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A LEVEL-OF-SERVICE CONCEPT FOR PLANNING FUTURE WATER SUPPLY PROJECTS UNDER PROBABILISTIC DEMAND AND SUPPLY FRAMEWORK[1]

Tirusew Asefa, Alison Adams, and Nisai Wanakule[2]

ABSTRACT: One of the most challenging tasks of water supply utilities is planning the timing and quantity of new water supply sources as demand for water consumption grows. Many water supply utilities target on meeting 100% of their customers' needs based on scenario-based deterministic demand projections numbers even though there are uncertainties in both supply and demand values. This may result in under or overly conservative approach in assessing future needs. In this article, a level-of-service concept is introduced to capture a utility's willingness to accept a given level of risk, plan for it, and invoke a management strategy during extreme events than build a facility to accommodate those in planning for new water supply sources. Accounting for uncertainties in both supply and demand help quantify reliability by achieving a prescribed level of service. The major benefit of such an approach for planning future water supply is that it allows policy makers to evaluate the use of adaptive water management strategies and develop supply in an incremental fashion as demand warrants it. For example, if a given level of service cannot be reliably met with the existing system at a future time *t*, an incremental water supply project would come online to bring the required reliability level up but no more.

(KEY TERMS: level-of-service; reliability; water supply planning; probabilistic supply and demand; water utilities.)

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INTRODUCTION

An aspect of water supply system reliability is the availability of supplies when needed. Many customers in the United States (U.S.) and developed countries have come to expect the water to be there when they open the tap and often take it for granted. There is a wide perception that when settlement occurs, water will follow. In reality, there are several factors that could impact future supply reliability such as climate change and climate variability, growth pace, environmental conflict, and aging infrastructure. Ensuring a water supply utility's ability to be there when needed in future is far from an exact science. Consequently, one of the most challenging tasks of water supply utilities is planning the timing and quantity of new water supply sources as demand for water consumption grows. When planning for future water supply, utilities try to strike a delicate balance between constructing additional supply capacity now *vs.* deferring it to some future time, *t*, depending on the projected demand growth and confidence on projections. Projecting future demand is one of the most notoriously difficult tasks. For example, a May 2013 Water Research Foundation workshop that convened over

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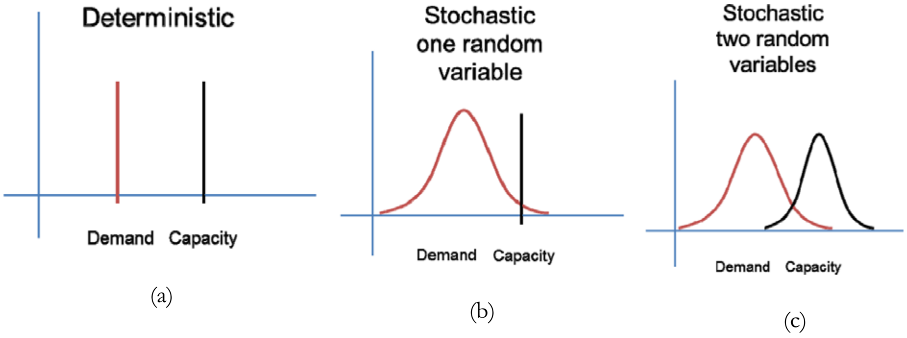
[2] Systems Decision Support Manager (Asefa), Chief Technical Officer (Adams), and Lead Engineer (Wanakule), Tampa Bay Water, 2575 Enterprise Road Clearwater, Florida 33763 (E-Mail/Asefa: tasefa@tampabaywater.org).

20 high-level utility managers across North America recounted almost unanimously "getting it wrong" in some form. The difficulty of improving projections was highlighted by the debate over how low usages would go as well as whether usage will rebound once the economy rebounds (WRF, 2013). Another complicating factor that must be taken into account while planning for future supply needs is bringing a new supply project may take up to 5-10 years from project inception to full implementation, depending on the complexity, public acceptance, financial, and regulatory constraint on a project. This is on top of uncertainties in both supply, which utilities try to develop, and the demand, which they try to meet over a relatively long-range planning horizon. In addition, weather which is the common denominator between the two variables is related: a multi-year drought not only decreases the available surface water but also increases the demand on a system. Several approaches are used for planning future water supply by agencies across the nation. Figure 1 presents the evolution of water supply planning by utilities. Figure 1a shows the prevailing approach by medium and small utilities where both supply and demand are assumed to be deterministically known quantities. Future water supply planning in this case would involve figuring out the timing and quantity of supply deficit and bringing additional supply online when needed. This approach is prone to error the most. Because of uncertainties, it is very easy to under- or overestimate the quantity of future supply needed. Most large utilities have gone away from this approach for estimating future supply needs. An improvement on this approach is shown in Figure 1b where one acknowledges the uncertainty in demand projection, but uses a known (fixed) system "capacity" through a quantification of some form of safe or firm yield of the system (no matter how the term is defined) (Linsley *et al.*, 1992). Usually demand projections are not represented by a continuous probabilistic distribution rather than as a discrete scenario that prescribes deterministic, say, low, medium, and high projections. Another hybrid of this approach is to treat supply as stochastic variable, but use scenario-based discrete demand projection (say, likely and high demand) (ICPRB, 2010). Identifying the future supply need then consists of selecting a specific demand scenario and comparing it to current system capacity and estimating the timing and quantity of the gap between supply and demand. Implicit in this approach is the assumption that each scenario has an equal chance of realization and the combination of the (three) scenarios would cover the range of possible demand projections over the planning horizon. This is the most common approach used by many utilities today. Figure 1c shows yet another improvement over the above two approaches where one treats both supply and demand as random variables — each having its own probabilistic distribution. In this case, the gap between supply and demand at any planning year, which is the driving criterion for capital improvement projects in bringing new supply sources, is not trivial as in the above two cases. Estimating the probabilistic distribution of both supply and demand requires understanding the sources of uncertainty/variability for both variables and their interdependence. This sets up an environment in which an adaptive management strategy could be exercised (see next section). Gap analysis and thereby future supply planning would require analyzing the joint distribution of these parameters. To our knowledge, such an approach has yet to be used for planning future water supply projects to date. In addition, targeting on meeting 100% of customers' needs based on a scenario of deterministic demand projection could result in under or overly conservative estimates in assessing future needs should reality deviate significantly from projection, which often is the case. In this study, we present a Monte-Carlo framework that uses the joint demand-supply distribution in order to quantify the timing and quantity of future supply needs. As a natural result to such an approach, we



(a)

(b)

(c)

FIGURE 1. Evolution of Water Supply Utilities Planning: (a) Both Demand and Capacity (supply usually reflected as safe or firm yield) Are Assumed to Be a Fixed Quantity in a Deterministic Framework; (b) Demand Is Assumed to Be Variable but Supply Is Fixed; (c) Both Demand and Supply Are Stochastic Random Variables.

introduce a level-of-service concept representing the willingness of a utility to accept a level of risk to be managed by invoking a management strategy rather than build extra supply to cope with extremes. The level of service may be thought as an "informal" contract between a utility and its customers for a certain degree of "inconvenience." The reliability of meeting a given level of service is then quantified through a joint probabilistic supply and demand distribution modeling where the underlying weather that affects both supply and demand is consistent. Use of level-of-service criterion by utilities is not a new idea. Seattle Public Utility, for example, incorporates level of service, life cycle costing, and triple-bottom criteria into their sewer maintenance program (Martine, 2012; The Johnson Foundation, 2012). But the use of reliability-based level-of-service approach for planning the timing and quantity of future water supply needs is a new paradigm. A distinction is made here between the reliability of meeting a level of service for water supply planning purposes *vs.* the day to day, or even hourly operation of a utility's distribution system (Germanopoulos *et al.*, 1986; NRC, 2006); or for cases where the level of service is a goal that a utility must try to meet based on regulatory constraints such as required pressure or water quality levels at a specific location. The scope of the level-of-service discussion in this article is limited to supply planning as a result of growing demand and variable hydrological conditions.

Water Supply Planning and Adaptive Management Decision

An adaptive management strategy is needed when one has to make a decision on the face of uncertainty and have a chance to learn from management decisions through careful monitoring of key variables. It provides a flexible decision-making framework that can be adjusted as an outcome from management decision and other events become better understood (NRC, 2004). In water supply planning, projecting key parameters that drive regional demand (e.g., housing stock, and income) over a long-planning horizon is not only highly uncertain but variable year to year. The projected demand profile, as a result, would have uncertainty associated with it. However, decisions have to be made about future supply needs well in advance of the demand being realized as bringing online additional supply could take up to 5-10 years. Therefore, accounting for uncertainties in both demand and supply and making water supply planning decisions in an incremental fashion is paramount. For example, Tampa Bay Water currently updates its long-term demand forecasting model on an annual basis using the updated socioeconomic outlook of the region and monitors key decision variables.

CURRENT APPROACH ON WATER SUPPLY PLANNING BY MAJOR UTILITIES

Planning for future water supply is a unique endeavour taken by different utilities in a different manner. Table 1 summarizes the approach taken by some of the major utilities across the nation. As shown in the table, almost all utilities that are primarily based on surface water supply source define a safe or firm yield of their system, which is used to satisfy demand. Below is a brief description of each of these utilities. Interested readers are pointed to supporting documents for each utility.

Seattle Public Utility

Seattle Public Utilities (SPU) relies on surface water to meet its drinking water needs except during peak seasons and emergencies, when water from two well fields is available. Seattle Public Utilities' policy statement (Seattle Public Utilities, 2006) on supply reliability states that SPU plans to meet full water demands of "people and fish" under all but the most extreme or unusual conditions, when demand can only be partially met. The policy includes seven specific items, including using a 98% engineering planning standard for determining long-term yield from water supplies. This standard is used to determine the amount of water available in all but the driest 2% of years. SPU defines firm yield and supply reliability. Firm yield is the amount of water that SPU is able to supply system-wide at a given delivery pattern, while meeting the supply reliability standard, instream flow requirements, and other system constraints. Firm yield is expressed as an average annual delivery rate in million gallons per day (mgd) from all sources operated conjunctively. Current SPU Water System Plan projections that include short-term water conservation targets indicate that the average demand for SPU are forecasted to stay flat up through 2023 and then decline for a couple of decades before rising to return back to current levels by 2060 (Seattle Public Utility, 2012) (Figures 2-4). In addition, SPU conducted a probabilistic demand projection that accounts for uncertainties in demand projections and was compared to the current firm yield in order to assess future demand/supply gaps. The result shows that even the 90th percentile demand projection was below the current firm yield

TABLE 1. Major Water Supply Utilities Water Supply Planning Approach.

Utility	Characteristics	Planning Criteria	Reference
Seattle Public Utilities	• Surface water-based system except for peak season and emergency situations • Define safe yield (average annual delivery rate in mgd[1] from all sources operated conjunctively) and reliability measures	• 98% supply reliability target • Assures delivery in all but the 2% driest years to both "human and fish" demand • Simulation based on 76-year reconstructed historical flow	Seattle Public Utilities (2006)
San Francisco Public Utilities Commission	• Surface water-based system • Reliability goal of meeting dry-year delivery needs, while limiting rationing to a maximum 20% system-side reduction in water service during extended droughts • Firm yield based on a three year dry event of a 8.5 year design drought	• Uses 82 years (1920-2002) historical record • Based on meeting a projected demand under two historical design droughts, 6 years (1987-1992) and 2.5 years (1976-1977) scenario • Currently projected to meet 100% of the first year of an event based on the 2030 demand projection	San Francisco Public Utilities Commission Water Enterprise (2009)
Metropolitan Water District of Southern California	• Based on both surface and groundwater sources mainly surface water sources • System reliability estimated under three scenarios	• Based on evaluation 26 year moving window hydrology of 82 years (1922-2004) historical record • Sets future reliability under range of resources management strategy based on projections of demands, conservation, imported supplies, and storage • Current projects reliability between 93% to 95%	The Metropolitan Water District of Southern California (2010)
New York City Department of Environmental Protection	• Primarily surface water-based system • Consisting of 19 reservoirs where turbidity is the main factor in operations	• Define safe yield as the maximum continuous demand that can be met by the City water supply system during a repetition of the drought of record while maintaining a 25% storage reserve	New York City Department of Environmental Protection (2010)
Miami-Dade Water and Sewer Department	• Groundwater-based system • Supply availability is based on permit from South Florida Water Management district • Safe yield based permit	• Has groundwater allocation that increases through 2027 • Additional demand above the allocation will need to be met by alternative source	Personal communication
Denver Water	• Surface water-based system • Firm yield was calculated as the maximum water demand that could be met during a representative hydrologic study period	• Cost associated with triple-bottom criteria (social, environmental, and financial)	Denver Board of Water Commissions (2002). Update to 2002 is on hold.

[1] Million gallons per day.

highlighting the need for no additional supply until after 2060.

San Francisco Utilities Commission

San Francisco Public Utilities Commission (SFPUC) has a reliability goal of meeting dry-year delivery needs, while limiting rationing to a maximum 20% system-side reduction in water service during extended droughts. SFPUC evaluates its firm yield in normal years, single-dry years, and multiple dry-year events. A multiple dry-year event is defined as a three-year event and is based on years 2-4 of SFPUC's 8.5 year design drought. SFPUC can meet 100% of deliveries in the first year of such an event based on its projected demand at 2030. For the purposes of regional water system planning, the SFPUC

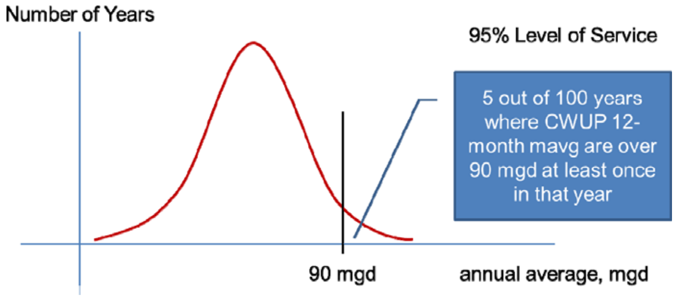


FIGURE 2. Level-of-Service Concept. At 95% level of service, there is a 5% chance that the system cannot meet the demand without invoking an adaptive management strategy or in Tampa Bay Water's case exceed the groundwater permit rule. Currently, the rule limits groundwater production to a 12-month moving average of 90 mgd.

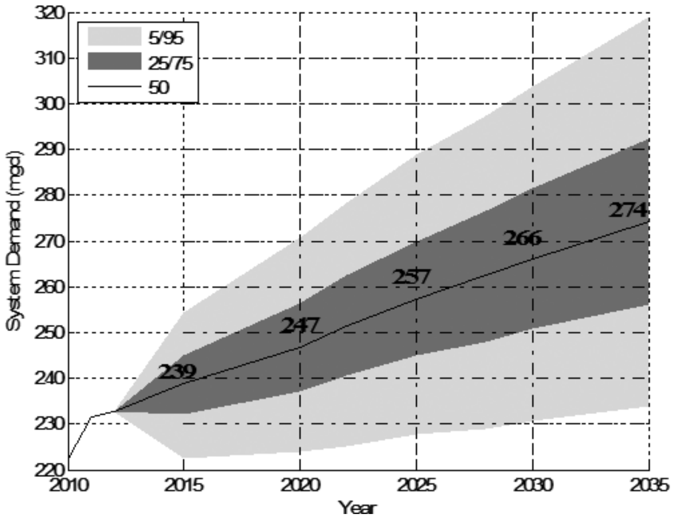


FIGURE 3. Stochastic Demand Projections. Each value represents a mean value averaged over 100 years that accounts for weather variability.

uses a design drought that anticipates and plans for a more severe drought than historical events and evaluates the system firm yield assuming that the system is experiencing the design drought. The SFPUC's design drought is based on the hydrology of the 6 years of the worst historical drought (1987-1992) plus the 2.5 years of the 1976-1977 droughts, for a combined total of an 8.5-year design drought sequence. SFPUC demand projection models incorporate economic and demographic forecast data, including projection of population, housing stock, and employment. Future need analysis is conducted by comparing projections for years 2015 through 2035 with supplies coming from three scenarios: during normal year, single dry-, and multiple dry-periods. SFPUC, with its existing and future supply, is expected to meet demand in all years but 2015. The deficit in 2015 is estimated to be within the margin of error and/or conservation assumption of the demand projection model (San Francisco Public Utilities Commission, 2013).

The Metropolitan Water District of Southern California

The Metropolitan Water District of Southern California (Metropolitan) is the wholesale water provider for a six-county service area consisting of 19 million people using both groundwater and surface water. Metropolitan's primary sources of supply are surface water sources, the Colorado River Aqueduct, California's State Water Project (San Luis Reservoir), Los Angeles Aqueduct, local streams, storage, and transfers with other water districts. The agency evaluates its future water supply reliability using a mass balance model that integrates projections of demand, conservation savings (through adjustments to demand projections), and local supply projects survey of local governments under a range of resource management strategies. The model uses 83 years of historical hydrology (1922-2004), in a sequential fashion over, say, 25 (2010-2035) forecast years to characterize system reliability (shortage frequency and magnitude). Agency evaluates system reliability under three scenarios: current approach, imported focus, and enhanced regional focus (where the agency develops rather than import water for future needs). In all cases, frequency of shortage is 5-7% of time (reliability of 93-95%), while the magnitude of shortage is different depending on the type of scenario (The Metropolitan Water District of Southern California, 2010).

New York Department of Environmental Protection

New York City's water supply system consists of 19 reservoirs and three controlled lakes that provide 580 billion gallons of storage. These reservoirs and controlled lakes are included in the City's three raw water systems; the Delaware, Catskills, and Croton. The City has determined that its most reliable, highest quality water comes from the Delaware reservoirs. Approximately, 95% of the total water supply is delivered to the consumer by gravity. One billion gallons of water are delivered each day to meet the needs of over nine million people. The City manages its reservoir system in a way that protects water supply reliability and balances multiple objectives, including water quality and quantity, as well as environmental and economic objectives. Reliability of system is reflected by calculating safe yield as the maximum continuous demand that can be met by

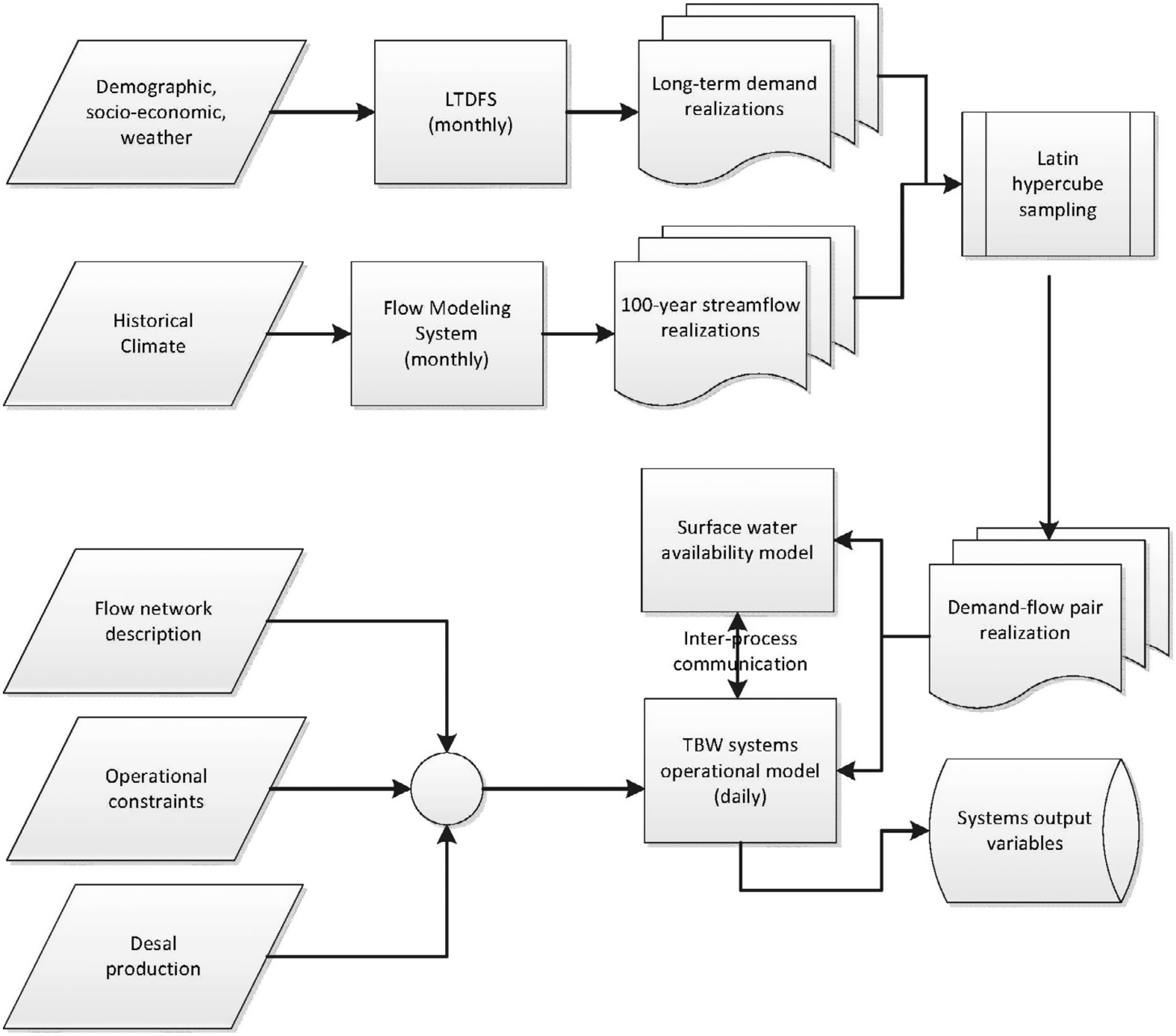


FIGURE 4. Systems Model Schematics.

the City water supply system during a repetition of the drought of record, while maintaining a 25% storage reserve in the collection reservoirs of the Catskill and Croton Systems and in Rondout Reservoir (New York City Department of Environmental Protection, 2010).

Miami-Dade Water and Sewer Department

Miami Dade's primary source of water is groundwater. The amount of water that can be withdrawn from the aquifer is permitted by the South Florida Water Management District. Miami-Dade was issued a 20-year water use permit in November 2007 for an annual allocation of 152,741 million gallons of water (418 million gallons per day) from the Biscayne and Upper Floridan Aquifers. The monthly allocation is limited to 13,364 million gallons. South Florida Water Management District imposes the "regional availability rule" which essentially determined that the safe yield of the Biscayne Aquifer has been reached, and therefore any future water supply demands would probably need to be met from alternative sources. The permit provides for annual limits from each source by years. For example, through 2012, each source allocation is limited: Biscayne Aquifer annual allocation is 126,425 million gallons (346.4 mgd) and the Upper Floridan Aquifer annual allocation is 6,723 million gallons (18.4 mgd). These annual limits increase from 2023 to 2027 with 142,000 million gallons coming from Biscaye Aquifer and 10,741 million gallons from Upper Floridan Aquifer. The water use permit also provides very specific well and well field production limits.

Denver Water

The majority of Denver's water supply is rivers and streams with 10 reservoirs. The following information was extracted from Denver Water's 2002 Integrated Resource Plan (IRP) (updating the 2002 IRP is on hold pending regulatory decision regarding enlarging Gross Reservoir). When Denver Water developed its 2002 IRP, the concept of firm yield was used. At that time, firm yield was calculated as the maximum water demand that could be met during a representative hydrologic study period. This approach assumed that Denver Water's current water supply facilities and water rights existed over the historical study period. To accomplish this analysis, Denver Water relied on an integrated system of computer program that simulates streamflows, diversions, return flows, and reservoir functions operating under Colorado's water laws and numerous operating agreements. As such, the model is continually updated and revised to incorporate new facilities, water rights agreements, and operating assumptions. Denver Water has determined that the hydrologic study period from 1947 to 1991 is representative of the long-term conditions for the river basins of concern. This period encompasses the critical drought periods for all watersheds in Denver Water's collection system. The weather and streamflow hydrology for the period 1947-1991 are applied to existing and proposed operating conditions. The model simulates the operation of the water collection system to determine the maximum amount of water demand the system could meet without shortages through the study period. Although this water demand is reported as a fixed average number expressed in acre-feet per year, the actual demand and water supply that is needed varies daily, monthly, and from year to year, and is modeled that way in the model.

Methodology

A policy issue for many utilities is the desired level of reliability required for their water supply system. This becomes an important issue for utilities, especially when it is difficult to predict with certainty when water is available for use. With the cost of developing new supplies increasing and growth in new customer accounts decreasing in some areas, management strategies to extend the useful life of existing supplies are needed. The first step toward delivering a reliable water supply system in the future is to establish the reliability of its current system. Most large water utilities, relying on surface water and storage reservoirs, characterize their systems in terms of system-wide reliability, incorporating both supply side and demand side evaluations. Firm or safe yield values are no longer sufficient as the sole basis for determining the system reliability or making decisions about future water needs. Streamflow variability, compounded by changes in climatic variability and change, is causing utilities to use probabilistic or multi-scenario approaches in water supply reliability evaluations and planning. For some utilities reliability is not necessarily a sole target for planning future water supply but the term is used when evaluating multiple management objectives. In this study, we introduce an approach that explicitly accounts for uncertainties in both demand and supply side of a utility's planning efforts. It also incorporates the notion of level of service, a proxy for customer "inconvenience" through implementation of a management strategy such as when watering restriction is invoked.

Toward a Level-of-Service Approach for Planning Future Water Supply Projects

The role of uncertainty in both demand and supply planning is acknowledged by many utilities. For example, Denver Water is incorporating a water supply "safety factor" in case unexpected situations arise (http://www.denverwater.org/SupplyPlanning/Planning/IntegratedResourcePlan/). Metropolitan uses a 10% "planning buffer" approach to underline the need for accounting for uncertainties on both supply (envisioning some water supply projects may be delayed or not completed) and demand (uncertainty in growth and projection).

Historically, at Tampa Bay Water, the largest regional utility in the southeast U.S. with a customer base of more than 2.3 million, planning for future water supply was based on a fixed system capacity and conditions were stipulated in its governing documents: (1) if demand exceeds permitted capacity by 75% during any 12-month period, initiate the preparation of permit applications for new supply projects; (2) if demand exceeds permitted capacity by 85% during any 12-month period, file permit application; and (3) if actual delivery during any 12-month period exceeds 94% of aggregated permitted capacity, it is considered a production failure (Tampa Bay Water, 1998). Such an approach worked very well when water supply was based only on groundwater. But as the agency shifted over half of its supply to alternative sources (such as direct river flows, offsite reservoir, and desalinated water), an approach that explicitly accounts for variability and uncertainties in both demand and supply are needed. As such, defining a fixed number for utility's "capacity" is challenging because of the diverse source of supply mixes and uncertainty associated with these sources across time and space. An approach that is solely dependent on comparing actual demand and "capacity" to plan for future supply runs the risk of overbuilding facilities because of uncertainties on both demand and supply. For example, a single, less frequent extreme event may trigger the process.

Here, a level-of-service concept is introduced to explicitly account for a utility's willingness to accept a certain level of risk, plan for it, and invoke a management strategy during unforeseen extreme events rather than building bigger facilities to accommodate these "rare" occurrences. This level of service is tied to the frequency of drought events that could trigger an agency's adaptive management strategy (for example, invoking a level IV water shortage mitigation plan at Tampa Bay Water, the highest level of drought, or other measures that are available in a utility's portfolio, but are not used frequently) and results in customer inconvenience because of restrictions. The regional water supply planning document for the state of Florida (Florida Statutes Chapter 373.709) recognizes the need to acknowledge uncertainties in both supply and demand and recommends the use of a level-of-certainty planning goal based on drought frequency. "The level-of-certainty planning goal associated with identifying the water supply needs of existing and future reasonable-beneficial uses must be based upon meeting those needs for a 1-in-10-year drought event" (Florida Statutes, 2013). The level-of-service concept is not a new idea. It has been widely used in other fields such as transportation engineering where roads have a classified level of services A to F based on their effects on drivers, passengers, bicyclist, and pedestrian's perception of the quality of service provided by the road (NCHRP, 2008). Once a given level of service is established based on a utility's adaptive management strategy, full uncertainties in demand and supply are captured through quantification of reliability for achieving a given level of service. Figure 2 shows the concept of a 95% level of service for a single realization that combines both supply and demand uncertainties. From the figure, it can be seen that 5 out of 100 years regional demand may not be met without invoking an adaptive management strategy or exceeding current groundwater withdrawal permit (90 mgd is the maximum allowable 12-month groundwater production level the utility is permitted). Crossing the 90 mgd permit level is considered an unsatisfactory state or condition. The 90 mgd level shown here is a specific example as applied to Tampa Bay Water system. For other utilities, this simply means not meeting the demand.

Mathematically, let $X_{t(i)}$, $t = 1\ldots T$, be a simulated time series of a parameter of interest, such as total supply capacity at time t, used as an indicator of a system's performance when compared with a criterion, $C_{t(i)}$, such as system demand for the ith realization. The comparison would then indicate the system being in either satisfactory, S, or unsatisfactory, U, states. Defining a state variable Z,

where,

$$Z_{t(i)} = \begin{cases} 1, & X_{t(i)} \epsilon S \\ 0, & X_{t(i)} \epsilon U' \end{cases} \tag{1}$$

Then the level of service or the policy level is the time that the system is in satisfactory state defined as

$$C_{P(i)} = \frac{\sum_{t=1}^{T} Z_{t_{(i)}}}{T}, \tag{2}$$

where $C_{P(i)}$ is the policy level criterion. For example, a 90% $C_{P(i)}$ value indicates that the system is in the satisfactory state (meet demand) and 90% of the time for the ith realization. Furthermore, let $W_{(i)}$ be an indicator for the system meeting a predefined policy level of service p such that

$$W_{(i)} = \begin{cases} 1, & \text{if } C_{p(i)} \geq p \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

Then the system reliability of achieving a prescribed policy level of service p is given by

$$C_{R(p)} = \frac{\sum_{i=1}^{N} W_{(i)}}{N} \tag{4}$$

where N is the total number of realizations.

Supply Side Modeling

Asefa *et al.* (2014a) presents a detailed exposition of the suit of models used for supply side simulation. One thousand ensembles, each 100-year long were generated using the following models: (1) monthly scale Seasonal Markov Mixture models to simulate rainfall using a historical record of over 100 years.

These were used to drive a rainfall/runoff model. (2) A Multivariate Seasonal Auto Regressive with eXogenous variable model was used to simulate streamflows at three locations (Alafia River, Hillsborough River, and Tampa Bypass Canal). (3) A Multivariate Nonparametric Disaggregation model was used to disaggregate the monthly simulations into daily traces, which were used by operational models, including surface water use permits.

Probabilistic Demand Projections

One thousand realizations each 100-year long containing demographic and socioeconomic characteristics of the projections for the time periods of 2015, 2020, 2022, 2025, 2028, 2030, and 2035 were generated. The ensemble of realizations for a given planning year is named as the demand slice for that year. An existing probabilistic demand forecasting model (Hazen and Sawyer, 2012) was modified to generate the ensemble of demand realizations having socioeconomic characteristics of a given time slice, say 2020, but prevailing over a long period of weather conditions that are consistent with supply side simulation were simulated as follows. First, a projection and/or assumption on socioeconomic growth and policy condition for each of Tampa Bay Water's demand service areas was generated using data from a variety of sources such as American Community Survey, Moody's Analytics, the Florida Department of Transportation, and other planning agencies. Then uncertainty around point projections was stochastically simulated using historical data and a multivariate nonparametric resampling framework. Finally, each socioeconomic ensemble was derived with an ensemble simulation of weather variables constituting the forecasted demand time series for the service area. Precipitation that drive both demand and supply are consistent in that two of the parameters for demand projection namely number of rainy days above two thresholds are consistent with supply side simulation. Figure 3 shows the stochastic demand projections that resulted from this process. The light gray area indicates the 5th/95th percentile range and the dark grey area indicates the 25th/75th percentile range. The median whose values at each demand slice are labeled is represented by a solid line. Note that values shown for each demand slice are time averaged (over 100-year) that collapses the effect of the long-term weather variability on demand. This modeling approach explicitly accounts for, if for example, the socioeconomic characteristics of a given demand slice, say, 2030 were to stagnate, the year-to-year variation in demand (over 100-year) would only come from climate variability.

Joint Demand-Supply Sampling and Operational Modeling

The above procedure results in 1,000 demand realizations each 100-year long for each demand slice representing the socioeconomic characteristics over a range of wide climate variability that is consistent with the supply side weather. In this case, the 1,000 realizations reflect the uncertainty in socioeconomic variables. These demand realizations were then paired with 1,000 realizations of supply side simulation also 100-year long. A total of 1 million combinations would result for each demand slice. In order to make the computation tractable, a previously developed Latin hypercube-based (e.g., Iman and Conover, 1982) resampling technique was used to select a subset of samples that are capable of representing the variability on both demand and supply side (Asefa *et al.*, 2014b). This results in 334 realizations, 100-year long for each of the seven demand slice years. Figure 4 presents the schematics of the system models used in this study. The top two rows of Figure 4 depict the demand- and supply-side simulation processes producing demand-flow pairs. These demand-flow pairs would then feed to surface water availability models and Tampa Bay Water's operational models, both running at daily time-scale. In addition to the demand and supply simulations, input to the operational model include flow network description, systems and operational constraints, and desalinated seawater production. Output from the model is used to calculate the level of service for each realization. The level of service is calculated based on meeting the projected demand over a long-period of time without violating current permit conditions. Since groundwater permit is on a monthly basis, results were aggregated to monthly level. A failure to meet demand for at least one month would constitute the year as a failure. Level of service A has a failure of exactly 1 year out of 100, Level of service B would have a failure of 5 years out of 100, and so on (Table 2). Adaptive management tools that curtail demand such as watering restrictions will be invoked in actual implementations, which would enable the system to meet the reduced demand. For a given demand slice, by aggregating each realization's level of service, reliability for achieving a given level of service was then obtained. Note that the joint demand-supply modeling presented here may not be necessarily applicable in some areas; and the time and spatial characteristic of the variables must be taken into account. In areas where demand and supply are spatially "disconnected" and may operate at a different time scale, a different approach may be needed. One such example is the Metropolitan Water Dis-

TABLE 2. Policy Level of Service.

Policy Level of Service	Interpretation
A	99 years out of 100 or 99% successful in meeting the range of possible demand in a given realization for the considered time slice (1 out of 100 years adaptive management implementation is planned for). There is only 1% chance of event occurrence in a given year.
B	95 years out of 100 or 95% successful in meeting the range of possible demand in a given realization for the considered time slice given time slice (5 out of 100 or 1 out of 20 years adaptive management implementation is planned for). There is only 5% chance of occurrence in any given year.
C	90 years out of 100 or 90% successful in meeting the range of possible demand in a given realization for the considered time slice (10 out of 100 or 1 out of 10 years adaptive management implementation is planned for). There is only 10% chance of occurrence in any given year.
D	85 years out of 100 or 85% successful in meeting the range of possible demand in a given realization for the considered time slice (15 out of 100 or 1 out of 6.7 years adaptive management implementation is planned for)

trict where the mountain snowpack in Colorado and Wyoming are important for the supply side, whereas demand may be driven by prevailing weather in California.

RESULTS

Existing System

Figure 5 shows the reliability of the current system in meeting different level of services defined earlier. The bottom line indicates the reliability of meeting a Policy Level of Service A which allows only 1% of the time for the demand to be greater than available supply. It is important to note that since this is the highest level of service with stringent requirement, the reliability of meeting this kind of level of service with the existing system deteriorates quickly (see the shape of the graph too) as demand increases: from 83% reliability in 2015 to 25% reliability in 2035. The gap between this level of service and all others is stark, demonstrating a huge cost associated with raising the reliability of a system to meet rare events. However, the level of services B, C, and D, which allows a utility to take higher and higher levels of risk all start at 100% reliability in 2015 but drop, respectively, to 54, 67, and 76% of reliability in 2035. If, for example, Florida Statutes level-of-certainty (corresponding to level of service C in Table 2) is considered, the current system achieves those cases with reliability above 90% through 2025 (100% in 2015, 99.7% in 2020, and 93% in 2025). Table 3 presents the range of projected demand met by a given level of service and the associated reliability of achieving this prescribed level of service. Color codes from red to blue indicate worst to best reliability values. For example, a 239 mgd to 258 mgd or less demand can be met at 99.7% reliability in 2020 at a policy level of service C, but can only be reliably achieved at 63% for the level of service A. Note that from Figure 2, the median demand projection for 2020 is 247 mgd.

Future Supply Need Based on a Level-of-Service Criterion

One of the benefits of the level-of-service framework introduced in this study is that it explicitly accounts for a utility's willingness to accept a certain level of risk. This risk is tied to the level of inconvenience to customers in the form of watering restriction or any other measure. The level of this inconvenience can be determined ahead or could be adjusted as needed within an adaptive management framework. This allows for a utility to have in its "tool box" a mechanism to deal with extreme events rather than accommodate them through construction of costly capital improvement projects. It is also possible to solicit customers regarding the level of service that they would like to have and are willing to pay for (Seattle Times, 2014). The level of service is directly tied to the frequency of water supply shortages because of droughts. Once a level of service is defined by State Statutes or otherwise, the reliability of meeting those level-of-services captures the uncertainty embedded in both demand and supply simulations. The decision to be made by a utility is then how much incremental supply source would be needed to bring the reliability to an acceptable level. Even though it was not done in this study, the cost associated with raising the reliability to an acceptable level can be calculated easily. Figure 6 shows the changes in reliability by bringing online incremental supply sources as needed (on demand). For example, a 5 mgd additional supply would raise the reliability level of service A to over 90% in 2015, but raise it from 25% to only 33% in 2035, considered still a very low reliability. The same amount of future supply would bring a policy level C reliability to 78% by 2035. Even a 20 mgd additional supply source would not bring policy level service A to what is achieved at policy level C for the same planning horizon. This clearly demonstrates the huge cost

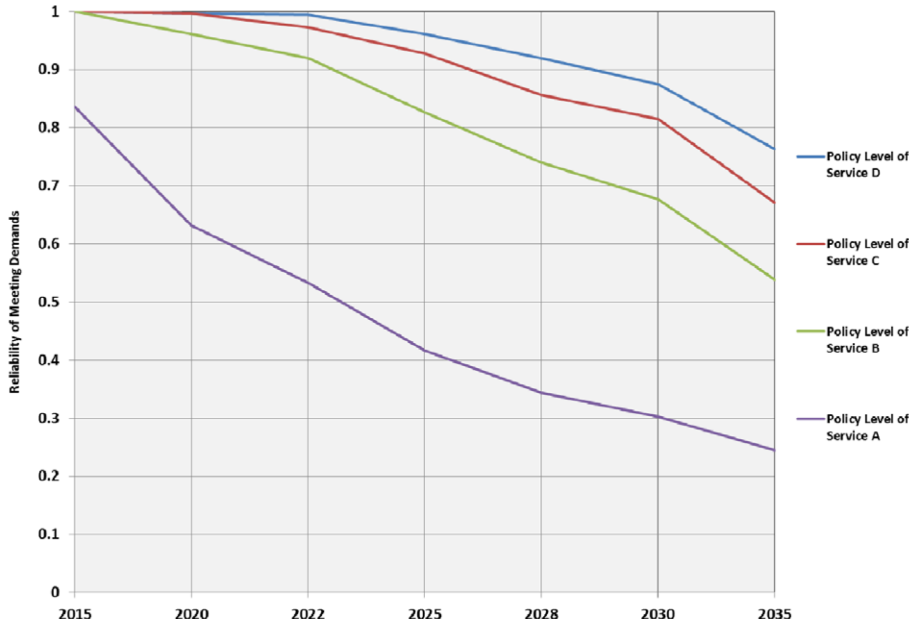


FIGURE 5. Reliability of Meeting a Given Policy Level of Service across Planning Horizon.

TABLE 3. Demands Met by a Given Level of Service and Change in Reliability across Planning Horizon.

	Policy Level of Service A		Policy Level of Service B		Policy Level of Service C		Policy Level of Service D	
Time Slice	Most Likely Demand Range (mgd)	Reliability (%)	Most Likely Demand Range (mgd)	Reliability (%)	Most Likely Demand Range (mgd)	Reliability (%)	Most Likely Demand Range (mgd)	Reliability (%)
2020	233-246	63	239-255	96	239-258	99.7	239-258	99.7
2025	235-250	42	241-261	82	242-265	93	242-266	96
2030	238-255	30	242-266	68	247-270	81	248-275	87
2035	238-258	25	245-269	54	247-274	67	250-279	76

needed in trying to bring reliability of achieving a very high level of service that corresponds to very rare drought events (those occurring once in 100 years). Table 4 presents the change in reliability of achieving a prescribed level of service with an incremental supply source of 5, 10, 15, and 20 mgd capacity at different times during the planning horizon. Again, as in Table 3 color code ranges from red (worst) to blue (best). In 2025, an addition of 5 mgd brings reliability to above 90% in cases except level of service of A. In fact, even adding a 20 mgd capacity to existing system brings it barely above 50%, again illustrating that trying to handle extreme events through more supply production than invoking a management strategy if and when they occur would require huge capital investment, which may not be in the best interest of rate payers.

DISCUSSION AND CONCLUSION

The level-of-service criterion approach for quantifying a utility's future water supply need explicitly accounts an agency's willingness to take some level of risk through prescription of the percent of time a management strategy may be invoked, which include watering restriction in order to meet demand. This approach, which explicitly specifies the level of customers' inconvenience, is tied to frequency of drought. Here, we defined four levels of services A, B, C, and D, depending on how the system successfully meets the range of demands. Level of service A is the most stringent by allowing only 1 in 100 years unsatisfactory condition. While level of service D is the most risk accommodating option which calls for 1 out of 6.7 years for some form of demand manage-

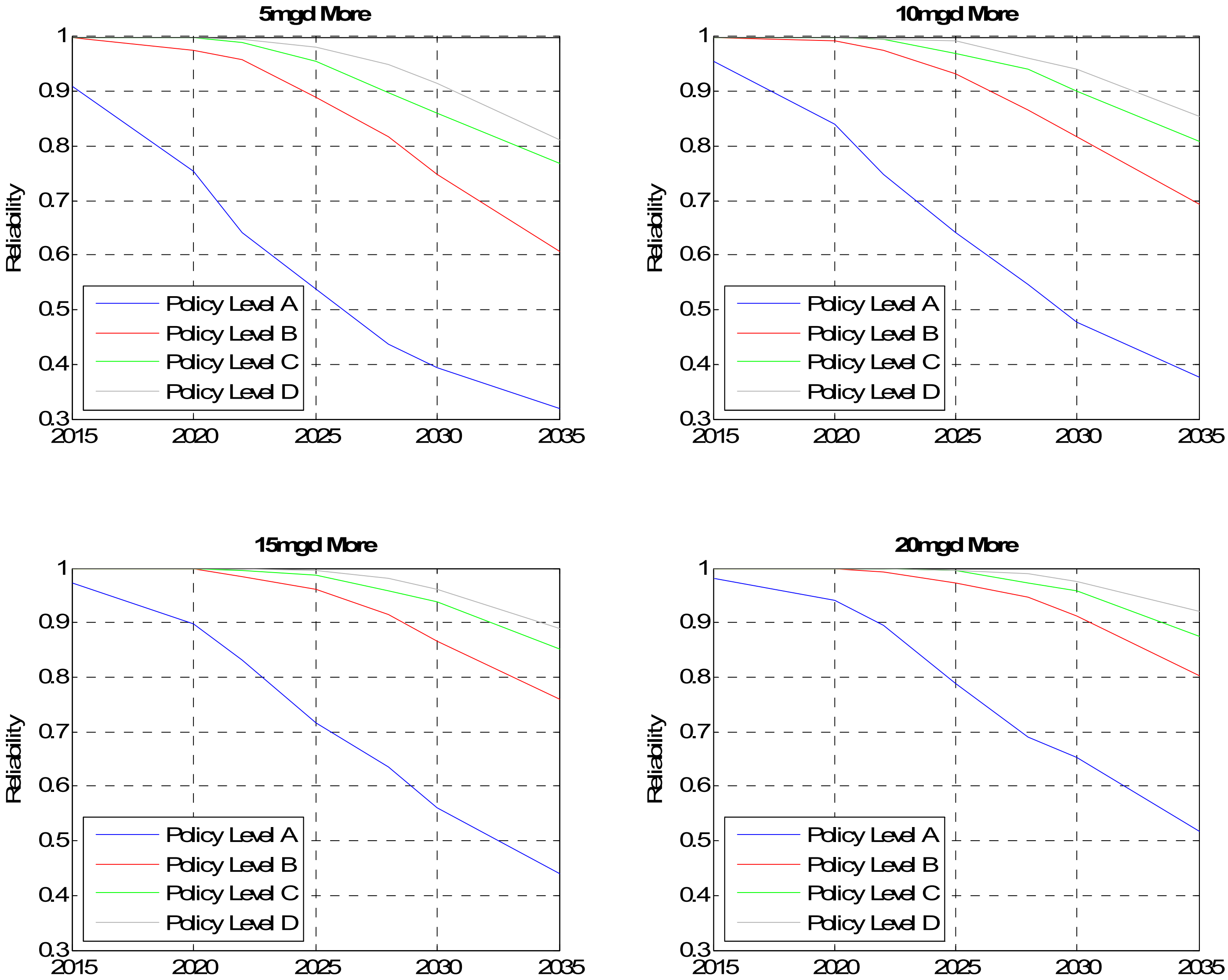


FIGURE 6. Improvement in the Level-of-Service Reliability through Addition of Incremental Supply.

TABLE 4. Improvement in Level-of-Service Reliability across Planning Horizon.

Policy Level	Existing Supply Reliability (%)	5 mgd Reliability (%)	10 mgd Reliability (%)	15 mgd Reliability (%)	20 mgd Reliability (%)
(a) Results of additional supplies by 2025 compared against existing system					
A	42	54	65	72	79
B	82	89	94	95	96
C	93	95	97	99	99
D	96	98	99	99	99
(b) Results of additional supplies by 2030 compared against existing system					
A	30	40	48	56	65
B	68	75	81	88	91
C	81	87	90	93	95
D	87	91	94	95	98
(c) Results of additional supplies by 2035 compared against existing system					
A	25	33	38	45	53
B	54	61	70	78	81
C	67	78	80	86	88
D	76	81	85	90	93

ment strategy to be in place. Once a level of service is set through the State Statutes or otherwise, the reliability of achieving a given level of service can easily be estimated by accounting for uncertainties in both demand and supply simulations. A demonstration of this approach is presented using Tampa Bay Water's integrated water resources system. First, 1,000 realizations of demand, each 100-year long containing socioeconomic conditions of 2015, 2020, 2022, 2025, 2028, 2030, and 2035 were generated. Second, the 1,000 realizations corresponding to the supply side variable incorporating the climate variability were generated. The combined demand-flow pair samples were selected using a Latin hypercube technique in order to make the computational burden tractable. The level of service for each realization was computed and compared to an *a priori* prescribed level of service the utility is willing to execute and was used to classify a realization as successful or not. Aggregating these results over the entire realization provided the reliability of achieving a given level of service. It is shown that the current system maintains a reliability of over 90% through 2025, if one uses the Florida Statutes level-of-certainty guidance for water supply planning. Providing a higher level of service than that would require at least an additional 5 mgd by 2025. Over the 20-year planning horizon used here, if one selects an A level of service, even adding as much as 20 mgd can only bring the reliability of achieving it to only about a 50/50 chance of meeting demand. This demonstrates the huge cost that utilities would incur if they do not leave room for adaptive management or are not willing in taking some level of risk. The approach developed here makes it easy for utilities to plan for incremental supply source which will only be activated on demand within an adaptive management strategy framework. Even though this study did not explicitly include cost, it is easy to extend the current study to incorporate incremental cost of new supply as a function of raising the reliability of achieving a given level of service. The authors are not aware of any study that explicitly tries to tie the level-of-service concept into water supply utilities' future water supply planning. Clearly, through incremental use of additional supply when needed, utilities would reduce the risk of over (under) building infrastructures that could be a burden to rate payers (results in shortage crisis). In its simplest theoretical form, the rate payers have the option of selecting the level of service, which would indirectly specify their willingness for inconvenience through water restriction at the time of drought. Given the high level of uncertainty in demand and supply projection over a long range (10-20 years and beyond), an approach that accounts for uncertainty on both as well as leaves a room for an adaptive management strategy is useful. Since most utilities update their long-term master water plan every few years (usually 5 years), the effectiveness of a given level of service can be revisited to keep it in check with the utility's original goal as well as rate payers' expectation.

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