a holistic assessment of system LOS. The coupled modeling helps TBW evaluate candidate infrastructure investment options and determine the timing of new infrastructure investments. The SWRE+FRAT framework has been successfully utilized to support over $200 million of new infrastructure investments in the coming decade. The coupled modeling framework was the product of a successful collaboration between engineers at Tampa Bay Water and a team of interdisciplinary researchers from the University of North Carolina, Chapel Hill and Cornell University. The success of SWRE+FRAT illustrates the benefits of coupled water supply and financial modeling and highlights the potential of collaborations between practitioners and researchers.

Another choice regarding system dynamics in LOS evaluations is the planning horizon used to evaluate future performance. Planning horizons vary depending on many factors, including technical considerations, regulatory requirements, and local policies. Selecting an appropriate planning horizon is a challenge for water managers – water supply infrastructure has a service life of multiple decades. However, uncertainties regarding future system conditions increase as projections extend further into the future. Figure 6 illustrates the frequency of planning horizons utilized by water utilities surveyed in this study. Half of the water agencies use planning horizons between 25-45 years. Three agencies use planning horizons between 10-25 years, and two utilities utilize planning horizons greater than 45 years. The choice of planning horizon has important implications for water supply LOS, shaping how future uncertainties are incorporated into planning. In the next section, we explore methods that water agencies use to incorporate uncertainty into LOS evaluations.

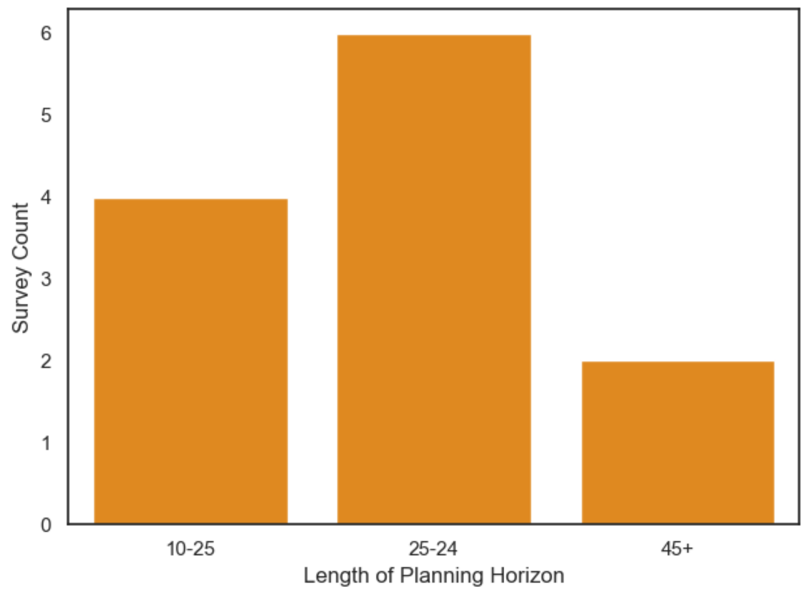


Figure 6: Planning horizon used by surveyed water agencies

3. Uncertainty and Scenario Development

The sources of uncertainty considered and how they are sampled within water supply LOS evaluations have strong implications for decision-making. Neglecting to evaluate plausible but challenging future conditions or overlooking important sources of uncertainty may cause decision-makers to overestimate water supply LOS, exposing a system to future water supply failures (Asefa et al., 2015). Conversely, LOS evaluations that include implausible combinations of uncertainties or unrealistically unfavorable samples of future conditions may underestimate water supply LOS, increasing future costs and heightening financial risks (Herman et al., 2014; Gold et al., 2023). The 12 water agencies surveyed in this study face a wide range of uncertainties impacting future supplies and demands. In this section, we review the primary sources of uncertainty considered by the 12 agencies and summarize how the uncertainties are incorporated into their LOS evaluations.

Sources of uncertainty

Figure 7 summarizes the sources of uncertainty considered by the 12 surveyed water agencies by grouping sources of uncertainty into the five categories presented in Table 1. All surveyed agencies recognize stationary hydrologic variability, water demand, and climate change as important sources of uncertainty for water supply planning. However, the manifestation of climate change-related uncertainties varies depending on the geographic location and portfolio of available supplies used by the water agencies. For example, the Philadelphia Water Department is currently focused on incorporating climate change into water supply planning by modeling future sea level rise, which may increase the salinity of water supplies drawn within the tidal Delaware River. In contrast, agencies in the Western US that depend on the Colorado River incorporate climate-driven changes in precipitation and temperature into water supply planning efforts. The surveyed agencies that receive Colorado River water also indicate policy uncertainty as an important factor for water supply planning.

Table 1: sources of uncertainty utilized by surveyed water utilities

Source of uncertainty	**Description**
Stationary hydrologic variability	The variability of rainfall, evapotranspiration, and streamflow from the observed historical record
Water demand	Changes to water demand stemming from future population growth/loss, water consumption patterns, and water efficiency
Climate change	Climate-driven changes in the statistical properties of the hydroclimatic system, changes in demand, or changes in other system attributes such as water quality
Financial conditions	Factors that influence the financing of future infrastructure, such as interest rates and budgetary changes
Policy	External policy changes that may impact water supply availability (e.g., future Colorado River agreements, water quality standards)

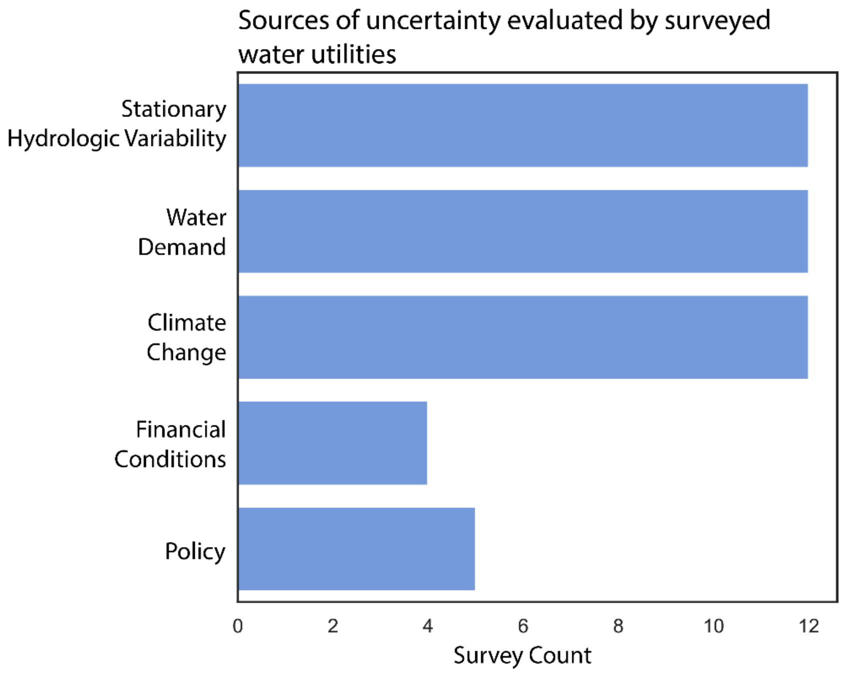


Figure 7. Sources of uncertainty incorporated during LOS evaluation by surveyed water utilities

Accounting for uncertainty in LOS evaluation

The method of sampling uncertainties in water supply LOS evaluation should reflect the type of uncertainties facing the system (Reed et al., 2022). Figure 8 introduces four broad strategies for exploring uncertainty in water supply systems planning. The top row of panels in Figure 8 illustrates each strategy for a single uncertain parameter (water demand is used here for illustration purposes), and the bottom row illustrates strategies for sampling two parameters simultaneously (illustrated with water demand and change in available supply). Deterministic projections (Figures 8a and 8e) rely on point estimates representing the best guess or expected value of future system inputs. Deterministic projections are easy to communicate and may be appropriate for near-term predictions that are supported by large amounts of observational data. However, deterministic projections do not convey the spread of possible outcomes and may lead to overconfidence in future projections.

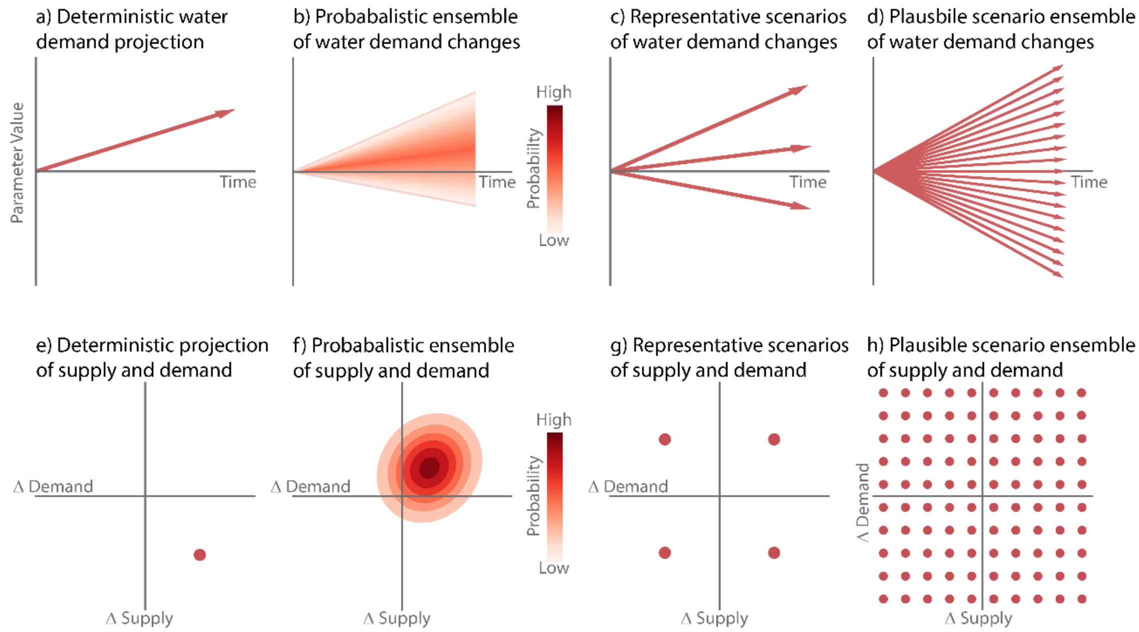


Figure 8: Uncertainty sampling strategies ranging from deterministic projections (left) to plausible scenario ensembles (right). The top row of plots illustrates each method for a single uncertain (water demand is used here for illustration purposes). The bottom row illustrates sampling for two uncertainties simultaneously (water demand and available supply).

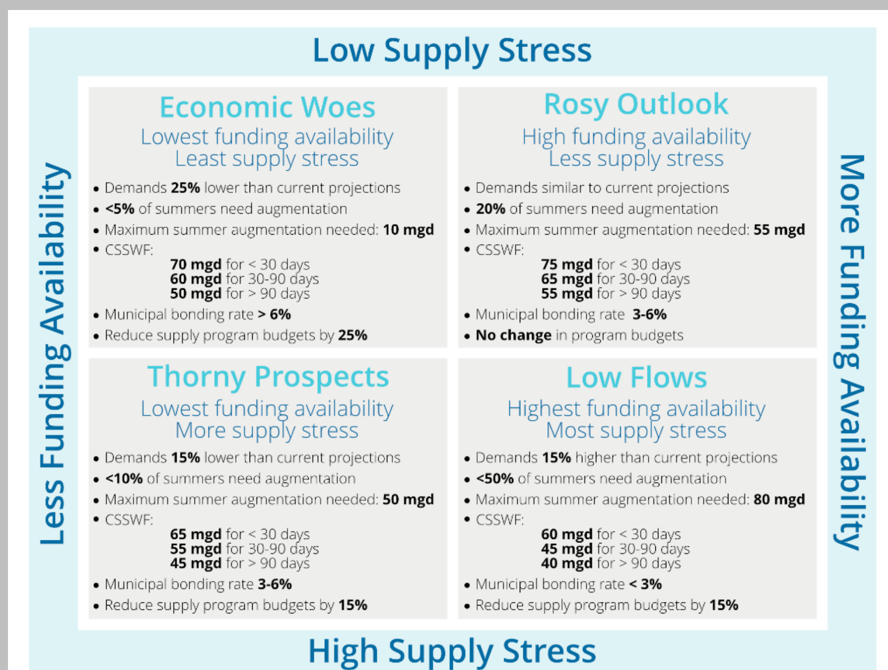
Probabilistic projections, illustrated in Figures 8b and 8f, are intended to explore uncertainties that are well-characterized by historical data and a strong understanding of underlying statistical properties (Asefa et al., 2015). Rather than relying on a point estimate of future change, probabilistic projections use observational data and knowledge about system processes to construct probability distributions that describe future conditions. These distributions are then sampled to develop future states of the world to use as input for LOS evaluation. While probabilistic projections were standard practice for water resources risk assessment for many years (Asefa et al., 2015), water resource managers have recently begun to acknowledge that they cannot suitably capture long-term uncertainties facing water supply planners, such as climate change, technological innovation, and changing demographics (Kaatz et al., 2015; Trindade et al., 2019; Wasley et al., 2020; Wasley et al., 2021;). These long-term uncertainties can generate fundamental shifts in water supply systems, reducing water agencies' ability to use historical data to project future conditions.

In long-term (decadal to multi-decadal) planning contexts, such as the sequencing water supply infrastructure investments, water managers are challenged by *Deep Uncertainty*, defined as conditions where decision-makers do not know or cannot agree upon the probability distribution of key system inputs, the system and its boundaries, and/or outcomes of interest (Lempert et al., 2002; Kwakkel et al., 2016; Marchau et al., 2019). Under conditions of Deep Uncertainty, decision-makers do not have the strong understanding of the statistical properties of uncertainties required to use probabilistic models effectively and must utilize alternative methods to explore plausible future conditions (Kwakkel & Haasnoot, 2019). In long-term planning contexts, *narrative scenarios*, illustrated in Figures 8c and 8g, can be helpful in framing future decisions. Narrative scenarios simplify complex and high-dimensional uncertainties into a small set of divergent futures, allowing planners to consider "what-if" questions about the future performance of water supply systems. These what-if scenarios allow planners to efficiently explore trade-offs between supply reliability and financial stability by envisioning representative future states of the world that encompass multiple climate, demand, and financial uncertainties.

Computational resources available to water management agencies have experienced exponential growth in recent decades. The increase in computational resources provides an opportunity for water managers to expand the breadth of uncertainties incorporated into LOS evaluations. Exploratory modeling is one increasingly popular strategy for leveraging computational capacities to expand the exploration of "what-if" questions within water supply planning (Bankes et al., 1993; Moelemi et al., 2020). Exploratory modeling refers to carefully constructed computational experiments to explore ensembles of future conditions and discover which combinations of uncertainties generate consequential outcomes for water supply systems. The computational experiments use *scenario ensembles* that capture a large number of future conditions, each treated with an unknown probability of occurrence (Figures 8d and 8f). Using exploratory modeling, water managers first evaluate many plausible future states of the world, then determine which combinations of uncertainties are most consequential for water supply LOS. This methodology, often referred to as "Scenario Discovery" (Groves & Lempert, 2007; Bryant and Lempert, 2010) can be used to select a smaller number of representative scenarios for framing decision outcomes and communicating to stakeholders. By emphasizing multiple plausible future states of the world, exploratory modeling shifts the focus of LOS evaluation from a "predict-then-act" paradigm to a decision-focused, consequence-oriented framework (Lempert et al., 2006).

During the evaluation of water supply LOS, water agencies may employ multiple definitions of "plausible" future conditions to explore different dimensions of LOS. For example, stress-testing exercises may utilize a broad definition of "plausible" future scenarios in order to capture extreme events and compounding hazards. Broadly sampled scenario ensembles allow users to ask questions such as "how far from current conditions does the system need to change before we observe adverse outcomes?" and "what combinations of uncertainties are responsible for adverse outcomes?". In contrast, analyses seeking to formally quantify operational LOS may choose a narrower definition of "plausibility" to reduce the likelihood of making large capital investments that are only cost-effective under the most extreme future conditions. The range of samples incorporated into LOS quantification is highly context-dependent, particularly in reference to discovered vulnerabilities, but may be guided by state and local resources. For example, the California Water Code requires municipalities to use the driest five consecutive years on record as a starting point for short-term drought planning (California DWR, 2021).

Box 2: Scenario Planning by the Portland Water Bureau



Adapted from Portland Water Bureau & Jacobs Engineering, (2021)

The Portland Water Bureau is a municipal water department in Portland, Oregon, serving drinking water to nearly one million people. To evaluate future water supply LOS, Portland Water developed a non-probabilistic scenario matrix that summarizes future changes in water supply and financial conditions. Supply stress is determined by water demand, the frequency and volume required for "summer augmentation" - referring to a drought mitigation strategy that compensates for low volumes in major supply sources - and the production capacity of a groundwater wellfield (CSSWF). Supply stress also encompasses moderate to extreme climate change impacts on demand and supplies. Financial uncertainties include the municipal bond rate and the changes to the supply program budgets. Portland Water uses the scenario matrix within an adaptive planning framework. Each year, the utility monitors how water supply and financial conditions are changing and uses updated data to inform future water management decisions. In the long term, the scenario matrix allows water managers to plan for a range of future water supply LOS outcomes and explore the impacts of future water management decisions.

Figure 9 summarizes the uncertainty sampling approaches employed by the surveyed water agencies. All 12 agencies utilize representative scenarios to guide LOS evaluations. These scenarios often capture future changes in water demand, climate, and financial conditions. For example, the Portland Water Bureau (detailed in Box 2) defines four representative planning scenarios encompassing changes in supply availability, water demand, and financial conditions. In addition to representative scenarios, most surveyed water agencies employ probabilistic ensembles. The water agencies use ensembles to capture the natural variability of the hydro-climatic system (five agencies) and uncertainty in future water demands (eight agencies). Four surveyed agencies use plausible scenario ensembles to explore future LOS. These ensembles usually couple uncertainties in the hydroclimatic with changes in water demand. For example, Tampa Bay Water sampled from 1,000 future scenarios of demand growth and precipitation to create an ensemble of future states of the world to explore the performance of infrastructure investment alternatives.

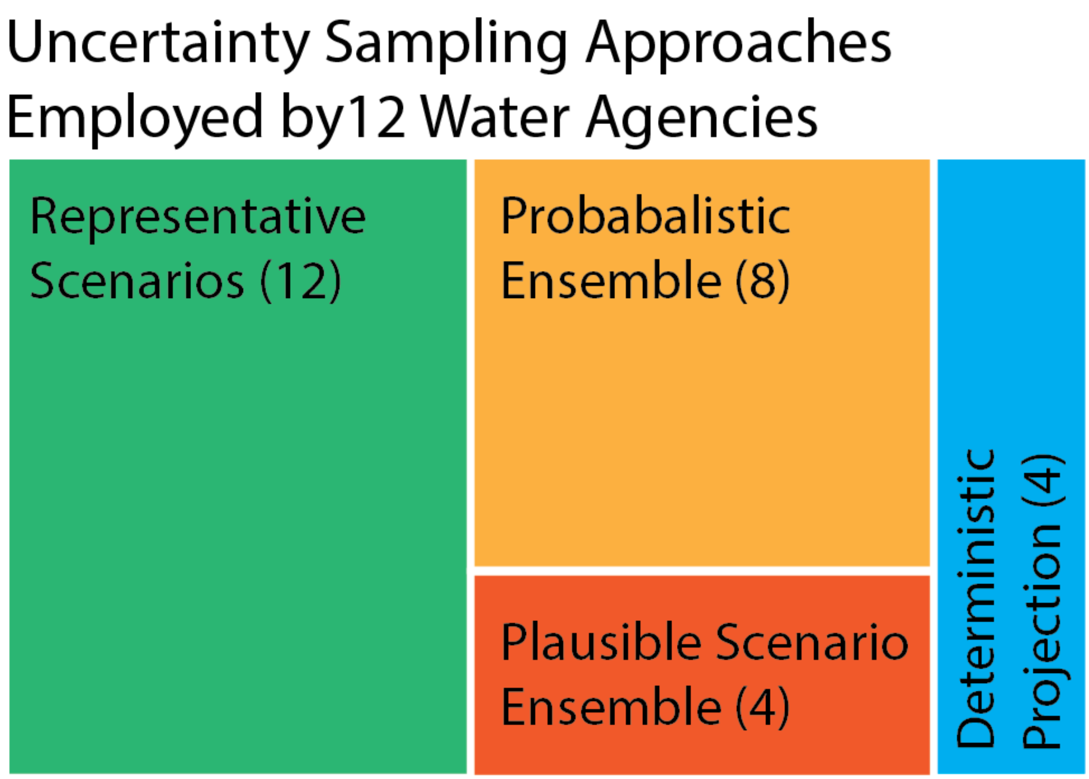
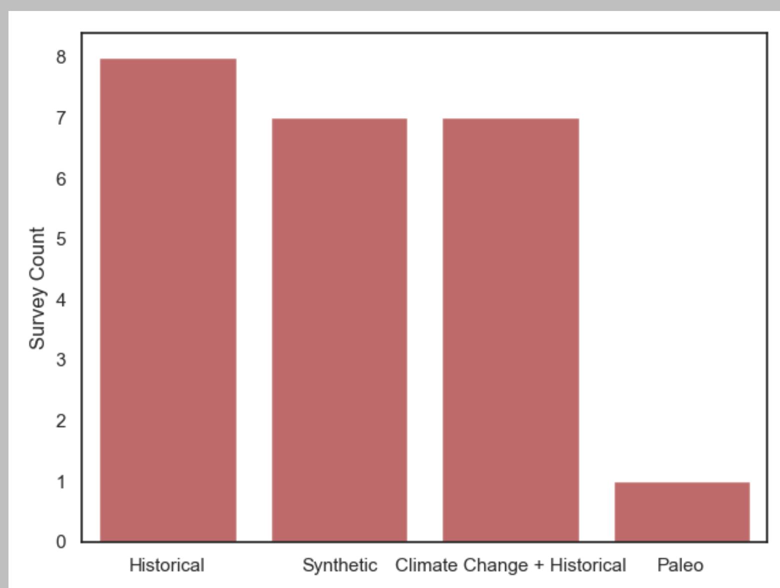


Figure 9: Uncertainty sampling strategies employed by surveyed water agencies. The area of each box corresponds to the number of water agencies that utilize each sampling approach

Surveyed water agencies often utilize multiple strategies for sampling uncertainties within LOS evaluation. For example, the Metropolitan Water District of Southern California's Integrated Water Resources Plan coupled representative scenarios with probabilistic and plausible scenario ensemble modeling (Metropolitan Water District of Southern California, 2024). Water managers first solicited input from regional decision-makers, stakeholders, and external experts regarding key drivers of system vulnerability. These uncertainties were further explored using plausible scenario ensembles to determine the most important combinations of system uncertainties. Modeling results were used to develop four planning scenarios capturing structural uncertainties within the model, including the stability of imported water supplies and demand. Finally, these scenarios were coupled with probabilistic ensembles that explore the natural variability of the system. The approach to identify uncertainty used in Metropolitan Water District's Integrated Water Resources plan is one example of how water agencies can use careful experimental design to stress test the system across challenging future states of the world while maintaining the realism necessary to hedge against over-investment. Another critical component needed to strike this balance is the selection of informative performance indicators for LOS, which is discussed in the next section.

Box 3: Survey highlight: Hydrological uncertainties

All surveyed water utilities indicated that they consider stationary hydrologic variability as an uncertainty during LOS evaluation. However, hydroclimatic systems often exhibit non-stationarity, meaning the statistical properties of the future system are different from historical periods (Milly et al., 2008). To account for the non-stationarity of the hydrologic system, the water agencies utilize a variety of methods, summarized in the figure on the right. While most agencies use historical records



to capture baseline natural variability, seven surveyed agencies utilize synthetic methods to explore hydrological uncertainties. Synthetic methods use statistical techniques to create plausible realizations of future hydroclimatic conditions with statistical properties that resemble the historical record (Stedinger et al., 1982). These properties can be altered to simulate plausible non-stationarity in the system. Many surveyed agencies apply climate change projections to the historical record to explore future conditions in warmer futures. One agency employs paleo-reconstruction, which uses tree rings or geological data to recreate hydrological conditions in the distant past, predating human measurements (Stahle et al., 2000; Gupta et al., 2023). These records often reveal extreme events beyond the range of the observed historical record and can be useful for stress-testing water supply systems.

4. Performance indicators

Performance indicators transform data about water supply system attributes into decision-relevant metrics for evaluating water supply LOS. To explore how decision-makers incorporate system attributes into performance indicators, we draw on the concepts of reliability, vulnerability, and resilience from water resources systems literature (Hashimoto et al., 1982). Figure 10 illustrates these concepts using total storage as the system attribute. Reliability describes the frequency of adverse events. In Figure 10, reliability represents the total number of months when the total storage (blue line) remains above a performance threshold (red dashed line). Vulnerability describes the severity of adverse events. In Figure 10, vulnerability describes the maximum distance total storage drops below the performance threshold. Resilience describes how quickly a system recovers from adverse events. In Figure 10, resilience is represented by the maximum duration of time for which the total storage remains below the performance threshold. Figure 11a summarizes the types of measures used by the surveyed water agencies. Reliability measures are most commonly employed, followed by vulnerability and resilience measures.

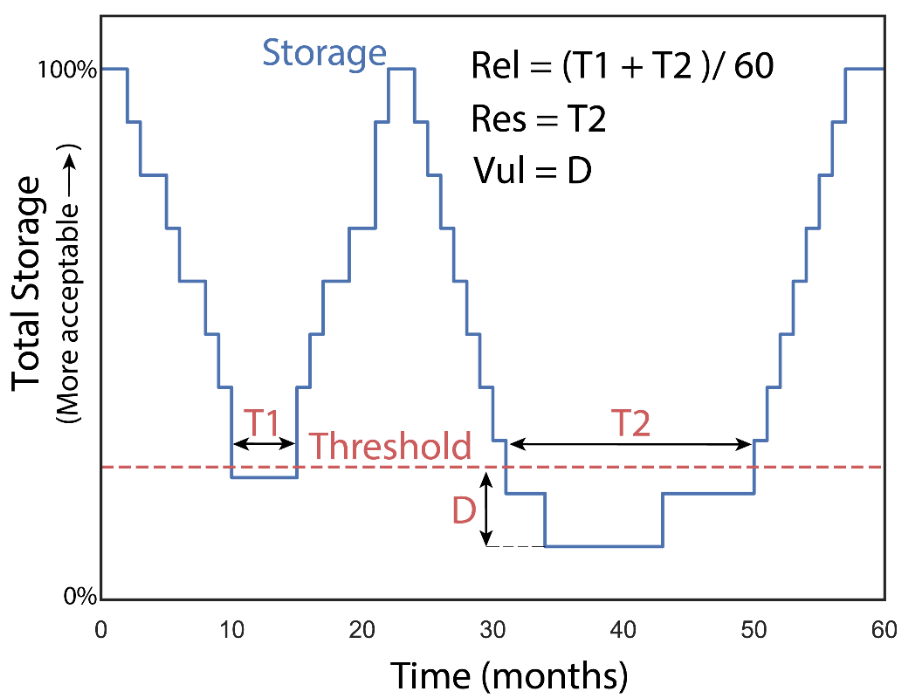


Figure 10: A conceptual illustration of common methods for how system attributes are transformed into water supply performance indicators. In this figure, total storage is the system attribute, and decision

makers have set a performance threshold indicated by the red dashed line. Over 60 months, the storage drops below the threshold two times, first for a period of T1 months, then for a period of T2 months. Reliability (Rel) is the total amount of time during which the total storage is below the threshold. Resilience (Res) is the longest period in which storage remains below the threshold. Vulnerability is the maximum depth below the threshold over the 60 months (defined above as D).

The twelve water agencies surveyed in this study utilize diverse performance indicators to assess their water supply systems. To provide a summary of the performance indicators used by the water agencies, we categorize each indicator according to what system attribute is measured and how each attribute is transformed into a performance indicator. We organize system attributes into four categories: supply–based, restriction-based, shortage-based, and regulatory/water quality. Supply-based indicators measure the volume of available water supplies, including surface water, groundwater, or both. Restriction-based indicators focus on voluntary or mandatory water use restrictions or demand curtailments during drought. Shortage-based indicators measure the gap between water demand and available supply. Regulatory/water quality indicators track permit violations, such as groundwater withdrawals, or direct water quality measures, such as turbidity. Figure 11b summarizes how the surveyed water managers utilize each system attribute within LOS performance indicators. Across the twelve utilities, storage-based indicators are the most prevalent, followed by shortage- and regulatory/water quality-based indicators.

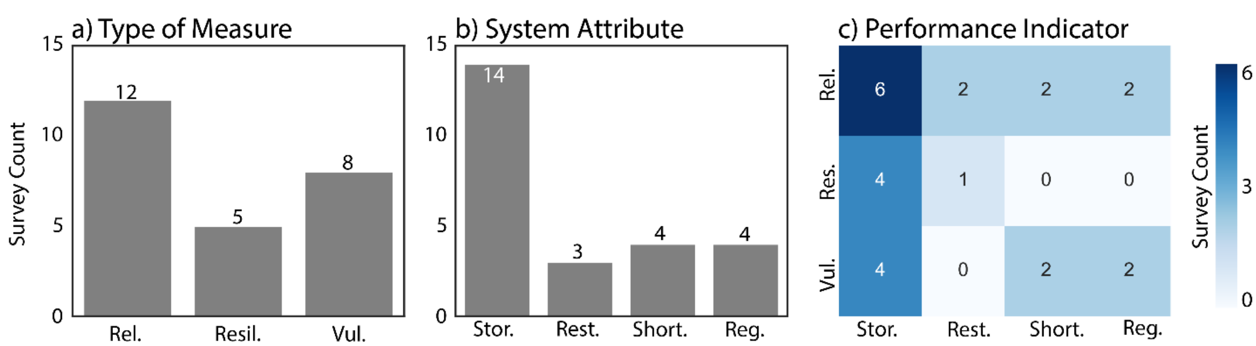


Figure 11: The components of performance indicators used by surveyed water utilities to define water supply LOS. a) The frequency that reliability, resilience, or vulnerability are used in performance indicators, b) the frequency of storage, restrictions, shortage, or regulatory attributes, c) the frequency that each system type of measure and system attribute of focus are used in combination to develop performance indicators across the surveyed water utilities.

Figure 11c summarizes how water agencies combine system attributes and measures to develop water supply performance indicators. The saturation of the colored cells represents the number of measures that incorporate each attribute-measure combination. The surveyed water agencies utilize storage-based reliability indicators most commonly. The surveyed water agencies also use reliability to measure restriction, storage, and regulatory violation frequency. Resilience measures are mainly applied to storage attributes, though one utility measures resilience using restrictions. Vulnerability is most frequently applied to storage attributes, though it is also employed to measure shortage and regulatory violations.

In sum, the surveyed water agencies utilize a wide variety of attribute and measure combinations to develop performance indicators for water supply systems. These performance indicators summarize water supply system dynamics across sampled uncertainties into relevant measures of water supply LOS. However, to be effectively incorporated into LOS evaluations, performance indicators must be coupled with acceptable or target performance thresholds that reflect the risk tolerance of water agencies. In the next section, we explore how water agencies apply risk tolerance to create clear definitions of water supply LOS and review how the 12 surveyed water agencies apply risk tolerance during LOS evaluation.

5. Risk Tolerance

A water agency's risk tolerance specifies actionable criteria defining acceptable performance thresholds and the frequency with which they may be violated. For example, a water agency may specify that supply levels must remain above 20% of capacity for 98% of an ensemble of system simulations over a time horizon of 45 years (Trindade et al., 2019). Operating water managers may first evaluate different risk tolerance thresholds and then specify identified thresholds in coordination with governing boards, elected officials, or other representatives of the general public.

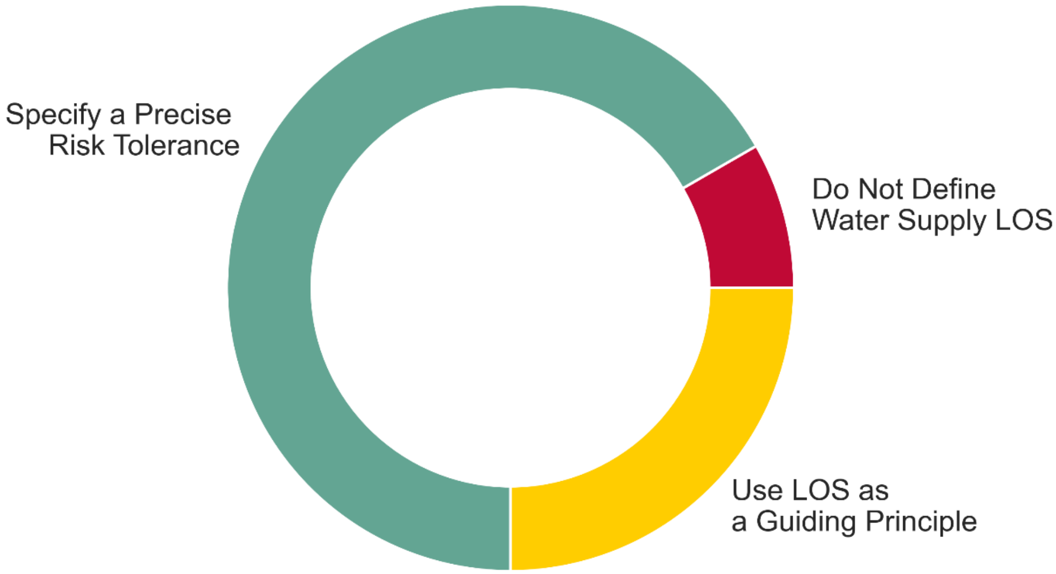


Figure 12: Risk tolerance thresholds within water supply LOS definitions of surveyed water agencies. A majority of water agencies surveyed utilize clear risk tolerance thresholds for water supply LOS. Three agencies use LOS as a guiding principle for infrastructure investment decision-making, and one agency does not utilize LOS concepts during planning.

Figure 12 summarizes how the surveyed water agencies incorporate risk tolerance into water supply LOS. The majority of surveyed agencies (8 of 12) utilize a precise risk tolerance standard to define LOS. Three surveyed agencies use LOS as a guiding principle to frame future decisions, and one has no working definition of water supply LOS. While most agencies clearly specify risk tolerance standards, there are significant differences in their applications. Several agencies indicated that their LOS standards reflect no tolerance for risk. For example, one water agency requires 100% reliability of water supplies through 2045. Another agency uses the "uninterrupted supply of drinking water" as a guiding criterion for water resources planning. Other surveyed water agencies have LOS requirements that reflect choices regarding system dynamics, scenario development, and performance indicators (as illustrated in Figure 2). For example, Seattle simulates its water system across an ensemble of historical flows and defines a firm yield that has a reliability standard of 98%. That means reservoir levels remain above a minimum operating level in all but the driest 2% of conditions (Seattle Public Utilities, 2019). Similarly, Vancouver historically specified 1-in-50 years as the acceptable frequency for water shortages; however, in recent years, water supply studies have been directed to assume 100% reliability of water due to significant growth in the population and economy of the region.

While the majority of water agencies surveyed in this study indicated clear risk tolerance criteria that specify water supply LOS, two challenges stand out from the survey responses. First, the survey results in this study indicate that a highly conservative risk tolerance for water supply shortage is the traditional default for water managers. However, achieving extremely low water supply risk often entails large infrastructure investment, which increases financial risk for water agencies (Gorelick et al., 2023). By setting highly conservative risk tolerance thresholds for supply shortage, decision-makers may inadvertently expose their agencies to increased financial risk. The practical exploration of trade-offs between water supply and financial risk requires an expanded control volume for modeling system dynamics, illustrated in Figure 4b. Of the 12 surveyed water agencies, only three employ a coupled modeling approach for water supply and financial modeling (Figure 5). The development of coupled modeling frameworks that jointly evaluate water supply and financial risk represents a substantial opportunity for water agencies to improve water supply LOS evaluation.

While the specified risk tolerance thresholds of surveyed water agencies varied, no agency indicated that water supply failures were ever acceptable. Instead, supply risks that cannot be actively eliminated through standard operational management measures are addressed using residual risk policies that govern water supplies during drought. Residual risk management plans include augmenting existing supplies through emergency sources, promoting temporary water conservation programs, and implementing demand curtailment when necessary. Explicitly incorporating residual risk portfolios into LOS evaluations represents a further opportunity for water agencies to specify risk tolerance standards that recognize the practical limitations of current supplies and financial risks. Crisis response planning exercises, such as the use of serious gaming scenarios to explore risk tolerances and evaluate planning alternatives, also show potential for improving risk tolerance criteria for water supply systems (Fleming et al., 2020).

A second challenge for specifying effective risk tolerance criteria in LOS evaluations is Deep Uncertainty. In the presence of deep uncertainty, the likelihood of adverse outcomes cannot be assessed, challenging the implementation of actionable risk tolerance criteria. While several utilities in this study acknowledged the presence of Deep Uncertainty and included exploratory modeling methods as part of their planning process (Section 3), no surveyed water agency discussed how Deep Uncertainty is incorporated directly into their measures of water supply LOS. Recent developments from water resources literature may help fill this gap (Francois et al., 2024). The concept of robustness – the insensitivity of design performance to errors, random or otherwise, in the estimates of those parameters affecting design choice (Matalas & Fiering, 1977) - has been adopted in literature to explore the performance of systems under deep uncertainty (Herman et al., 2015; Beh et al., 2017; Erfani et al., 2018; Borgomeo et al., 2018; Brown et al, 2020; Gold et al., 2023). Robust systems are designed to perform well across a wide range of plausible future conditions rather than optimally across a single predicted future. The definition of "plausible" is highly context-dependent and may have strong implications for the perceived balance between supply reliability and financial stability. While evaluating robustness, decision-makers can explore multiple "rival framings" of future conditions, each representing competing hypotheses of what futures are considered "plausible" (Quinn et al., 2020).

To incorporate robustness into water supply LOS, performance indicators must first be evaluated across many plausible future states of the world (using plausible scenario ensembles, described in Section 3). Next, a robustness metric summarizes the system performance across futures without applying probabilistic estimates of outcomes (McPhail et al., 2018). For example, satisficing metrics measure the fraction of future states of the world where a system is able to meet a set of performance criteria determined by decision-makers. A water agency may seek a robust solution by examining how many future states of the world the system maintains 99% reliability while ensuring debt covenants are met. For more details on robustness metrics, see Herman et al., 2015 and McPhail et al., 2018.

6. Equity

The choices made regarding the treatment of system dynamics, uncertainty evaluation, performance indicators, and risk tolerance shape the definition of water supply LOS. However, an additional and historically under-considered factor is whether water supply LOS – and the costs needed to achieve sufficient LOS – are equitably distributed across customers. Recent work has highlighted the need for water resources modelers and managers to improve the representation of equity and affordability considerations in water resources planning and management (Osman & Faust, 2021; Fletcher et al., 2022). In the United States (US), more than two million people lack access to clean drinking water at home (US Mission to the United Nations, 2023). Nearly 12% of the US population faces unaffordable water rates (defined by the US EPA as households that face water bills over 4.5% of household income), primarily located in urban areas (Mack & Wrase, 2017). Further, climate change may disproportionately impact water supply reliability and affordability for historically disadvantaged communities (King et al., 2023; Water Utility Climate Alliance, 2024a; Water Utility Climate Alliance, 2024b, Water Utility Climate Alliance, 2024c). To effectively incorporate equity into water supply LOS, water agencies must ensure that modeled system dynamics effectively capture water supply for historically disadvantaged communities. Water managers must also carefully consider the choice of performance indicators used to evaluate the system and how performance is spatially and temporally aggregated. To incorporate equity considerations into LOS evaluations, the water affordability implications of achieving sufficient levels of water supply LOS must also be evaluated.

While these issues have historically been challenging for water managers to address, the majority of the 12 water agencies surveyed indicated that equity considerations were a priority in LOS evaluation (Figure 13). For example, Seattle Public Utilities uses an Equity Planning Toolkit to incorporate equity considerations at the earliest planning stages. The agency works with equity Subject Matter Experts to operationalize equity considerations within the planning process using defined procedures for processes such as stakeholder analysis, inclusive outreach, and public engagement. Other water agencies, such as Austin Water and the Portland Water Bureau, have emphasized equity considerations in asset management and water pricing planning, prioritizing equitable delivery of high-quality water supply and water affordability within the planning process. While equity challenges are pervasive within water supply systems in the US, these policies can serve as examples for other utilities looking to incorporate equity considerations into water supply planning better.

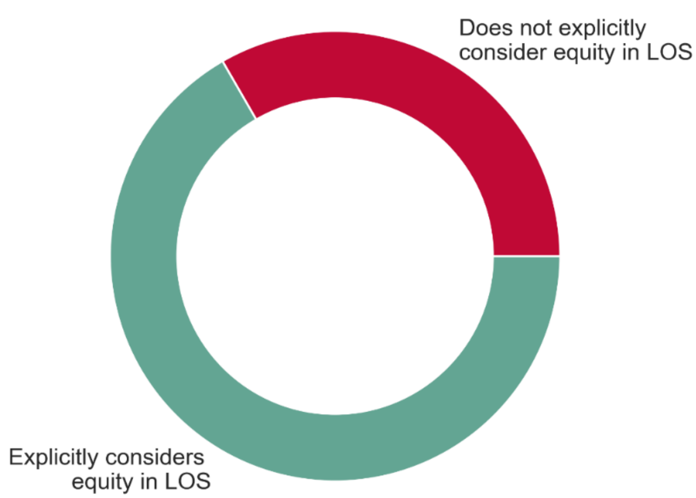


Figure 13: Equity considerations in water supply LOS across 12 surveyed water agencies. Eight of 12 surveyed agencies explicitly consider equity in water supply LOS evaluations.

7. Conclusion

This report presents a framework for defining water supply LOS using five core elements: systems dynamics, future scenarios, performance indicators, risk tolerance, and equity. Through a series of structured interviews with 12 water agencies from major urban areas across North America, we explore how each element of the proposed LOS framework is put into practice, identify commonalities and differences across surveyed agencies, and highlight ongoing challenges for LOS evaluation. Common elements of LOS evaluations across surveyed agencies include the use of sophisticated computational models to represent water supply system dynamics, the use of probabilistic methods and narrative scenarios to explore future uncertainties, and the prevalence of storage-based metrics of supply reliability to evaluate system performance. Clear definitions of risk tolerance thresholds and consideration of equity were also features of water supply LOS evaluation by most surveyed agencies. Despite these similarities, each surveyed water agency defined water supply LOS differently. Surveyed agencies utilized a wide range of uncertainty sampling strategies, performance indicators, and risk tolerance thresholds within water supply LOS evaluation.

Trade-offs between financial stability and water supply reliability challenge water managers during the evaluation of water supply LOS. Few surveyed agencies utilize a coupled modeling strategy to simultaneously evaluate water supply and financial risk, possibly hiding trade-offs between these two critical factors. Deep uncertainty in future system attributes presents a further challenge for urban water managers, complicating how risk tolerance criteria are translated into actionable LOS metrics. Recent contributions in water resources planning and management literature regarding coupled water supply and financial modeling and robust decision-making offer opportunities for urban water agencies to address these challenges and improve the development of robust and financially stable water supply infrastructure investment portfolios.

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Appendix A – Questions for Water Utilities

The questions below were used to frame a set of structured discussions with representatives from twelve water utilities across North America between March and November, 2023.

1. **What does the phrase "Level of Service" mean in your organization with regards to planning (such as infrastructure planning)?**

2. **How does your organization rank and evaluate potential infrastructure projects?**
   a. *What metric(s) do you consider when measuring the performance of your water supply system (i.e., reliability, resilience, restriction frequency, firm yield)?*

   b. *What uncertainties do you consider when evaluating system risk? How do you accommodate (sample) them?*

   c. *Do you have a level of acceptable risk? If so, how is it defined/mandated by your organization?*

   d. *Demand conservation actions: How do you manage those acceptable risks? (Some define this as residual risk):*

   e. *Do you have different strategies for prioritizing different types of infrastructure projects (i.e., groundwater, surface water etc.)?*

   f. *Does water quality get considered in this?*

   g. *What timescales and spatial scales are you using in your supply planning analysis (modeling)?*

3. **What information does your organization use to inform when to invest in new infrastructure?**
   h. *Is climate change factored into this?*

   i. *Who makes the decision?*

4. **How do you model your water supply system and how is this used to inform levels of service or system reliability?**

5. **What conditions trigger drought mitigation actions or curtailment? Is this linked to infrastructure investment level?**

6. **How do you navigate trade-offs between financial risk and supply reliability?**

7. **How does equity figure into level of service planning work in your utility (WUCA encourages equity considerations)**