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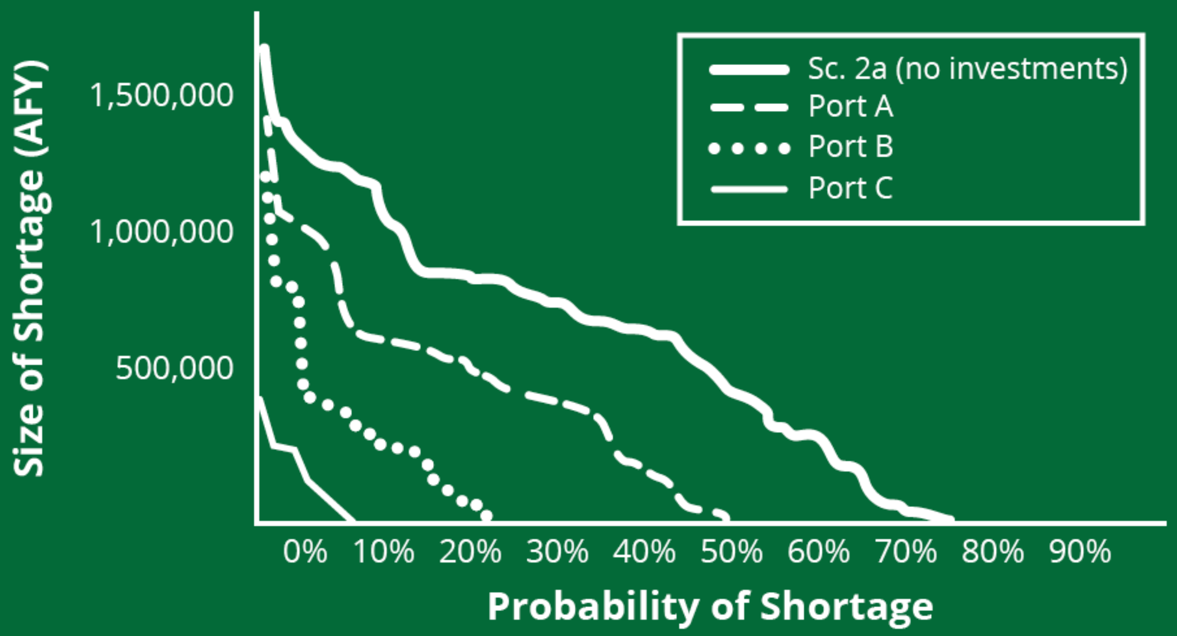

Review of Water Supply Reliability Estimation Related to the Sacramento-San Joaquin Delta

Delta Independent Science Board
DELTA STEWARDSHIP COUNCIL

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Report Cover Figure

Metropolitan Water District of Orange County Delivery Shortage Probabilities for Different Regional Portfolios in Year 2040, in acre-feet per year (modified for accessibility from MWDOC, Orange County Water Reliability Study, 2016)

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Stephen Brandt, Ph.D., Chair
Professor, Department of Fisheries and Wildlife, Oregon State University

Lisa Wainger, Ph.D., Chair Elect
Research Professor, University of Maryland Center for Environmental Science

Jay Lund, Ph.D., Past Chair
Director, Center for Watershed Sciences; Professor of Civil and Environmental Engineering, University of California, Davis

Virginia Dale, Ph.D.
Adjunct Professor, University of Tennessee

Harindra Joseph Shermal Fernando, Ph.D.
Wayne and Diana Murdy Professor of Engineering and Geosciences, University of Notre Dame

Tanya Heikkila, Ph.D.
Co-Director, Center for Policy and Democracy; Professor, School of Public Affairs, University of Colorado Denver

Thomas Holzer, Ph.D., CEG
Scientist Emeritus, United States Geological Survey

Diane McKnight, Ph.D.
Professor in the Department of Civil, Environmental and Architectural Engineering, University of Colorado Boulder

Robert Naiman, Ph.D.
Emeritus Professor, School of Aquatic & Fishery Sciences, University of Washington

The following former members of the Delta Independent Science Board contributed to the development of this review from 2017 until the end of their term.

Contributors:

Tracy Collier, Ph.D. (until August 2020)
Science Director for the Puget Sound Partnership, Retired

Richard Norgaard, Ph.D. (until August 2020)
Professor Emeritus, Energy and Resources Group, University of California, Berkeley

Vincent Resh, Ph.D. (until August 2020)
Professor of the Graduate School, Department of Environmental Science, Policy, and Management, University of California, Berkeley

John Wiens, Ph.D. (until August 2020)
Emeritus Distinguished Professor, Colorado State University; Courtesy Faculty, Oregon State University

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Preface

Managing water in California is becoming more challenging as changes in climate, ecosystems, water demands, technology, and regulations alter water availability, variability, and costs. California's complex water system has helped the state thrive economically for a century, and this system has adapted with some successes in recent decades despite some glaring shortfalls. The most successful parts of California's water system have managed supplies and demands conjunctively for planning and operational horizons, which is known as *portfolio management*. Water management portfolios increasingly include groundwater banking, water market transfers, joint facilities, and integrated system operations. Central to the large investments and integration are assessments of the likelihoods and probabilities of benefits and costs from various actions and investments in terms of overall system performance over a range of wet and dry conditions, and with a changing climate.

These management successes require assessments of water supply reliability. California's future water management, with less certain and more variable conditions, will place greater demands on estimation of water supply reliability for both traditional human purposes (cities, agriculture, hydropower, etc.) and highly disrupted and vulnerable ecosystems. The policy and operational discussions needed for adaptation can be improved with systematic, transparent, and shared system and reliability analyses.

This report reviews the scientific and practical condition of water supply reliability assessments in California for its ever-evolving water uses and systems. The focus is on water supply reliability estimation because a forward-looking and more common understanding of reliability estimation is an essential foundation for management and policy assessments, discussions, and solutions.

Executive Summary

The Sacramento-San Joaquin Delta Reform Act of 2009 mandates the balancing of the coequal goals for the Delta: providing a reliable water supply for California and protecting, restoring, and enhancing the Delta ecosystem and the Delta as an evolving place. Of these coequal goals, water supply reliability might be the most amenable to quantitative assessment by formal water supply reliability estimation. This review by the Delta Independent Science Board (Delta ISB) presents findings and recommendations on the science and practice of estimating water supply reliability for both the Delta and California.

This report responds to the Delta ISB's legislative mandate to review the adequacy of science supporting adaptive management for the Delta. Accordingly, the Delta ISB undertook a review of formal methods and underlying science used to estimate water supply reliability. The review sought perspectives from stakeholders, managers, and experts by formal presentations and questionnaires, a workshop, and interviews. It draws heavily from these forums and the scientific literature.

A reliable water supply for California is defined in the Delta Plan as "better matching the state's demands for reasonable and beneficial uses of water to the available supply." Water supply reliability estimation, the subject of this review, is the formal process of quantitatively predicting the variable performance and delivery from a water supply system. Estimates of reliability usually are expressed as probabilities of achieving water system performance objectives. The most common performance metric is a probability distribution of water delivery quantity for either seasonal operations or long-term policy and planning horizons. A variety of engineering, public health, economic, social, and ecosystem health metrics, however, are increasingly in use.

A reliable water supply is critical to California's public health, economic prosperity, ecosystem health, and social well-being. Achieving a reliable supply, however, is challenging because of California's diverse landscape and climate, unequally distributed and variable precipitation, complex infrastructure, decentralized institutions, and competing water demands from agriculture, cities, and ecosystems. In addition, California's climate is undergoing major long-term change from global greenhouse gas emissions.

Extreme events, such as droughts, test water management systems and require public and political authorities to consider, adopt, and invest in new solutions and approaches. Droughts always focus attention on the need to improve California's water reliability (Pinter et al. 2019). Recent droughts show that water supplies are more reliable in communities and regions that have made effective long-term preparations and investments (Lund et al. 2018). Improvements in runoff and water quality predictions with a warmer climate also are urgent. Reliability estimation is fundamental to reasoned design of investments and preparations across the wide range of water management events, actions, and purposes.

This review identifies two major challenges for water supply reliability analyses: (1) addressing climate change and environmental concerns, and (2) improving technical and management aspects of water management portfolios. The first major challenge, which is primarily scientific, includes anticipating and preparing for changes in water and environmental systems caused by a warming climate and incorporating management of water flows to support ecosystems into water reliability analysis. Supporting aquatic habitats and ecosystems adds a new type of reliability assessment as flows and water quantity, quality (e.g., salinity, nutrients, and temperature), and physical habitat combine to affect the ability of species to survive and reproduce.

Meeting this ecological challenge requires improved understanding and quantification of environmentally needed flows and their management with changing and variable conditions. The second major challenge consists primarily of technical elements in an institutional context. It includes multiple efforts to improve water supply reliability estimates and extend their use in management and policy making for water supplies at local, state, and regional scales. This requires increasing the breadth and realism of water management portfolios (i.e., multiple water sources, operations, and demand management) represented in in water supply reliability analyses. These portfolios also must support implementation of adaptive management. Modeling of water supply reliability for such complex and changing conditions can be more useful by: a) applying risk based decision making, particularly given the uncertain and non-stationary aspects of climate change; b) including more formal analysis of multiple performance objectives that are inherent in water planning and operations; c) introducing forecast-informed reservoir operations (FIRO) to accommodate multiple reservoirs and portfolio elements; and d) adopting new technologies to develop and share data and models.

Findings and Recommendations

This review led to the following findings and recommendations on the science and practice of water supply reliability estimation and analysis. Implementing the recommendations will improve reliability estimates and their communication for policy and management discussions and decisions, as well as help identify promising alternatives for managing water.

Findings

Broad Importance of Water Supply Reliability and Estimations

1. Water supply reliability estimation and analyses are increasingly being applied to adaptively manage water supplies in systems with interacting changes in climate, water demands, regulations on water quality and environmental flows, and system disruptions from extreme events.

2. Most major water suppliers (urban and state projects) and regulators employ formal reliability analyses to improve water operations, planning, and policy decision-making in California and the Delta.

3. Meeting ecological goals requires reliable water supplies and will require reliability analyses for environmental purposes. Methods to quantify water reliability to meet ecological goals, including recently developed methods, need significant improvement and wider application.

4. Reducing risks to human, agricultural, and ecological systems from drought under changing future climates is a major motivation of current efforts to improve water supply reliability analyses.

Water Supply Reliability Estimation and Analysis

5. Improving reliability estimation and analysis for water supplies will require managing many risks and uncertainties. These risks include drought, natural catastrophes (such as floods, wildfires, and earthquakes), mechanical breakdowns, chemical contamination, and changing climate. It also will require addressing maladapted or inflexible management systems designed for past conditions including regulatory restrictions, over-allocation of water, and human water use behavior.

6. A portfolio approach, i.e., integrated management of both demands and supplies, has a long history of effectiveness in California. Urban water systems, particularly in southern California, are international leaders in combining portfolio management and reliability analysis. Agricultural users are moving in this direction by using new water management approaches. Water systems that support ecosystems could become more adaptable, resilient, and effective by employing portfolio management of supplies and demands for water and habitats. Water management portfolios often include cooperation across water use sectors, regional and statewide.

7. Reliability under a changing climate depends on early and effective preparations by local and regional water agencies. In particular, both sea level rise in the Delta (and its effects on encroaching salinity, flooding, and water quality) and increased water temperatures affecting ecosystems will have wide-ranging implications on the reliability of water supplies in California for all water uses.

8. Many approaches have been used in California to estimate water supply reliability. Each approach has advantages and limitations. Methods developed for narrow applications tend to be more rigorous but are not easily adapted to other applications.

9. Two approaches to estimate water supply reliability are in use. Probabilistic approaches capture much of the variability of changing conditions and, therefore, support development of balanced water management portfolios. Non-probabilistic scenarios and sensitivity analyses are useful to explore the stability, impacts, and adaptability of water management solutions under uncertainties that cannot be reliably predicted. Results from both approaches may be challenging to communicate with decision-makers, stakeholders, and the public.

Reliability Analyses for Management and Policy

10. Water supply reliability estimates are sensitive to underlying assumptions, but the potential impacts of uncertainty on management recommendations are rarely made clear and explicit to managers and stakeholders.

11. Water supply reliability analyses are widely employed but could be better integrated into and communicated to water operations, planning, and policy decision-making to improve, focus, and structure deliberations on performance and trade-offs among multiple objectives.

12. State, regional, and local agency expertise in water supply reliability estimation is scarce and often not current with the state of the science and escalating challenges and opportunities. This staffing problem is likely to worsen as demands on agencies increase and senior staff retire.

Recommendations

Practice

1. *Most water supply reliability analyses in California should reflect more complex portfolio-based water management to improve cost-effectiveness and equity of regional water management among diverse entities*. Portfolio management includes evaluating interacting surface-water and groundwater sources, infrastructure operations, and water demand management within and across water use sectors. (Findings 3,4,5,6,9,10)

2. *Performance assessment of water system reliability should be broadened beyond technical reliability to include multiple benefits that support public health, economic, ecological, and social objectives.* Performance-oriented assessments are particularly urgent for ecological objectives and will require co-development of performance indicators among stakeholders, regulators, modelers, and system managers. (Findings 1,2,3,10)

3. *More formal quality control and documentation of water supply reliability analyses should be encouraged and sometimes required.* More formal documentation, testing, and data and model availability would improve compatibility of results among studies and alternatives, and aid in integrating water supply reliability estimation into decision-making and policy discussions. (Findings 1,2,3,7,10,11,12)

4. *A common State water accounting system that includes documentation, interpretation, testing, and standardization should be developed to improve analysis quality, comparability, and communication for technical and non-technical audiences.* The California Department of Water Resources and the State Water Resources Control Board could jointly administer such an accounting system and its technical expectations. Other states, such as Colorado, provide good examples. (Findings 1,2,5,8,9,10,11)

5. *The next generation of State-sponsored water supply system models for reliability estimation should be developed, updated, and evaluated by a broad consortium of State and federal agencies and external experts that applies the best feasible science and addresses regional needs.* Well-led collaboration and coordination could reduce costs of development while improving model utility and coordination across regional operations and management issues. The ongoing need for system-specific models and expertise for some decisions favors a layered approach to model integration.

Developing system specific models with different but interconnected levels of sophistication would increase model comparability, facilitate upgrades, and broaden the scope of analyses. (Findings 5,8,9,10,11)

Research

6. *Specific performance metrics and analysis methods for water supply reliability estimation for environmental purposes should be further developed and employed to better inform policies that support the Delta's coequal goals.* An approach based on functional flows, assessed empirically or mechanistically, shows promise to reflect the reliability of meeting ecosystem water demands spatially and temporally and improving water management for ecosystems. In addition, meaningful engagement with additional cultural, commercial and recreational stakeholders would deepen understanding of broader environmental flows in water operations compatible with a range of water system users. (Findings 1,3,4,6)

7. *Estimation methods should be updated to reflect accumulated and expected climate change effects and combined with uncertainty analysis.* This would improve long-term planning and policymaking as well as seasonal operations planning. Combining scenario-based and probabilistic analyses can quantify uncertainties and identify promising adaptable portfolios of management actions. (Findings 1,4,5,7,9)

8. *Investment in research and education should increase to improve water supply reliability estimation science and practice.* Some recommended areas of research and funding emphasis include: a) nexus of water quality and water supply reliability; b) modeling portfolio planning and operation for large regional water systems with local water systems and climate uncertainties; c) applications of ecosystem performance indicators in water and environmental management; d) applying and communicating uncertainty analyses in planning and policy decisions; and e) education of staff in State agencies to promote more rigorous, advanced, and insightful analyses. (Findings 2,3,4,5,6,9,10,11,12)

1. Introduction

"The present only touches you:
But oh! I backward cast my eye,
On prospects dreary!
And forward, though I cannot see,
I guess and fear!"
To a Mouse, Robert Burns 1785

California's prosperity, ecosystems, and quality of life depend on water. Yet, it is not always feasible to eliminate all water scarcity without incurring excessive financial, environmental, and opportunity costs. Thus, the estimation of water supply reliability is central for balancing water policy and management discussions and decisions for the Sacramento-San Joaquin Delta and California. This report examines the supporting science and methodology of water supply reliability estimation to help improve these public and management discussions and decisions.

Water supply reliability estimation, as discussed here, is the formal process of quantitatively predicting the variable performance and water delivery from a water supply system. Reliability usually is expressed as a probability of achieving water system performance objectives. The most common performance metric is a probability distribution indicating the relative likelihood of the range of possible water delivery quantities, but other technical, public health, economic, social, and ecosystem health metrics also are used.

1.1: Delta ISB Mandate and Scope of this Review

The Sacramento-San Joaquin Delta Reform Act of 2009 mandates the balancing of two coequal goals for the Delta: providing a reliable water supply for California and protecting, restoring, and enhancing the Delta ecosystem and the Delta as an evolving place. This report responds to the legislative mandate to the Delta Independent Science Board (Delta ISB) to review the adequacy of science supporting adaptive management for the Delta to achieve these goals. This report reviews scientific and formal methods to estimate water supply reliability as practiced in the Delta and California. Water supply reliability touches a broad and diverse range of issues in the Delta and California.

This report, the first Delta water supply review by the Delta ISB, focuses on the methodology of estimating water supply reliability so that future water supply reliability reviews might focus more on other aspects and applications of water supply reliability. This report presents findings and recommendations on the science and practice of estimating water supply reliability. It is based on perspectives of stakeholders, managers, and experts and draws significantly from formal presentations and questionnaires, a workshop, and interviews. It also draws heavily from the scientific literature.

Formal performance assessments help improve management and policy discussions and actions. This is particularly true for complex and changing situations involving many managers and stakeholders with diverse objectives. Of the state legislated coequal goals under the Delta Reform Act, providing a reliable water supply for California might be the most amenable to formal quantitative assessment.

This report is organized in seven sections. Following this introduction, Section 2 reviews sources of water supply unreliability and provides a partial inventory of water supply reliability estimation efforts in California. Section 3 reviews major scientific and technical challenges for water supply reliability estimation with particular emphasis on climate change, portfolio management, water quality and quantity, environmental water supply reliability, uncertainty analysis, and analysis for multiple-objectives and conflict management. Section 4 summarizes commonly employed metrics to assess water supply reliability.

Section 5 presents methods and considerations to improve quality control of reliability estimation and its effectiveness. Section 6 focuses on water supply reliability in decision-making. And finally, Section 7 includes overall concluding remarks. Three appendices present some important technical issues for water supply reliability modeling and analyses, summarize insights from the pre-workshop questionnaire and post-workshop interviews, and define acronyms used in the review.

1.2: Water Supply in California

California is semi-arid with highly variable precipitation across seasons, years, and geography. Its Mediterranean climate delivers almost all precipitation from November to March, with much stored seasonally as snow at higher elevations. However, California's April to October dry season is generally drier and longer than the worst drought ever experienced historically in the eastern United States. California's annual precipitation also is the country's most variable, with far more dry and wet years (Figure 1, Dettinger 2011).

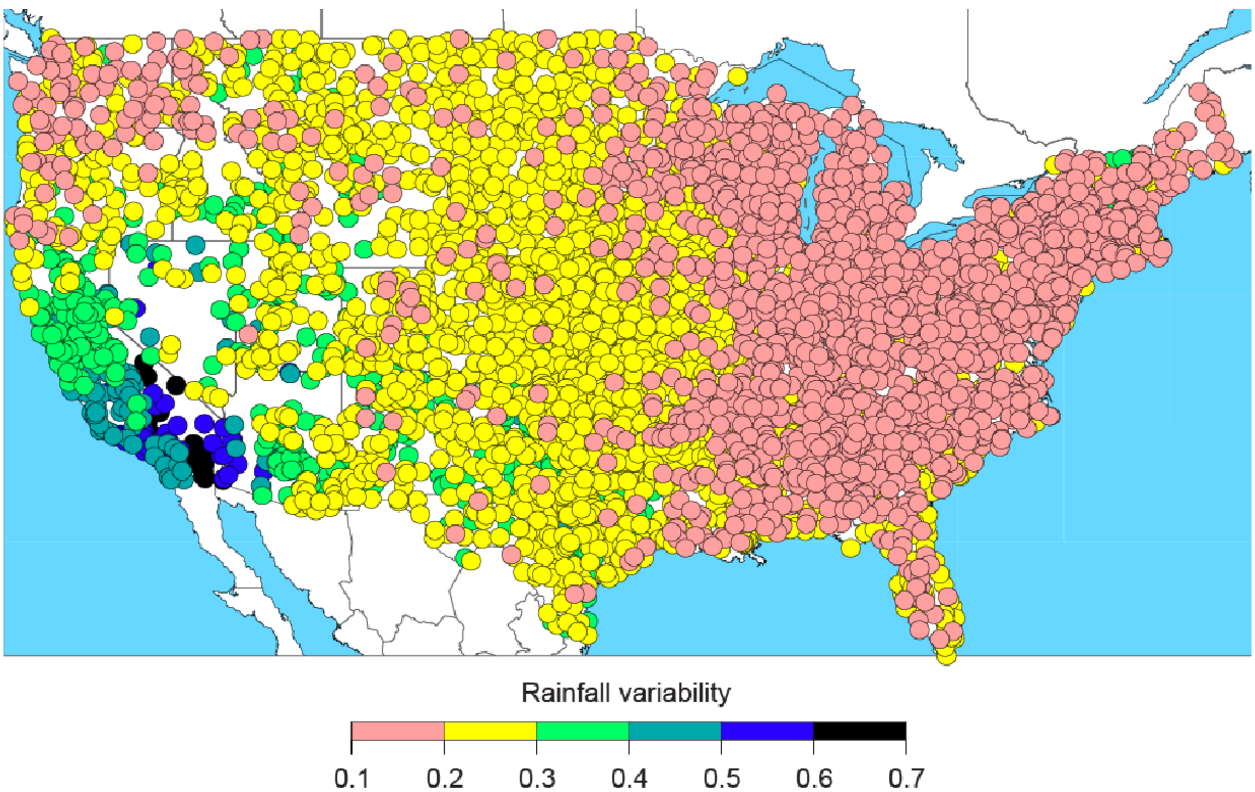


Figure 1. California has the nation's most variable annual precipitation. Annual coefficient of variation for precipitation stations in the continental US. (Coefficient of variation = standard deviation/average) (Dettinger 2011).

In California, water supplies and demands are mismatched in space and time for human uses: about 70 percent of the state's precipitation falls in the north while water demands are mostly in the south; and the winter precipitation season does not coincide with the summer season of highest water demand. Unreliability in water supplies is unavoidable with California's great hydrologic variability, diverse water demands, and allocated water rights that greatly exceed average water availability (Grantham and Viers 2014).

The location of the Delta makes it the major hub of California's water system (Lund 2016). Upstream reservoirs and aquifers are managed to shift water availability from winter and spring to summer and fall, and from wet to dry years. These reservoirs and associated conveyance infrastructure support large water diversions upstream of the Delta and alter seasonal inflow patterns to the Delta, from which additional water is diverted for state, federal, and local water projects. In wetter years and seasons, some Delta water diversions are stored in reservoirs and aquifers in the southern Central Valley, Southern California, and the Bay Area.

Local water agencies and water users manage local and imported water sources to fulfill water needs. These operations are often coordinated with near and distant neighbors, by using contracts, water market transactions, and government regulations, to better serve economic, public health, and ecological objectives. Shortages of water to local water users are common and become deeper and more widespread during droughts. Such water shortages often can be addressed by re-managing local and regional water supplies and demands, including infrastructure re-operation, water market transfers or agreements, and reductions in water use by additional conservation and land fallowing.

The Delta and its management are critical to this intricate and dynamic water supply system. There is often not enough freshwater available to the Delta to fully supply all water uses, including environmental needs. Continuous balancing of widespread and diverse water supplies and demands under widely varying weather and other time-varying conditions is essential. Achieving this balance falls under the state goal of *Water Supply Reliability* (in the Delta Reform Act of 2009), which receives intense interest from policymakers, stakeholders, water managers, and researchers alike.

1.3: Overview of Water Supply Reliability Estimation

A reliable water supply for California is defined in the Delta Plan as “better matching the state’s demands for reasonable and beneficial uses of water to the available supply.” Water supply reliability estimation, the subject of this review and as previously noted, is the formal process of quantitatively predicting performance and water delivery from a water supply system under a variety of conditions. Reliability usually is expressed as a probability of achieving water system performance objectives. The most common performance metric is a probability distribution of water delivery quantity, but a variety of engineering, public health, economic, social, and ecosystem health metrics are in use. Reliability is commonly estimated for seasonal water operations in each year and for various long-term water and environmental policy and planning horizons.

Formal water supply reliability estimation originated in civil engineering in the late-19th century to size new reservoirs to meet urban and agricultural demands that would supply water with 100% reliability based on the historical streamflow record (Rippl 1883). This approach estimated the so-called “firm yield” of a stream and reservoir, the maximum annual demand that could be supplied without shortage under variable annual weather conditions (Linsley et al. 1992). “Firm yield” approaches were used to design most major water projects during the early and mid-20th century. Many water project delivery contracts in California have been based on providing high-priority deliveries from a project’s firm yield, while lower-priority contracts only receive deliveries when the firm yield is exceeded in wetter years.

The firm-yield approach has been replaced by a more probabilistic understanding of relationships between variable streamflow, water storage capacity, and water delivery, given fluctuating water supplies and demands (Hazen 1914; Hirsch 1978; Klemes 1987). This approach recognizes that 100% reliability is infeasible to guarantee given the many sources of variability in the supply system and instead aims to estimate the relative likelihoods (probabilities) of the range of plausible water deliveries today or in the future. Probabilistic estimation of reliabilities for major water supplies was introduced in California in the 1970s and became common by the 1980s. However, many water contracts retain elements of the older approach (DWR 1983; Barnes and Chung 1986).

Figure 2 shows the main components and data flow of a typical model for modern water supply reliability analysis. Such modeling requires representation and integration of hydrologic, water demand, infrastructure capacity, component connections and interactions, and management aspects of water supplies, including their variability and uncertainty over time (see Appendix A for details). Because many highly variable factors are used to estimate probabilities, different approaches to estimating future behavior will lead to differences in reliability estimates.

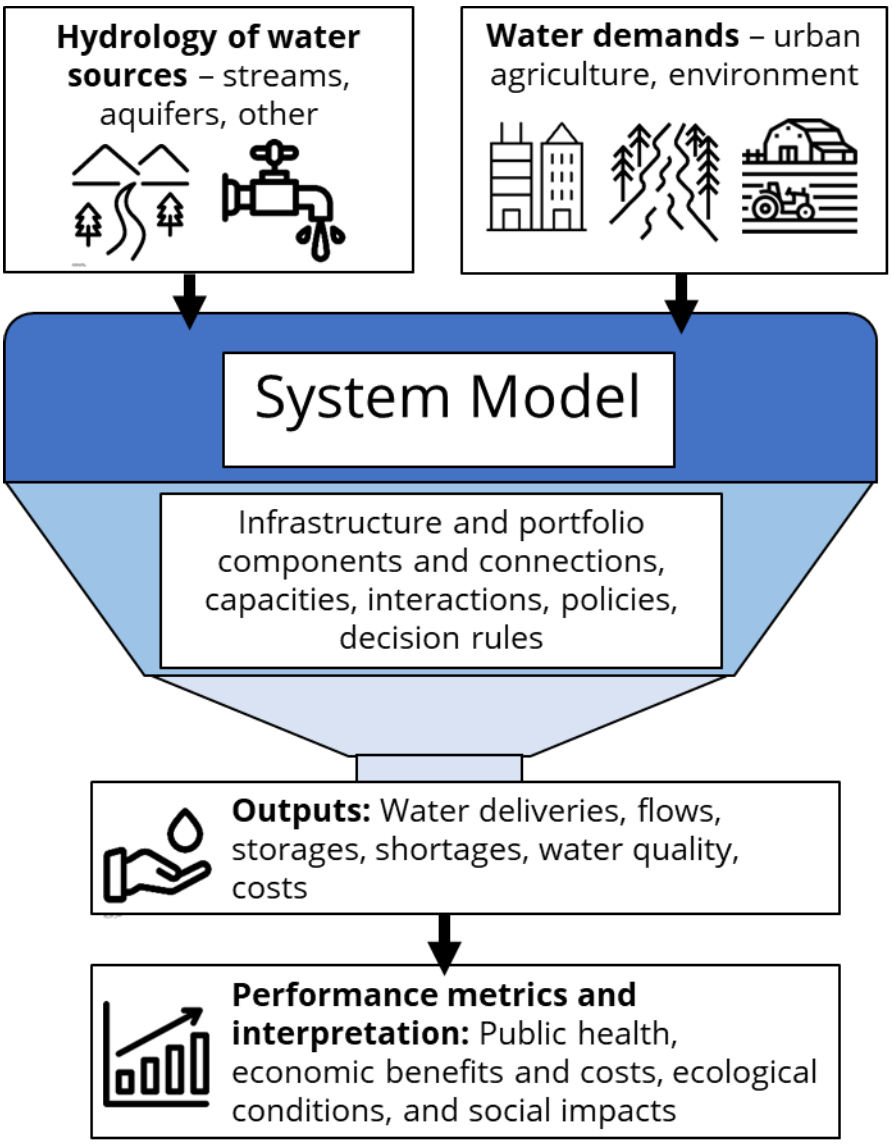


Figure 2. Main components of a typical water supply reliability analysis.

Water demands and hydrology of water sources are the major inputs to water supply reliability analyses and are usually represented as time series to represent variability seasonally and between years. The model representation of the water management system includes the capacities and connectivity of infrastructure elements among each other and with water sources and demands, as well as diverse policies for long-and short-term management of water infrastructure operations, conservation, and allocations. Water inflows, demands, and operating decisions are modeled as an inter-connected series of daily, weekly, or monthly time-steps extending over decades of varying hydrologic and operating conditions. Model outputs can include time series of water deliveries, flows, storages, shortages, quality, and costs. Model outputs are then further examined and interpreted in terms of performance metrics, such as probability distributions of water delivery or water shortages. These details are discussed in Appendix A.

Over time, water supply reliability analysis and management have adapted to changing conditions, as discussed in Box 1.

Box 1. Adaptive Management and Water Supply Reliability

The Delta Reform Act of 2009 establishes adaptive management as the guiding approach for managing the Delta. Much has been written about adaptive management since the approach was originally presented for environmental management (Holling 1978), including its application to Delta ecosystems (Wiens et al., 2017; Delta ISB 2016).

How does adaptive management apply to the state's Delta water supply reliability objectives? In practice, traditional water supply agencies have long employed many aspects of adaptive management for their water supply missions. Large agencies have extensive monitoring and modeling, and analysis of their system's behavior and performance, which they use to update their understanding of current and potential conditions and problems and to improve management. Monitoring and modeling are used to compare alternative management decisions for a range of policy, planning, and operational conditions and contexts to support decision making.

Water supply reliability estimation is a routine part of water supply agency modeling and analysis for understanding how these systems work, how they fail (and how likely it is), and what might be done to improve performance. Such analyses help assess the adequacy of water supplies and overall system management, and better understand vulnerabilities, opportunities, and their likelihoods. Reliability estimation helps identify more promising solutions as conditions evolve over planning and operational time frames. As such, water supply reliability estimation has long been vital to the adaptive operation and management of major water supply systems.

Modern water supply reliability estimation methods have evolved and broadened considerably since the early emphasis on urban and agricultural supplies. Water supply reliability and its estimation in California face many new challenges:

- Adapting California's extensive statewide, regional, and local water systems that transport and store water.
    - Further development of integrated portfolios of management activities - including diverse surface, aquifer, desalinated, and reused water sources, as well as management of water demands, including long-term and drought use reductions.
    - Changes in water storage, conveyance, and treatment infrastructure and technologies, and water management improvements (e.g., reoperation of reservoirs to balance flood management and water supplies; restoration of floodplains and wetlands; groundwater recharge; some capacity improvements).
    - Greater awareness of potential system failures from catastrophic events, such as major earthquakes, floods, contaminant seepage, water-supply terrorism, pandemics, and facility failures.
    - Increasing concerns for drinking water quality and treatment.
    - Complex interactions among the many parts and objectives in California's water system.
- Water flows have environmental consequences.
    - Recognition of the importance of environmental impacts of water supply and management decisions, and the needs of ecosystems for adequate amounts and timing of water availability.
    - Broader and deeper water quality considerations for ecosystems.
    - Environmental regulations that alter urban and agricultural water supplies and demands.
- Increased recognition of social justice concerns.
    - Water availability, safety, and quality for rural drinking water supplies.
    - Employment impacts on rural and urban residents.
    - Costs and affordability for lower income water users.
    - Increased appreciation of implications for Delta, tribal, and small communities, including related social justice concerns.
- Climate change.
    - Ecosystems and hydrologic systems will experience changing thermal and weather regimes.

- Historical records of unimpaired flows will have diminishing value for estimating water supply availability for both long-term planning and seasonal operations.
- The ability of the Delta to supply water of suitable quality for urban and agricultural water diversions will be diminished.

- Regional and global changes affect water demands.
  - Factors outside of the water management system often affect water demands and performance, including changes in societal and environmental attitudes, human behavior, land use, population growth and migration, technology, law, and crop and energy prices.
- Overall water demands will often exceed available and economically feasible water supplies.
  - In much of California, water demands often exceed water supplies, particularly during drought.
  - Limits on groundwater overdraft from the Sustainable Groundwater Management Act, increases in both environmental flows and traditional water demands, and over-allocation of available water supplies increase the need for water scarcity management.

Although water supply reliability estimation in California is among the most sophisticated in the nation, water supply reliability estimation has not traditionally incorporated most of these factors. Adding them into estimates should improve estimates and their value for policy and management decision-making, but brings new technical challenges. As an example, water quality, timing, and spatial distribution of flows are important to species in ecosystems, but specific requirements are highly uncertain and sometimes unknown. Modifying design needs to address climate changes and future human adaptations further compounds uncertainties. Making long-term water supply estimates involves many unknowns, but better analysis is often insightful and sets a more solid base for making controversial decisions and major public investments.

Another important consideration is surprises. Surprises happen in water management and should be considered and be prepared for in water supply reliability estimation, analyses, and planning. In fact, surprises are inevitable (Box 2) and can be overlooked in water supply reliability estimation. Decision makers need to be prepared to consider a wide range of expected and novel extreme events using both probabilistic and robust sensitivity analyses (e.g., Marchau et al. 2019).

Box 2. Challenges of High-impact, Unlikely (Black Swan) Events (i.e., Surprises)

The novel coronavirus (COVID-19) pandemic illustrates a major challenge for uncertainty methods. How can system analysts anticipate and treat very low probability events with major impacts that are difficult to identify and characterize in advance? Their omission in design is often excused by their small probability, but they are real and, may overwhelm human and natural systems.

Rare and often poorly characterized (or unknown) high impact events fall into two major categories. The first category consists of imaginable events. These are based on historic precedent or a causal understanding for their anticipation. The second category consists of events not imagined by most planners, engineers, experts, leaders, or the public due to a lack of precedents in human history or inadequate understanding for developing meaningful scenarios. Events in the former category are sometimes developed to test project robustness or resiliency. Ironically, such tests are often called worst-case scenarios, although they reflect only imaginable dire circumstances (Brown et al. 2012).

Many events could significantly degrade water supply reliability by damaging larger water projects and systems in Delta. These include climate changes, “megadroughts,” sea level rise, failures from earthquakes and floods, volcanic ash, water contamination, increased ecological uses, political upheaval, and terrorism. Once recognized, challenges arise in characterizing these events. The first major challenge is estimating their frequency needed to calculate risk. This is especially true for events known primarily from geologic and historical records. Second, their magnitude may be difficult to assess. For example, coring in today’s Delta reveals volcanic ash layers from large Cascadian volcanic eruptions that once choked the modern Delta region in the Pleistocene. Although many details are unknown, a reoccurrence would be a hazard to turbine pumps, human health, water quality, agriculture, and ecosystems today (Maier et al. 2015). Third, some scenarios are based on nonstationary processes. For example, a recent investigation used dendrochronology in the American West to identify megadroughts that occurred on the average approximately every 240 years (Williams et al. 2020). While this information is useful to estimate their frequency, climate change may alter this frequency. Indeed, anthropogenic warming strengthened the 2000 to 2018 Western drought. Finally, human responses to extreme events are often highly uncertain, particularly in decentralized managed systems, where many actors must overcome diverse perspectives to agree on management objectives and approaches.

Unimagined surprise events, the second category, are the unknown unknowns popularized by former U.S. Secretary of Defense, Donald Rumsfeld. In Nassim Talib’s The Black Swan (2007), these are unpredictable events with massive consequences that can be rationalized only retroactively. Although unimagined events are inherently difficult to accommodate in engineering design, their existence may expose a system vulnerability caused by ignorance or human limitations. Humans tend to focus on things they know and disregard things they do not know. Acceptance of ignorance or limitations of thinking capacity and controllability of events may encourage increased resiliency and preparation for adaptation in designs. Multiple component failures might wreak havoc even in well-engineered systems, as in the 2011 Tohoku, Japan, earthquake and tsunami.

The COVID-19 pandemic and low-probability, high-impact events in general beget humility. Operational success is not fully guaranteed regardless of how well a probabilistic method for design is formulated. History is replete with catastrophic events, imagined and unimagined, that with advantage of hindsight fell in the tails of prior probability distributions. History also shows numerous cases where well organized, adaptable, and well-prepared systems responded effectively, despite damages and losses, to large unpleasant surprises.

2. Water Supply Reliability Analysis in California

Many human and environmental water users in California draw their water directly from the Delta (averaging about 5 million acre-ft/year). Still greater volumes of water are drawn indirectly from the Delta by upstream surface and groundwater users. The Delta is the major hub of the Central Valley Project (CVP) and State Water Project (SWP), the backbone of California's water supply network. Thus, the Delta is central to the extensive and often overlapping integrated portfolios of water supplies, demands, and infrastructure managed by hundreds of agencies and millions of users. Today, water in and from the Delta is becoming more important and increasingly threatened by droughts, floods, climate change, groundwater depletion, population growth, vulnerable infrastructure, and deteriorating ecosystem health (Lund 2016; Schwarz et al. 2020).

Regulatory requirements add to the water management challenge by allocating water to meet new objectives. The federal Endangered Species Act and Clean Water Act required increasing the dedicated water supply for fish, other organisms, and ecosystem processes. California's Sustainable Groundwater Management Act (SGMA) will end groundwater overdraft and further shrink supply to more sustainable levels. The expected increase in surface water demands on the Delta and other sources due to implementation of SGMA is about 2 million acre-feet/year (maf/yr), and the sources for meeting this demand have not been identified (Dogan et al. 2019). New proposals for Delta and tributary environmental flows or voluntary agreements could further modify water operations and Delta water availability for diversions.

Three successive droughts with accompanying water delivery cutbacks, declining fish populations, deteriorating environmental conditions, increased attention to levee fragility (Roe et al. 2016), and increased litigation and demands for greater environmental regulations, led California's legislature to pass the Sacramento-San Joaquin Delta Reform Act in 2009 (Frank 2010). The Act declares two coequal goals for the Delta: (1) provide a more reliable water supply for California and (2) protect, restore, and enhance the Delta ecosystem, while protecting and enhancing the unique cultural, recreational, natural resources and agricultural values of the Delta as an evolving place. Reliable water supplies are critical to meet the coequal goals, and to successfully manage California's water resources. Droughts continue to highlight diverse water supply reliability concerns in California (Durand et al. 2020; Box 3).

Box 3. Water Supply Reliability and the Ongoing 2020 - 2022 Drought

The 2021 water year (October 1, 2020 – September 30, 2021) was the 3rd driest year in more than 100 years of precipitation record. The 2020 water year was the 9th driest year in the precipitation record. The resulting drought has affected available water supplies for a wide range of agricultural, environmental, and urban water users and could continue for several more years.

So far, major cities have been mostly well prepared for this drought with long-term water use reductions, groundwater banking, initially full reservoirs, better connections to external water supplies, and water market agreements with farmers. Some smaller towns have been less well prepared with several towns requiring 30-40% reductions in water use. Larger cities could follow suit if the drought continues and requires mandatory water rationing.

Agriculture has seen large surface water reductions, especially in the San Joaquin Valley, but also in the Sacramento Valley and smaller river valleys statewide such as the Russian and Klamath river basins. Farmers have increased groundwater use to reduce drought impacts, but this often affects shallower rural domestic water supply wells.

Under the Sustainable Groundwater Management Act (SGMA), farmers will need to replenish the additional groundwater pumped during the drought, meaning some reductions in lower-valued crops in wetter years so that aquifers can recover to sustain permanent crops in future droughts. Few basins can sustain aquifers with managed aquifer recharge alone; many will need deep reductions in aquifer pumping in wetter years. This reduced groundwater supply will increase pressure to sustain or increase water diversions from the Delta.

Forests and aquatic ecosystems are experiencing major impacts, especially wildfires and salmon runs (including near-elimination of naturally-spawning winter-run salmon in 2021) and re-installation of the Delta salinity barrier at West False River. Gartrell et al. (2022) has an excellent analysis of Delta operations and flows from 1980-2021. Because the 2022 water year is also dry, agricultural and environmental impacts will increase and urban impacts will expand for some larger urban areas.

The 2020-2022 drought, like the 2012-2016 drought, has been much warmer than previous droughts because of global warming caused by climate change. Higher temperatures worsen droughts by increasing evapotranspiration and reducing the proportion of precipitation that becomes runoff available to fill reservoirs and recharge aquifers (Shukla et al. 2015). Higher temperatures also lengthen wildfire seasons, and worsen conditions for cold-water fish species, such as salmon. Water supply reliability estimation and management will need to address these changes.

2.1: Causes of Water Supply Unreliability

It is rarely possible to identify and anticipate all possible failure mechanisms, and practically impossible to accurately represent all failure mechanisms explicitly in models. This problem is chronic for California's complex water systems. Complexity often brings flexibility and robustness, but sometimes introduces new sources of unreliability.

Estimations of water supply reliability tend to emphasize reductions of inflow, caused by drought and changes in regional climate and water demands. However, local water shortages may arise from diverse drivers such as from wildfires (Paradise, California), floods (disabling intakes and water treatment plants), internal management and operational failures (Flint, Michigan), upstream water quality declines, harmful algal blooms (Toledo, Ohio in 2014), contamination, black-swan events (Box 2; Chan and Ho 2019; Howe et al. 2018), mechanical and electrical infrastructure failure, earthquakes and limitations to operations from complex environmental and water rights regulations (Grantham et al. 2014, 2018).

Delta water source reliability is unusual compared to a typical water supply system. Because the Delta is connected to the ocean and is mostly at or below sea level, the Delta always has water available. However, the quality of this water at distribution points is unreliable due primarily to salinity concerns when Delta inflows are insufficient and exports are too great, among other factors. These water quality effects can limit water uses from western Delta diversion (such as the City of Antioch) and progressively affect additional in-Delta and Delta export diversions when net outflows diminish enough to allow ocean salts to intrude further into the Delta with tidal mixing (Young 1929; Fleenor et al. 2008; Jayasundara et al. 2020; Medellín-Azuara et al. 2014).

An ongoing example of infrastructure failure is the reduced capacity of the CVP's Friant-Kern Canal. Over-pumping of groundwater and land subsidence have lowered reaches of the canal and reduced its capacity (Borchers et al. 2014). Water shortages for human uses also may occur from any combination of increased demand, diminished supplies, new environmental and water quality regulations, and failure of agreements or institutional rules (such as failed water trades).

All estimates of reliability are fallible, so additional stress-testing analyses for improbable, but plausible, events can explore the robustness of designs and adaptations (Dittrich et al. 2016; Groves et al. 2019). Even imperfect water supply reliability analyses can help organize and focus discussions and planning as well as inform reasoned decisions on California's difficult water and environmental problems.

2.2: Selective Inventory of Reliability Estimation Efforts

California's largest water supply systems routinely estimate water supply reliability for policy, planning, and operational decision-making (Jackson 2006). Table 1 is a selective summary of many of these efforts.

Water supply unreliability does not usually translate directly into water shortages or large economic or environmental losses. Water supply reliability analyses fall into two categories: 1) examinations of source delivery reliability (DR-delivery reliability in Table 1) and 2) examinations of integrated system reliabilities (ISR-integrated system reliability in Table 1). Water source reliability estimates (category 1) are more limited than overall supply reliability (category 2) and focus only on the probability distribution of water available for delivery from a single source or project, such as the SWP.

Water system performance reliability estimates (category 2) combine reliabilities of various water sources and system components, as well as the significance of any resulting economic, human, or environmental losses, often mitigated by infrastructure operation and demand management activities, such as that done by the Metropolitan Water District of California (MWDSC). Every integrated system reliability study includes estimates of source reliability, as well as supply and demand adaptability to water availability conditions.

SWP and CVP source reliability studies are often employed within more comprehensive regional or local system reliability studies. For example, MWDSC (2015) integrates SWP and CVP source reliabilities and models into a wider portfolio of supplies and demand management activities to reduce overall losses and water shortages. Some examples are identified in Table 1.

Table 1. Selected water supply reliability estimation efforts in California (see acronym list in Appendix C).

Entity	System	Description (DR=delivery reliability; ISR = integrated system reliability)
California DWR		
SWP Planning	SWP + CVP	DR - CalSim, CalLite (DWR 2017, 2020)
SWP Operations	SWP ops.	DR - Delta Coordinated Operations (DCO)
	SWP MWQI	DR - DSM2 and CalSim (Hutton & Roy, in review)
Calif. Water Plan	Statewide	DR – WEAP
	SWP	ISR - WEAP/ CalSim, LCPSIM, SWAP
Climate Change	SWP, or CVP+SWP	DR - CalLite (Wang et al. 2018; Ray et al. 2020; Schwartz 2018, 2020)
SGMA	Central Valley	DR - Recharge availability (DWR 2018)
California SWRCB		
Water rights	Statewide	DR - Water balance analyses for water rights
Environmental flows	Sac. Valley +Delta	DR - SacWAM (WEAP) (SWRCB 2020)

Entity	System	Description (DR=delivery reliability; ISR = integrated system reliability)
Federal Agencies		
US Bureau of Reclamation	CVP	DR - CalSim, USBR CalLite (USBR 2004, 2016)
Local and Regional Agencies		
CCWD	Contra Costa area	DR - CalSim and others
EBMUD	East Bay	ISR - (EBMUD 2021)
SFPUC, BAWSCA	Bay Area	ISR - (BAWSCA 2015)
SCVWD	Santa Clara Valley	ISR - (SCVWD 2003, 2012, 2019)
MWDSC	So. California	ISR - IRPSIM (MWDSC 2015), Calsim (DWR), CRSS (USBR)
MWDOC	Orange County	ISR - WEAP version, MWDSC modeling (MWDOC 2016, 2018)
CCWD	Contra Costa area	DR - CalSim and others
EBMUD	East Bay	ISR - (EBMUD 2021)
NGO Studies		
TNC water storage	SWP + CVP	DR - CalLite (Lund et al 2014)
Restore Hetch Hetchy	Tuolumne + SF Bay Area	DR - Simulation and optimization
Academic Studies		
UCLA	CVP	DR- System optimization (Becker et al 1976)
Water supply, UCD	Statewide	ISR - Hydro-economic optimization, CALVIN (many applications, Dogan et al. 2018, 2019; Arnold 2021)
Water supply, UCD	EBMUD	ISR - Spreadsheet (Lund et al. 1998)
Water supply, UCLA	Los Angeles	ISR - (Porse et al. 2017, 2018)
Hydropower, UCD	California	DR - Climate change (Madani 2009, 2010)
Conjunctive use, UCD	Central Valley	DR - Recharge availability (Kocis and Dahlke 2017)
Conjunctive use, PPIC	Central Valley	ISR - Recharge availability (Escriva-Bou & Hanak 2018)

Entity	System	Description (DR=delivery reliability; ISR = integrated system reliability)
SGMA reliability, UC	Central Valley	DR - Simulations (Escriva-Bou et al. 2020a)
Dracup, UC Berkeley	Merced R., American R.	ISR - (Vicuna et al. 2007)
Fish flows, UC	Statewide	DR - CEFF
Fish ops., UC Davis	Folsom, Shasta	ISR - (Adams 2017, 2018)
UCLA	CVP	DR- System optimization (Becker et al 1976)
Water supply, UCD	Statewide	ISR - Hydro-economic optimization, CALVIN (many applications, Dogan et al. 2018, 2019; Arnold 2021)

Note: DR=delivery reliability, examines only the reliabilities of water delivered; ISR = integrated system reliability, examines the reliabilities of a broader management portfolio, including sources, infrastructure, agreements, and demands.

The California Department of Water Resources has separate organizational units that estimate water supply reliability for seasonal State Water Project operations, State Water Project Planning (DWR 2017, 2020), the California Water Plan (DWR 1983, and later plans), climate change (Ray et al. 2020; Schwarz et al. 2018, 2020), and Sustainable Groundwater Management implementation (DWR 2018). The California Department of Water Resources in conjunction with the United States Bureau of Reclamation has developed sophisticated software called the Water Resources Integrated Modeling System (WRIMS), which support their CalSim and CalLite models (Barnes and Chung 1986; Draper et al. 2004; Islam et al. 2011). This modeling usually includes representations of salinity in the Delta, modeled using hydrodynamic (DSM2) or faster artificial neural network models (Jayasundara et al. 2020).

The California Department of Water Resources also has a capability to do more integrated system performance reliability assessments for SWP service areas, using CalSim or WEAP models for water source reliability, and economic models of local agricultural and urban water source and demand management.

The State Water Resources Control Board independently estimates water supply reliability for water rights in its Water Rights Division (river basin water balance calculations, SWRCB 2020) and environmental flow regulations (SacWAM, SEI 2019).

Water supply reliability estimates for Federal water projects in California are performed primarily by the U.S. Bureau of Reclamation in its operations and planning units, but sometimes they are performed by other Department of Interior agencies. Modeling for planning in the last 20 years has historically used versions of CalSim II, but USBR's CalLite is implemented in another simulation package. CalSim 3.0 is a newer model expected to replace CalSim II (DWR and USBR 2017). Some regional modeling studies use WEAP software (Mehta et al. 2013; Joyce et al. 2011).

Local and regional water utilities in California individually estimate water supply reliability in various ways for planning, policy, and operational purposes (e.g., EBMUD 2021, SFPUC, BAWSCA 2015, SCVWD 2003, 2012, MWDSC 2010, 2015, MWDOC 2016, 2018, SDCWA 2017, 2020). Southern California's urban water systems have tended to be leaders in portfolio management and more integrated system analyses. Environmental organizations also have done water supply reliability assessments for policy and planning purposes (e.g., The Nature Conservancy, Restore Hetch Hetchy, Environmental Defense Fund). Water supply reliability studies are conducted by both the sponsoring organizations themselves and partly or wholly by consultants that specialize in such studies. Cost, data availability, and technical staff capability are barriers for small water suppliers, which usually are more vulnerable to unreliability, particularly during droughts.

Academic studies have advanced methods and insights for water supply reliability estimation in case studies of several water systems in California. These have examined:

- Reliability and operations for CVP and SWP water deliveries (Becker et al. 1976; Mariño and Loaiciga 1985; Roche 2020)
- Water markets, conjunctive use, and integrated management (Jenkins and Lund 2000, 2004; Medellín-Azuara et al. 2008; Lund et al. 1998; Tanaka et al. 2006, 2011; Dogan et al. 2018; Arnold 2021)
- Regional water portfolio reliability (Porse et al. 2017, 2018; Howe et al. 1994; Groves et al. 2014)
- Sensitivity to hydrologic foresight and reservoir operations (Arnold 2021)
- Aquifer recharge with flood waters (Kocis and Dahlke 2017; Escriva-Bou and Hanak 2018)
- Aquifer recovery reliability under SGMA (Escriva-Bou et al. 2020)
- Distribution system reliability (Gheisi et al. 2016)
- Reliability of evapotranspiration estimates (Medellín-Azuara et al. 2018)

- Institutional reliability in conflict resolution (Al-Juaidi & Hegazy 2017)
- Climate change (Dogan et al. 2018; Medellín-Azuara et al. 2008, 2009; Kiparsky et al. 2014; Tanaka et al. 2006, 2011; Vicuna, et al. 2007; Joyce et al. 2011; and others).

Although beyond the scope of this review, reliability studies are common for major water supply systems globally and domestically as well. Globally, water supply reliability estimates increasingly take one of many variants on an integrated system approach, as described here. Examples include planning and operation analyses for New York City (Porter et al. 2015; NASEM 2018, 2020), South Florida (SFWMD 2020), Las Vegas (Ahmad 2016), Sidney (Australia) (Kidson et al. 2013), London (Matrosov et al. 2013, 2015; Morley and Savić 2020), northeastern Colorado (Michelsen and Young 1993), and other systems (Raucher and Raucher 2015). Lessons and methods for reliability estimation from outside California generally reinforce and support the points made in this review.

2.3: Delta Water Supply Reliability

The Sacramento-San Joaquin Delta is a major hub for water movement and water supply in California. The Delta, directly or indirectly (from upstream water diversions), is the exclusive water supply for many agricultural, urban, and environmental water uses, and a variable partial water supply for many more water users, including most the Central Valley, Bay Area, and Southern California, as well as Central Valley and San Francisco Bay ecosystems.

The availability of water in the Delta, even after management by sizable upstream reservoirs, is often not enough to fully supply all water demands by the state's agriculture, ecosystem, and urban water users. There are times when Delta inflows exceed all water demands, mostly in wet years (including floods). Even during drought, some winter storms generate enough runoff below major reservoirs to exceed local water uses and export pump capacities.

Every two years, the California Department of Water Resources estimates the reliability of SWP water deliveries and overall Delta water exports (DWR 2019). These estimates show highly variable water delivery availability from the Delta for water export users, as shown in Figure 6. This hydrologic variability also affects environmental and other water uses.

Inflows to the Delta supply water support various functions:

- In-Delta human and environmental consumptive uses (agriculture, urban, riverine, wetland, and open water evapotranspiration)
- Delta water exports (agriculture, urban, and some managed wetlands)
- Delta outflows to hold back seawater and Delta salinity (supporting local water quality for western Delta diversions and water quality within the Delta for interior Delta users and water export projects, a so-called "hydraulic salinity barrier")
- Delta outflows for ecosystem management
- Uncaptured storm or snowmelt outflows (which are often uneconomical to capture)

These functions are represented in water rights and contracts (riparian and appropriative water rights, water project contracts, and legal judgements), various state and federal water operation regulations (federal and state project authorizing and regulating legislation, State Water Resources Control Board water quality regulations and decisions, and federal and state endangered species regulations), and various water project operating agreements (such as the CVP-SWP Coordinated Operating Agreement – COA) (DWR 2019).

It is popular to debate the causes of this variability of water available for uses in the Delta. Major flows into and out of the Delta (its "water balance") and the regulations that limit them have been quantified by two independent groups, who came to similar conclusions (Gartrell et al. 2017, 2022; Reis et al. 2019). Table 2 presents the Delta's average water balance from 2010-2018 (Reis et al. 2019). Of estimated Delta unimpaired inflow over this period, on average 30% was diverted before reaching the Delta, 16% was pumped from the Delta, 4% was net use in the Delta, and 55% became Delta outflow.

Of Delta outflows during this period, almost two thirds are during wet periods when flows exceed capacities to store or pump water for export, 25% is managed to repel seawater from the Delta so that water exports (and in-Delta water diversions) remain fresh, and about 10% is for regulatory fish and ecosystem flows. In contrast, when the limiting factor was identified for each day's water export operations from 2011-2018, exports were limited in roughly 29% of days by the need to maintain outflows for repelling seawater from the Delta, in 25% of days by general state-mandated environmental flows (state water quality control plans, etc.), in 27% of days by federal endangered species restrictions for salmon or Delta Smelt, and in 16% of days by water diversion or storage infrastructure (Reis et al. 2019). Although such water accounting can provide insights, it is subject to different interpretations and controversies because much Delta outflow serves multiple purposes and regulations, sometimes muddying allocation of "responsibility" for outflows (similar to allocating water system fixed costs among customers). Gartrell et al. (2022) have updated this type of analysis from 1980-2021, including detailed and thoughtful analyses of implications for policy and management.

Table 2. Approximate average Delta water balance, 2010-2018. (Reis et al. 2019) (Note: sums sometimes exceed 100%).

2010–2018 flow	Ave. Volume (maf/yr)	Ave. Volume (10^9 m^3/yr)	% unimpaired Delta outflow	% actual Delta outflow
Unimpaired Delta outflow	27.0	33.2	100	
Upstream net use	8.1	10.0	30.1	
Delta inflow	20.2	25.0	75.1	
Delta net use	1.0	1.2	3.6	
Water project exports	4.2	5.2	15.6	
Other exports	0.2	0.2	0.6	
Delta outflow	**14.9**	**18.4**	**55.3**	**100.0**
Hydraulic Salinity Barrier	3.7	4.5	13.7	24.7
WQCP F&W	0.8	1.0	3.0	5.4
CVPIA b(2)	0.05	0.06	0.0	0.0
ESA RPAs	0.8	1.0	2.9	5.3
Anadromous fish RPA	0.4	0.5	1.5	2.8
Delta Smelt RPA	0.2	0.2	0.7	1.2
Simultaneous fish RPAs	0.1	0.2	0.5	0.9
Voluntary reductions	0.1	0.1	0.2	0.3
Other uncaptured outflow	9.6	11.9	35.7	64.6

Clearly, there are many causes for water scarcity and its variability in the Delta. There are considerable uncontrolled outflows from the Delta, most of which would be uneconomical to capture. Some uncontrolled outflows occur from local storms even in drought years (Gartrell et al. 2017, 2022).

Changes in climate will further decrease the reliability of water available to the Delta (Lettenmaier and Sheer 1991; DSC 2020; and others) and ending groundwater overdraft in the San Joaquin Valley increases unrequited water demands by about 2 maf/year (Escriva-Bou et al. 2018). Decreases in urban water use, new local sources and reuse, groundwater banking, and water markets somewhat reduce this water scarcity for urban areas.

As the major junction of California's water supplies, the Delta is a major balancing component for variability and imbalances between local and regional water supplies and demands – all of which are seeing challenges of local, regional, and statewide water scarcity. Another state policy in the 2009 Delta Reform Act is to reduce reliance on Delta water supplies generally. This policy is discussed in Box 4 in terms of its interactions with water supply reliability.

Eliminating all water scarcity at the Delta for all times would require great expense, and might not be economically worthwhile. Just as money and land are scarce in California, California will have to manage in perpetuity with water scarcity at the Delta in most years. How water users, water projects, and water and environmental regulators manage this scarcity is a major and growing challenge, punctuated emphatically during droughts. Such decision-making can be improved with information on water supply reliability.

Box 4: Reduce Reliance on the Delta and Water Supply Reliability

Water Code section 85021: The policy of the State of California is to reduce reliance on the Delta in meeting California's future water supply needs through a statewide strategy of investing in improved regional supplies, conservation, and water use efficiency. Each region that depends on water from the Delta watershed shall improve its regional self-reliance for water through investment in water use efficiency, water recycling, advanced water technologies, local and regional water supply projects, and improved regional coordination of local and regional water supply efforts.

State policy to reduce reliance on the Delta for water supply is incorporated into the state's Delta Plan (Chapter 3) and in DWR's guidebook for urban water management plans (DWR 2021). DWR interprets reliance on the Delta for water in terms of the absolute or percent volume of average total water use derived from the Delta watershed (including water use efficiency improvements as a non-Delta source).

Policies that reduce reliance on Delta water supplies tend to improve the average reliability of remaining Delta water supplies. (Conversely, reducing non-Delta water sources, such as the appropriate elimination of groundwater overdraft under state law, will increase reliance on remaining Delta water supplies). Other actions to increase Delta water availability for export (such as by importing more water from the Trinity River, increasing water storage capacity, or increasing Delta pumping capacity) would in theory improve Delta water supply reliability, but increase reliance on Delta water supplies.

Defining reliance based on average use of Delta supplies does not address the reliability of Delta water supplies in more than an average sense. For example, to achieve ecological, water supply, and community objectives, reliance on Delta supplies in dry seasons or years might be more important than average reliance on Delta supplies.

For example, consider two users that on average receive the same percentage of their use from the Delta watershed, but one user takes water more in summer seasons and in dry years. The dry-period user has a greater impact on Delta water supply reliability and other Delta objectives because water is scarcer and harder to supply at these times. In a sense this user relies more on Delta supplies because fewer alternative water supplies are available and reduced deliveries are likely to incur higher costs and impacts for alternative supplies or foregone water use. Most state policy objectives would be better met if users shifted their use of Delta water to wetter seasons or years, even if their average use of Delta water remained the same.

As weather extremes become more frequent in California's changing climate, it might be prudent to revise policy implementations to reflect performance for a range of conditions rather than less-frequent average conditions.

Reference: DWR (2021), Urban Water Management Plan Guidebook 2020, California Department of Water Resources, Sacramento, CA, March.

3. Major Scientific and Technical Challenges

The workshop, questionnaire, and interviews conducted for this review highlighted scientific and technical challenges in water supply reliability estimation (Appendix B). Topics that received the most attention in the three forums include: impacts from climate change on water supply; planning and management of multiple sources of water supply; environmental adaptive management, environmental water supply performance metrics; water quality; and methods to address multiple objectives and conflicts in water planning and operation. This section organizes these topics into two broad challenges for water supply reliability modeling and analyses: 1) climate change and ecology and 2) technical and management issues. Topics discussed here under each challenge are listed in Table 3.

Table 3. Summary of major scientific and technical challenges.

Topic	Challenge
Climate Change and Ecology	
Climate Change	Predict and prepare for a changing climate and hydrology
Ecological and Environmental Water Supply	Better represent and balance human and environmental water supplies. Better prepare for ecological changes.
Water Quality	Anticipate and prepare for changes in salinity, nutrients, contaminants, etc.
Technical and Management Issues	
Portfolios for Water Management	Integrated management of multiple water sources/locations and demands
Environmental Adaptive Management	Adjust management in response to changes, improved understanding, and real-time conditions
Multiple Objectives and Conflicts in Water Management	Optimize across multiple objectives and resolve conflicts
Forecast-Informed Operations	Incorporate real-time forecasts into system operations
Improved Regional Management	Integrate water supply reliability analysis and operations from local to state-wide scales, technically and institutionally
Uncertainty Analysis and Preparations	More widely employ risk-based analysis and decision making
Hydrologic Data and New Analysis and Management Technologies	Improve hydrologic data collection, synthesis, adjustment, and reporting, as well as modeling techniques

3.1: Climate Change and Ecology

3.1.1: Climate Change

> *"Another area that remains to be addressed is the management response to long term climate change." Lettenmaier and Sheer, 1991*

Climate change was the most frequently cited concern affecting future water supply reliability estimates in the questionnaire distributed before the review workshop (Appendix B). Seven of 17 respondents indicated that climate change uncertainty is a major factor limiting conventional reliability estimation for long-term management and decision-making. Climate change at local and statewide scales is increasingly being incorporated into water planning, but details of the climate's future remain significantly uncertain (Robinson et al. 2021; Le Bars 2018; Ruckert et al. 2017; Swain et al. 2020).

State and local governments in California have been remarkably progressive in considering future climate change in long-term water planning. California's Fourth Climate Change Assessment (2018) and a recent Delta vulnerability study (Schwarz et al. 2020) specifically address impacts on water supply. Temperatures are forecasted to increase by 3.1 degrees to 4.9 degrees C (5.6 degrees to 8.8 degrees F) by 2100, and sea levels are forecasted to rise by ~50 cm (~20 in) by 2050. Higher temperatures increase agricultural and urban water demands, and challenge water temperature management for cold-water species, such as salmon. Higher sea levels threaten Delta levee stability and management of the Delta's salt/freshwater interface during low river flows.

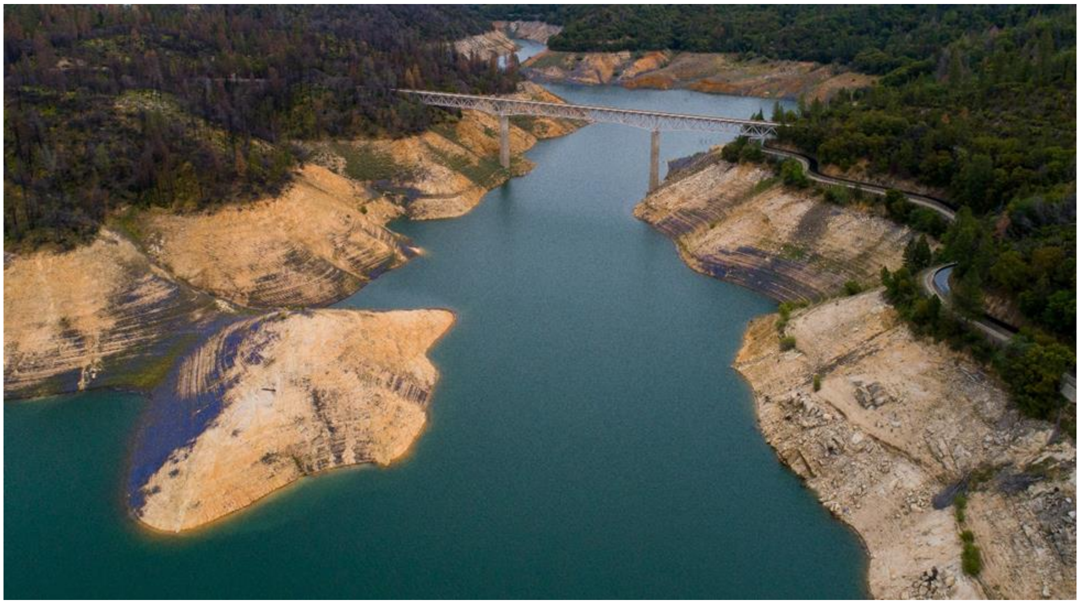
In addition, changes in weather dynamics are expected to increase the severity of both floods and droughts, even though mean precipitation might remain unchanged. Atmospheric rivers, which currently deliver 25 to 50 percent of California's annual precipitation, are forecasted to decrease in number by 10 percent, but become longer and wider because warmer air can carry more moisture. These changes coupled with shifts in seasonal spring runoff from diminishing winter snowpack are prompting water managers to make water supply forecasts based on different and nonstationary climates.

Most current modeling for water supply reliability estimation includes effects of climate change based on scenarios. Uncertainty of future greenhouse gas emissions, the main driver of climate change, along with other sources of uncertainty hinders conventional probabilistic estimates for decision making, (Box 5). A USBR (2016) investigation on change and variability in total Delta exports for multiple climate scenarios is one example. Basically, a sensitivity study, it indicates that climate change will likely reduce Delta exports. Another recent study found likely reductions in SWP exports over a wide range of plausible climate changes (Ray et al. 2020).

Substantial management and policy insights can be gained from analysis of single future scenarios (Tanaka et al. 2006; Dogan et al. 2019). However, examination of multiple climate scenarios improves understanding of uncertainties and identifies promising and robust actions. Alternatively, Bayesian approaches can more rigorously account for the relative likelihood of different scenarios, and how scenario likelihoods will change with time and experience (Fletcher et al. 2019; Hui et al. 2018; Herman et al. 2020). Stress testing management alternatives with diverse extreme scenarios also provides a prudent form of evaluation (Marchau et al. 2019).

Estimating the severity of droughts in future climate regimes is a particular challenge for scenario-based planning. East Bay Municipal Utility District, for its assessments of future droughts, relied on the historical record of droughts and then postulated hypothetical increases in drought duration and severity. Schwarz et al. (2018) conducted a simulation-based assessment of drought impacts on Sacramento and San Joaquin River flows in the Central Valley using a 1,100-year natural flow record (reconstructed from a dendrochronology record) to analyze vulnerability to low frequency climate variability. Their results indicated likely declines in many technical indicators of performance (e.g., supply, storage, Delta outflow).

Reductions in Delta water exports have been predicted in essentially every major study of climate change impacts on California water management. These studies use a wide range of scenarios, models, methods, and assumptions (Gleick 1987, 1989; Lettenmaier et al. 1988; Lettenmaier and Gan 1990; Lettenmaier and Sheer 1991; Tanaka et al. 2006; Vicuna and Dracup 2007; Ray et al. 2020; USBR 2016; Schwartz et al. 2018, 2020; Dogan et al. 2018, 2019; Medellín-Azuara et al. 2008; Connell-Buck et al. 2011).



3.1.2: Climate-Change Science in Water Supply Reliability Estimation

Basic methods for climate change analysis and implications for management in California began more than 30 years ago (Gleick 1987, 1989; Lettenmaier et al. 1988; Lettenmaier and Gan 1990; Lettenmaier and Sheer 1991). The main impacts identified have not changed fundamentally, although analyses are becoming more extensive and sophisticated (Herman et al. 2020; Schwarz et al 2018; Lettenmaier and Lund 2020). One limitation to most studies of climate change impact is that they examine effects of non-stationary hydrology with stationary water management policies in a system that is (and must be) managed adaptively. Water management might continue to be the most important non-stationary aspect of water supply reliability, as it has been for over 150 years in California. Analyses that address management dynamically over time with uncertain future climate and other conditions have only recently been formally considered (Herman et al. 2020) but could be used to identify policy options that are promising for improving social efficiency, including addressing inequities, in water allocation under climate change.

While scenarios and historical hydrologic observations will continue to be important in long-term water planning, scientific understanding of climate change and global climate models will continue to improve and provide useful directions and predictions of California's future climate. Hybrid approaches that combine the historical record and long-term climate models hopefully can provide useful insights to better estimate likely and extreme future hydrologies (Lund 2021).

The future climate of the Delta and California will progressively differ from the current one underscoring a need for ongoing adaptive management. Precipitation, evapotranspiration, water quality and timing of river discharge (Dettinger et al. 2015) and sea levels will all change. The actual future climate, however, will depend on how global society addresses greenhouse gas emissions, which is unknowable at present. The magnitude of climate change will require modifications in water system operations, regulations, infrastructure, demand management, and public policies to serve diverse users and adapt to changing needs. More integrative modeling of management and water supply reliability that includes the hydrologic impact of climate change will be critical to identify effective policies and to design infrastructure that meets performance objectives.

New and repeatedly updated understanding of climate must become the lynchpin of water supply reliability estimation, ultimately replacing stationary historical records. Huang et al. (2020) provide an example of how this approach prompted insights into precipitation changes of future extreme atmospheric river (AR) storms in a warming climate if business-as-usual greenhouse-gas emissions continue. They estimated that annual precipitation from ARs, which already provide much of California's annual precipitation, will increase substantially. Siirila-Woodburn et al. (2021) describe the impact of warming on future snowpacks. California's snowpack stores more water seasonally than all its surface reservoirs, delaying natural runoff by a few months into the dry season. The authors estimate that if greenhouse-gas emission remain unabated, snow water will decline ~25% by 2050, and no- to low-snow conditions will persist through the winter in ~35 to 60 years. Finally, Williams et al. (2020) shows how warming can intensify megadroughts (severe and persistent dryness for ~20 years). Using hydrologic modeling and a tree-ring reconstruction to infer soil moisture, they conclude that the 2000-2018 drought in southwestern North America was worsened by anthropogenic warming from a moderate drought to one of the worst droughts in the last 1200 years. Shukla et al. (2015) have similar findings for California's drought in 2014.

3.1.3: Ecological and Environmental Water Supply

Balancing ecological and human water uses to meet the mandated coequal goals of the 2009 Delta Reform Act continues as a major challenge to Delta management. Population levels of many native fish species are at dire levels, prompting listings as threatened or endangered species (Moyle et al. 2013). A wide variety of flow and habitat management responses are being proposed and implemented.

Considerable uncertainty remains in the effectiveness of many proposed actions. Operating favorable flow regimes will be challenging in a constantly changing backdrop of new biological opinions, engineered systems, public perceptions, and state and federal priorities and regulations. No single optimal solution exists to meet all water management objectives (Alexander et al. 2018). Multiple-objective optimization methods can help identify alternatives that maximize benefits or minimize losses across diverse stakeholders, but ultimately can only identify efficient trade-offs among imperfect alternatives (Null et al. 2021). These trade-offs will change over time with climate and other nonstationary conditions. When such methods include broad and diverse engagement of affected communities, they can improve both fairness and allocation of resources.

3.1.4: Science for Improving Environmental Water Supply Reliability

Management tools to achieve more favorable flow regimes for ecological systems are improving rapidly but require further development for policy application. Guidelines are needed for ecological flows that consider timing, inter-annual hydrologic variability, water scarcity, and water quality, and how to operationally integrate environmental objectives into water system decision-making (Davies et al. 2014; Arthington et al. 2018).

More mechanistic fish and ecosystem models based on habitat and flow conditions over seasonal life stages show some promise and should be actively extended (Delta ISB 2015; van Winkel et al. 1998; Bellido-Leiva et al. 2021; Tonkin et al. 2021). These should provide more solid means to estimate or quantitatively forecast species and ecosystem performance from water and habitat operations and investments.

“Reconciliation” approaches to ecosystem management seek to greatly expand habitat for native species living outside of protected areas by modifying human land and water use in coordinated ways to accommodate the most important benefits to each interest. Such approaches should be considered and developed for balancing water usage and ecological protection (Sommer et al. 2001; Rosenzweig 2003; Grimm and Lund 2016).

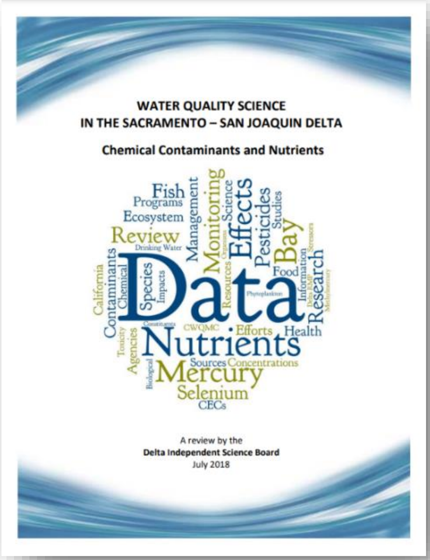
3.1.5: Water Quality

Water quality is fundamental to Delta water source and system reliability (Lund 2016) and involves multiple water quality parameters. Salinity (and its management) is an important Delta water quality reliability consideration. Intrusion of ocean water via San Francisco Bay and agricultural drainage water can be detrimental for environmental, in-Delta, and Delta export water uses (Gartrell et al. 2017, 2022; Reis et al. 2019). Operations and planning models sometimes have sophisticated representations of water quality aspects of system reliability (Jayasundara et al. 2020). A major concern as sea level rises is that greater Delta outflows or new infrastructure will be needed to prevent sea water dispersion into the Delta (Fleenor et al. 2008; Ruckert et al. 2017). Delta salinity barriers, other channel modifications, island failures, diversion locations, and diversion and channel gate operations all affect water quality and flows that support environmental and human water uses.

Harmful algal blooms (HABs), triggered by adverse nutrient concentrations and extended water residence times, are an increasing concern for recreational, municipal, and environmental water quality in the Delta. Real and potential HAB occurrences in reservoirs also affect water system operations and introduce human health risks, if not properly managed.

Water temperature is important to protect species, as demonstrated by failures in managing reservoir water temperatures during the drought of 2012-2016 (Durand et al. 2020). Omission of water temperature in models or inaccuracies in data and modeling for temperature can lead to overestimates of water availability that result in fish kills such as occurred in 2014 and 2015 for endangered winter-run salmon downstream of Shasta Dam. Water temperature increases from climate change could change water demands for ecosystems and affect water operations.

Disinfection byproduct precursors (especially bromide and dissolved organic carbon), pesticides, mercury, and other contaminants are additional water quality concerns that affect the reliability and impacts of water supplies for ecosystems and human purposes. Detection and toxicology advances are likely to increase future water quality requirements and costs (Delta ISB 2018; Hutton and Chung 1991; Chen et al. 2010). A previous Delta ISB review of water quality science in the Delta provides a broader discussion of Delta water contaminants (Delta ISB 2018).



3.1.6: Science for Water Quality Reliability

The ability to regulate, forecast, and operate while simultaneously addressing water quality concerns is important for urban and agricultural water supplies as well as environmental water supplies. The California Department of Water Resources already conducts water quality forecasting for municipal supply (Municipal Water Quality Investigations (MWQI)). Improved ability to quantify water quality effects on water supply is essential to develop and assess appropriate water quality investments, operations, and regulations (Kumpel and Nelson 2016).

Combined hydrodynamic and water quality modeling is the most rigorous and transparent way to understand water quality in the context of flows and habitat development. The California Department of Water Resources, private consultants, and academic research centers have developed extensive Delta flow and water quality modeling capabilities based on a range of 1-dimensional to 3-dimensional hydrodynamic models.

Improving such modeling will be essential for adapting the Delta and its water operations for sea level rise, new infrastructure, island failures, habitat restoration, and improving the health of ecosystems. Such modeling capability also provides a framework for integrating and applying scientific results, as well as identifying important science and data needs, in an adaptive management sense, and designing effective monitoring programs (Delta ISB 2018).

3.2: Technical and Management Issues

3.2.1: Portfolios for Water Management

Water supply systems traditionally have consisted of reservoirs on a single stream designed to supply a single fixed water demand and target delivery. Much of the success of California's modern water systems stems from incorporating water sources from multiple storage locations (surface and groundwater) combined with long-term and episodic management of water demands, a process known as portfolio management. This evolution of water system management as a portfolio of source and demand actions has been growing for decades and was formalized as State policy in 2019 when Governor Gavin Newsom issued executive order N-10-19 to State agencies to prepare a water resilience portfolio for California.

Potential portfolio elements are summarized in Table 4. Their adoption can create complex water supply systems that involve water trading, flexible operations, water conservation, and contracts or agreements with neighboring and distant water systems. This complexity creates water systems that are far more reliable, adaptable, and cost-effective than isolated water systems. Figure 3 illustrates the broad portfolio of sources and infrastructure involved in water supply reliability analysis for the Municipal Water District of Orange County.

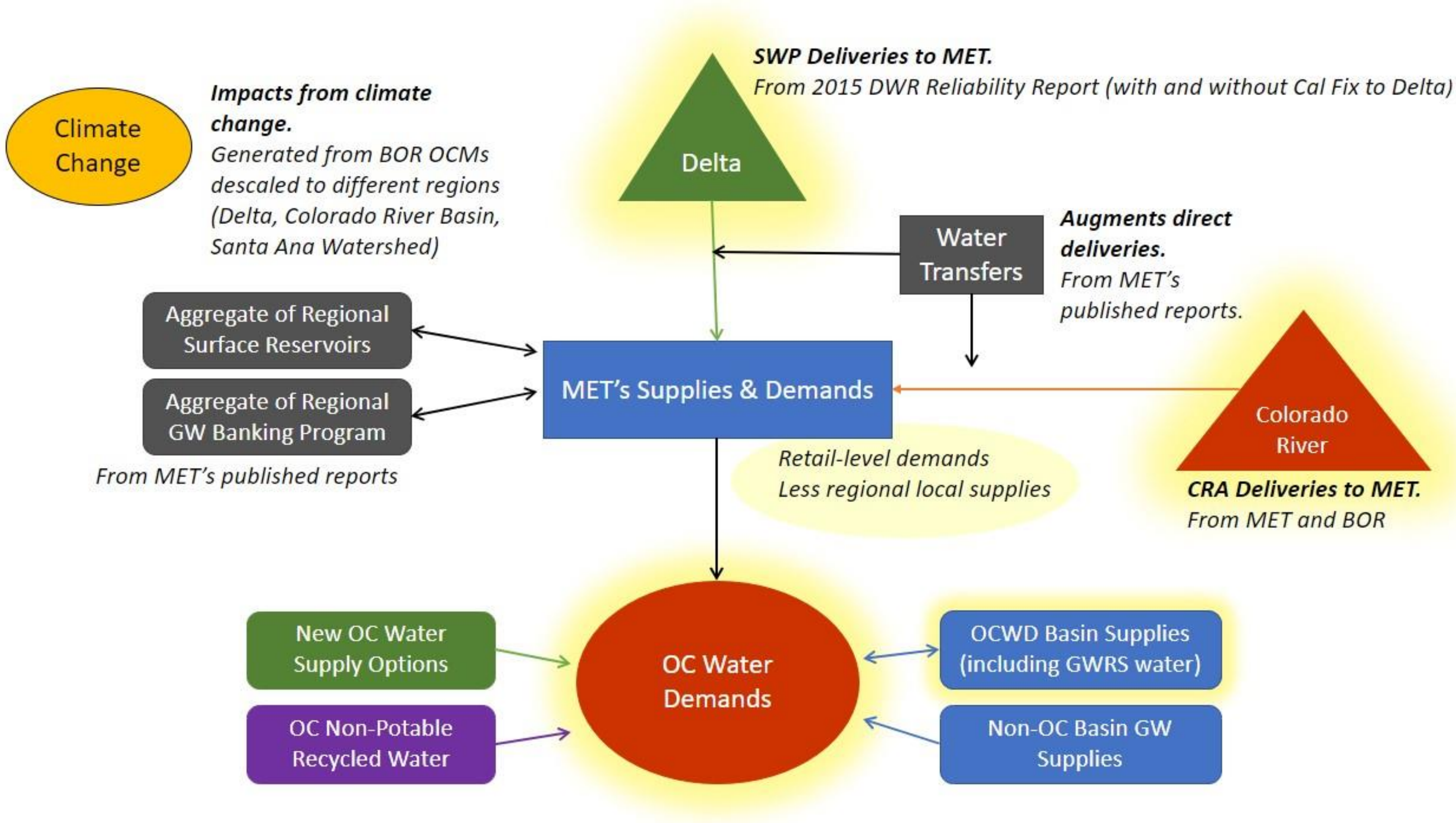


Figure 3. Water supply management portfolio for Municipal Water District of Orange County (MWDOC 2016, 2018, modified for accessibility).

Table 4. Portfolio elements available for managing modern water supply systems.

Type	Portfolio Elements Available	
Water supplies	Water source availability • Precipitation, streams, groundwater, wastewater reuse • Protection of source water quality Conveyance capacities • Canals, pipelines, aquifers, tankers (sea or land), bottles, etc. Storage capacities • Surface reservoirs, aquifers and recharge, tanks, snowpack, etc.	Treatment • Water and wastewater treatment • New treatment capacity • Wastewater reuse • Brackish and ocean desalination • Contaminated aquifers Operations • Reoperation of storage and conveyance • Conjunctive use with groundwater
Water demands and allocations	Long-term and episodic water use efficiencies and reductions in agricultural, urban, ecological, and other uses.	
Incentives to cooperate in management	• Education • "Norming", shaming • Pricing • Regulations • Markets	• Contracts • Subsidies, taxes • Regulatory requirements • Insurance

Water supply reliability results for such complex systems involve operating decisions for each of the portfolio elements. This is illustrated in Figure 4 for an agricultural water user. With low annual surface water delivery rates, the agricultural user may purchase water for trees. At slightly higher rates of annual delivery, the same user may fallow annual crops, or pump more groundwater. At even high levels of annual surface water delivery, the water user may have surplus water to bank, sell, or exchange.

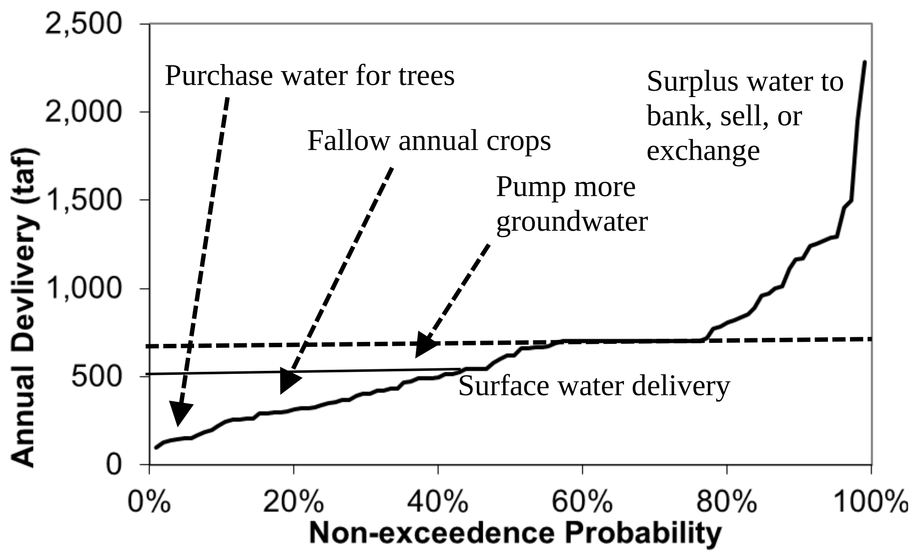


Figure 4. Illustrative portfolio components of annual water delivery (in thousand-acre feet) shown as cumulative non-exceedance reliability for an agricultural user.

Managers of water projects, water and irrigation districts, and farms and households all can act to reduce water shortages and minimize economic and other damages from droughts and other forms of unreliability. In the 2014 to 2015 drought year, farmers statewide lost about 30 percent of normal water supplies, but expanded groundwater pumping and water trades reduced shortages to about 10 percent of crop water demands. By allocating this on-farm shortage to less profitable crops, farmers further reduced loss of net farm revenues to only about 3 percent, including additional costs to pump groundwater (Howitt et al. 2015).

This portfolio of potential interactive actions by multiple water systems highlights the importance of agreements, contracts, regulations, and forms of persuasion that help coordinate a water system's many parts, with resulting interdependence for overall and individual water supply reliability. This is particularly true for joint facilities, conjunctive use, and water market actions, which involve multiple institutions. Modeling such complex and extensive systems, as well as systems of systems, is challenging given unavoidable discrepancies and errors in data and model representations, but is usually useful (MWDSC 2015).

The economic ability of any water provider or project to support a portfolio of activities varies regionally and institutionally. Each region has different access to diverse surface and groundwater sources, mixes of sometimes competing water uses and demands, economic costs for reducing or shifting water use (such as from fallowing or reducing landscape irrigation), geologic access to groundwater storage, surface storage capacity, conveyance connections internally and outside the region (and the costs of their development and use), and willingness-to-pay for water. Diversified supplies and demands also can support internal or inter-regional water markets, which add flexibility and adaptability. All of these activities can be motivated, shaped, and limited by state, local, and federal regulatory requirements.

Access to water supplies from the Delta and through-Delta conveyance capacity often supplements other regional water sources, and allows imports and exports of water and greater flexibility to adapt across wet and dry conditions, and with evolving economic and climate conditions. Thus, the Delta, and its water and infrastructure has become important in the water management portfolios of most large urban and agricultural water users throughout the state. These Delta users include sellers of water and groundwater managers in the Sacramento Valley, cities in the Bay Area, farmers in the southern Central Valley, and cities in Southern and Central California. In California, MWDSC's integrated water planning analyses come closest to routinely representing the broadest range of portfolio and reliability elements (MWDSC 2015). Urban water systems, particularly in southern California, have been leaders in explicitly combining portfolio management and reliability analysis (MWDSC, MWDOC, SDCWA, CCWD, EBMUD, SCVWD, etc.). Agricultural systems in California also benefit from the adaptability of more diversified water supply portfolios (Mukherjee and Schwabe 2015). Broad portfolio approaches also have been applied in academic studies to London (Matrosov et al. 2013, 2015); Sydney, Australia (Kidson et al. 2013; Sahin et al. 2017); Baja California, Mexico (Medellín-Azuara et al. 2009); Los Angeles (Porse et al. 2017, 2018); and California overall (Tanaka et al. 2006; Dogan et al. 2019; Arnold 2021).

California has greatly benefitted from a portfolio approach to water management (Lund 2016). Sophisticated integration of water supply, demand management, and incentive policies provide more reliable, economical, and environmentally effective performance of water systems. Portfolio-based systems can be far more adaptable and encourage agencies to collaborate. The mix of actions and policies improves physical and institutional flexibility to adapt to changing conditions from droughts, new regulations, and climate change, and has potential to further improve the performance and reduce conflicts with more explicit and complete analyses.

3.2.2: Portfolio Analysis Research

Despite the advantages of an integrated portfolio approach, discussions and surveys for this review confirmed that modeling efforts focus mainly on surface water delivery reliability, particularly in state and federal agencies, rather than including groundwater, which is the largest water storage for major droughts. Despite useful movement in this direction in recent decades, both water demand management and groundwater management could often be better included in analyses and discussions.

Explicit analysis of management portfolios would identify more promising sets of activities and provide insights for their selection (Lund 2016), but will require better representations for some portfolio elements. A more holistic approach would better represent actual water management conditions, options, and decisions. More transparent, collaborative, and publicly-available data, models, and model development and testing should allow more agencies and water users to benefit, negotiate, and collaborate as a more common technical enterprise.

The 2014 Sustainable Groundwater Management Act (SGMA) is placing new pressure on water users and regions that have depended on groundwater overdraft to apply a portfolio approach for their water supply planning (Questionnaire #6). Conjunctive use of surface water and groundwater has ancient roots in California, dating back to the establishment in 1929 of the Santa Clara Valley Water District (now known as Valley Water). SGMA brings new demands and opportunities for improving integration of groundwater modeling and management in regional and statewide water systems (Dogan et al. 2019; Escriva-Bou et al. 2020; Arnold 2021). Implementation of Governor Newsom's 2019 executive order for water resilience and implementation of SGMA should encourage water systems to adopt more complex management portfolios.

Much of California's recent water supply successes have been due to aggressive development of portfolios of water supply, infrastructure, and demand management locally, regionally, and statewide. Many urban water supply modeling and reliability studies include these approaches explicitly. However, many state, agricultural, and regulatory analyses include a narrow range of management options. This also is true for ecosystem and environmental management where representation of ecosystem performance also needs further development.

Droughts, reduced surface water availability, and overuse of groundwater stress the Delta and other water supplies. These and tightening regulations from SGMA encourage water managers to diversify supplies and management and reduce demands. Diversification includes underground and surface storage, water transfers and markets, conservation, recycling, storm water capture, desalination, oil-field produced water, and desalination (Arnold 2021). Major water infrastructure projects, such as the long proposed cross-Delta conveyance have seen little progress and are still being revised, but might slow or arrest reductions in water supplies for the Bay Area, the southern Central Valley, and southern California.

3.3: Environmental Adaptive Management

Recent declines of populations of native species in the Delta indicate that managing water and habitat for most ecosystems has been unsuccessful. Ecosystems are complex and understanding of interrelationships is often incomplete (Yarnell et al. 2015; Whipple and Viers 2019). Defining precise ecosystem objectives can be politically controversial; sometimes water supply conflicts occur among ecosystem objectives in addition to conflicts with urban and agricultural water supplies.

Water supply reliabilities often are over-estimated, which prompts concerns for curtailment of environmental flows when water shortages occur. There is a need to conceptualize and analyze more adaptively with all water uses, including contingencies for shortage management to avoid repeated failures in supplying water for ecosystems and species. Drought effects on ecosystems have not been comprehensively investigated and incorporated into environmental management (Durand et al. 2020; Stein et al. 2021). Because droughts in the future are predicted to be more extreme, adaptive systems that monitor and model ecosystem responses and provide data and management guidance for water managers will be needed to support the intended benefits of environmental flows (Kimmerer et al. 2019).

3.3.1: Research to Implement Adaptive Management

Integration of water supply reliability modeling for environmental water uses with adaptive management decision-making is needed. This approach brings many scientific and management challenges for representing ecosystem performance and demands in system models, including better representing the combined effects of habitat and flows on ecosystems.

Applied dynamic ecosystem models will be needed to support adaptive management, most likely starting with simplified models and growing in complexity to improve accuracy with understanding. Forecasting applications for such modeling might be the best approach for applied ecosystem model development (DISB 2015; Holling 1978; Bellido-Leiva et al. 2021; Davies et al. 2014). Efforts beginning with grander conceptual models have been slow to yield numerical fruits and syntheses (Williams 2010).

3.4: Multiple Objectives and Conflicts in Water Management

Conflicts among social and personal objectives are common in water management. Many aspects of water planning can be treated as multi-objective problems with tradeoffs (Cohon and Marks, 1975; Brill et al. 1982). Multi-objective analysis and planning is especially useful to balance public investments for performance across multiple-objectives. Modeling methods that explore approaches to address multiple goals simultaneously have been used to support decision making by identifying options that improve multiple goals simultaneously or minimizing harm. They can be particularly useful for meaningfully engaging stakeholders to balance competing objectives, based on a transparent discussion that includes scientific information on system constraints (Cohon and Marks, 1975; Null et al. 2021).

Models presenting multi-objective results and optimization have become more sophisticated in recent decades, but are not applied widely in water planning and decision making for the Delta (Alexander et al. 2018). The models have limitations for representing the complexity of systems, can require substantial data and knowledge to build, and may have trouble incorporating many policy constraints. Nonetheless, even in a simplified form, they offer tools for in-depth stakeholder engagement, scenario analysis, and tradeoff analyses that can improve decisions by lowering the cognitive burden of considering many processes simultaneously.

Efficient (Pareto-optimal) trade-offs for water allocations among agricultural and environmental water uses have been demonstrated, but are not typical in California studies (Homa et al. 2005; Vogel et al. 2007). Potential tradeoffs also exist for ecosystem and environmental flows among different species and ecosystem locations, such as between Delta outflows for Delta smelt and cold-water flows for salmon at different times and locations during drought (Durand et al. 2020).

3.4.1: Research for Employing Multi-Objective Analysis

For multi-objective modeling to be useful, the data and system understanding needs to be further developed to ensure that models incorporate major processes and feedbacks. In addition to biophysical studies, a wide variety of social analyses may be needed to characterize likely benefits and harms to people from management choices. Further, quantifying, depicting, and communicating uncertainties in trade-offs among objectives is an area where more research is needed (Arnold 2021).

Incorporating multi-objective analyses into transparent decision processes is a difficult institutional challenge that requires cooperation of government agencies, non-governmental organizations, key stakeholders and others. Many studies have tested approaches to engaging stakeholders using collaborative modeling approaches. They have shown promise for applying these tools to identify management outcomes that reduce burdens of regulation, increase benefits, and increase perceptions of fairness and legitimacy of management processes. Yet, many approaches are ad hoc and have mixed success. There is a need to identify and design elements of these institutional processes to improve confidence in models and lead to informed and balanced management solutions.

3.5: Forecast-Informed Operations

Forecast-informed Reservoir Operations (FIRO) use real-time data from monitoring stations and weather forecasts to improve reservoir management mostly by allowing more water supply storage to be retained during flood seasons (FIRO Steering Committee 2017). Success rests on the reliability of weather forecasts and the operational ability to take advantages of opportunities presented by forecasts for storing water and making flood pre-releases. Ideal FIRO applications are for moderate-to-large reservoirs with ample reservoir and downstream flood-release capacity, allowing appreciable flood control storage space to be evacuated within the flood forecast period (Yao and Georgakakos 2001; Nayak et al. 2018; Delaney et al. 2020).

As noted, much of California's annual precipitation and streamflow derive from large atmospheric rivers. These storms are somewhat predictable with a lead-time of several days (Lavers et al. 2015). This has inspired integration of atmospheric river forecasts with reservoir management (Delaney et al. 2020).

3.5.1: Research for Applying Forecast-informed Operations

A challenge is to identify specific reservoirs and precipitation intensities and durations where and when atmospheric rivers come ashore (Lamjiri et al. 2017). Studies of spatial-temporal variability of atmospheric rivers on a hierarchy of scales and attendant inland precipitation and runoff have potential to improve operations and performance.

Greatly broadening forecast-informed operations beyond single reservoirs to more integrated forecast-informed operations of more complex systems is a promising research area. Complexities include multiple reservoirs, support for environmental flows, upstream and Delta diversions, and groundwater recharge.

3.6: Improved Regional Management

> *"Any system of water works must be accompanied by a system of human enterprise that involves the allocation, exercise and control of decision-making capabilities in the development and use of water supplies." Ostrom, V. and E. Ostrom (1972)*

The Delta's complexity requires integrated efforts to manage limited water resources subject to many jurisdictions. In managing this complex physical, environmental, and institutional system, agency authorities must deal with complex and interdependent administrative and technical authorities and capabilities. Organized science, modeling, and analysis can help adapt and coordinate management under changing conditions and uncertainties, particularly in providing estimates of likely trade-offs for alternative actions (Holling 1978).

Improved management, somewhat greater standardization, and co-development of analytical studies and expertise might help the Delta's many agencies more effectively employ science to manage the Delta's changing problems, including those related to water supply reliability.

Information on interdependencies between critical water infrastructure elements - including ecological and human intervention responses - during system failure is a critical need for fragility and response modeling. System modeling of water management portfolios for diverse and changing conditions with optimization and probabilistic uncertainty where appropriate can help focus decision and policy discussions on promising alternatives.

Arnold (2021) and Nayak et al. (2018) provide useful examples for optimization modeling of complex water supply portfolios with multiple objectives and imperfect foresight. Dietze (2017) provides useful examples for ecosystem forecasting applications using ensemble models and computations.

To adapt to California's evolving water challenges, a better quantitative understanding of the integration of water supply reliability estimation with strategic and technical water management at local, regional, and statewide scales is needed. Achieving this understanding would be more likely and effective if it deeply involved a variety of major state and regional water agencies.

3.7: Uncertainty Analysis and Preparations

All estimates involve uncertainties. Analysis of uncertainties can be important for discussions and decision-making. However, it is often difficult to communicate and incorporate uncertainties and their analysis in deliberations and decision-making. Analysis, preparations, and data management are important aspects of managing water given the many uncertainties involved.

Risk = Probability X Consequence

Managers of critical infrastructure must prepare for risks involving a wide range of contingencies, ranging from routine emergencies and opportunities to unusual, rare, and even surprise events. These contingencies can involve any event that threaten a system's performance (droughts, floods, chemical spills, a wide range of accidents, mis-operation, labor strife, sabotage, regulations, lawsuits, etc.). Routine and periodic maintenance, training, inspections, and other actions can reduce the likelihood of unfavorable events.

Analysis for preparing, planning, and allocating resources for the many forms of unreliability should be based substantially on the relative likelihood of each contingency, particularly for the most threatening and damaging events (i.e., with the highest risk). Reliability estimation assesses the probabilities of such events.

Because there is uncertainty in both probability estimates and event identifications, there is a substantial likelihood of error in probabilistic analysis and surprise from unexpected events. Thus, it is wise to prepare for a range of especially threatening contingencies, even some beyond what might be justified by probabilistic risk analyses. Organizations prepare for expected and unexpected contingencies by modeling and in-person emergency response exercises, stocking spare equipment and parts, training, maintaining a network of suppliers, experts, arranging mutual aid with nearby systems, and maintaining individual and organizational capacities for responsiveness and effective action.

For operations, planning, and policy purposes, four types of events can be considered, each of which requires different types of analysis:

1. **Routine events** are so frequent that we prepare for them without feeling a need to estimate their frequency or probability. Stocking routine spare parts, basic safety preparations, communications systems, and personnel training are often in this category. Many pipeline and mechanical failures fall into this category.

2. **Probabilistic events** can be frequent and infrequent but are usually fairly well defined. Relative frequencies are estimated using historical or modeling analyses for balancing outcomes and costs in planning, preparation, and operational decision-making. Maximum-entropy and Bayesian methods can estimate probabilities with very little data (Jaynes 2003; Hui et al. 2018; Fletcher 2019). Most drought and flood planning falls into this category, probabilistically considering hydrologic uncertainty, and sometimes other uncertainties.

3. **Identified events** are analyzed as contingencies, and can include probabilistic events as well as events rare or ill-defined enough that we do not estimate probabilities. However, we often give forethought and prepare for such events if their consequences would be great. For example, few water utilities do explicit probabilistic planning for earthquakes, but most have contingency plans for earthquake response.

4. **Surprise events** are events we have not identified, but we prepare for generally through other emergency training and response exercises, stocking of tools and materials, and mutual aid arrangements with other agencies. For example, most water agencies lacked contingency plans for a COVID-19 event, but other contingency planning and general preparations helped provide capabilities and disaster-response thinking that could be adapted to an unforeseen surprise to prevent it from becoming a worse catastrophe.

Box 5 summarizes many of the sources of climate change uncertainty in water supply reliability estimation.

Box 5. Uncertainties in Studies of Climate Change and Water Supply

Estimation of water supply reliability will need to evolve with California's changing climate even though the details of climate changes remain substantially uncertain. Temperatures are getting warmer with greater watershed evaporation and runoff shifting from spring to winter. Weather extremes also have become more frequent and extreme.

Most climate change estimates are based on a series of model results and statistical corrections, each of which can be done in different ways, and have somewhat different results, and are detailed in Appendix A (Barsugli et al. 2009; Lynam and Piechota 2021).

1. Climate change estimates begin with one of many potential future greenhouse gas emission scenarios.
2. General circulation models (GCMs) then estimate future global climate impacts, usually in terms of temperature, precipitation, and wind results (Sarofim et al. 2021). There are many such models, which give somewhat different results for California.
3. These model results tend to differ from recent climate records, and so are often "bias corrected" in one of various ways to better match recent observations (Bane 2020; Teutschbein and Seibert 2012).
4. The resulting temperature, precipitation, and wind time series results are coarse, determined by each GCM's computation grid (50-100km). To be used for water supply reliability analyses, GCM results must be then downscaled, by one of various methods, to finer watershed scales for water studies (Wood et al. 2004).

A major difficulty facing water managers is how to prepare for new and sometimes unanticipated events or conditions. Extraordinary events such as natural disasters (floods, extreme droughts, earthquakes, wildfires, harmful algal blooms, etc.), terrorist attacks, war, epidemics, and human error can drastically affect water supply systems. Vulnerability to such events occurs both for individual components and in overall water systems with cascading failures. Further development of tools to prepare and respond to emergencies is useful to resist, absorb, accommodate and quickly recover from catastrophic events.

Each component of a system responds in specific ways, affecting others, and the integrated response is complex and often nonlinear. Environmental fragility models focus on this integrated response, while including individual system elements. Some such analyses are often probabilistic, but many take the form of contingency scenario planning. Modeling for general adaptive capacity is likely to be valuable.

A range of numerical experiments using mostly Monte Carlo type techniques can give analysts and decision-makers much better feel for the range of likely outcomes and largest and most important uncertainties in major models and common important problems. The lessons from these numerical experiments should be useful to both understand uncertainties and prepare recourse options for both favorable and unfavorable circumstances.

3.8: Hydrologic Data and New Analysis and Management Technologies

3.8.1: Data Fundamentals, Adjustments, and Error Analysis

Various new approaches are available for making consistent and systematic adjustments to hydrologic data to reduce and characterize error (Kadir 2017). There is a difference between raw data (e.g., point field precipitation or evapotranspiration (ET) data) and processed data (which can be spatially distributed estimates of precipitation or ET for use in models). Systematic data adjustments and input data modeling can improve water accounting and form a better basis for Monte Carlo studies involving hydrologic errors. These efforts should also include closer and more consistent linkages between groundwater and surface water models and data.

A wide variety of approaches can be taken to error analysis for water supply reliability studies. These include various statistical (analytical, Monte Carlo, sensitivity, etc.) and stress-test techniques (Kadir 2017; Pasner 2021; Kuria and Vogel 2015).

A standard multi-agency State water accounting framework would improve the technical coordination and quality control for water supply reliability modeling, as well as a host of other regulatory and operations concerns in California. Such a framework might be standardized through the water data SCADA systems already employed by major local and regional water agencies (Escriva-Bou et al. 2020). Establishing a basic standard for error analysis would help analysts and decision-makers understand the importance (or unimportance) of various likely sources of error in water supply reliability and other analyses. An interagency technical standards board, including outside experts, would help establish and oversee research for such purposes.

Although each of the preceding trends is generally treated independently, the review discussions and survey results confirm that water planning and operations would benefit by explicitly considering these trends together in an integrated way. For example, development of complex portfolios (and even simple portfolios) often must consider environmental flows and their impacts on species and ecosystems, water quality, and climate change. The future must be managed with these collective trends in mind, as most manager and policy-makers realize.

3.8.2: New Technologies

Many new technologies, methods, and practices are available to improve data, models, and model runs that are the backbone of water supply system reliability analysis (Brown et al. 2015; Herman et al. 2020). These include: improved approaches and documentation for data management, access, and transparency; use of web services to share data, model runs, and post-processing; machine learning (learning empirically from the vast amounts of data available as opposed to explicit model formulations); and approaches to test performance over wide ranges of system conditions.

Advances in computing are making it possible to perform sensitivity and Monte Carlo analyses, as well as more sophisticated optimization analyses that would have been impossible a few years ago. Web services such as GitHub make it far easier to disseminate version-controlled code, documentation, and data that allows many contributors to test and improve code and methods.

4. Metrics of Water Supply Reliability

"When you get rid of what you don't want, you do not necessarily get what you do want and you may get something you want a lot less." Russell Ackoff

Many metrics of water supply reliability are in use. Most metrics have been developed for urban and agricultural water systems. However, there have been important efforts to develop indicators of water supply reliability for environmental purposes (Stein et al. 2021). Use of well-developed metrics helps analysts, managers, and policy-makers understand and explore both water system performance and alternative solutions.

Metrics for complex systems always overlook some (sometimes important) details. It is tempting to summarize indices to an extreme, such as developing indices of indices. The best metrics improve management and understanding by focusing voluminous modeled or observed results into a few informative statistics or depictions.

The definition and use of a metric itself can be complex and controversial. Indeed, social indicators used for decision-making become subject to corrupting pressures – Campbell's Law (1979). In essence, good metrics provide management or scientific insights by summarizing performance or conditions for the decision-maker or analyst. Poor metrics and poor use of metrics can mislead or distract management and scientific discussions from more important aspects of problems or solutions.

Assessment of metrics also rests on the accuracy of the data, models, and methods used to calculate them. Because all metrics have uncertainty, analysts should explore, identify, and quantify major uncertainties. Decision-making deliberations should keep these uncertainties and limitations in mind, and consider consequences and contingencies.

4.1: Common Metrics of Water Supply Reliability

Dozens of metrics have been proposed to assess water supply reliability for urban, agricultural, navigation, and hydropower performance (Rippl 1883; Riggs and Hardison 1973; USACE 1975; Hirsch 1978; Klemes 1987; Basson et al. 1994;

Hashimoto et al. 1982a, b). Table 5 summarizes some common metrics. Many additional metrics exist for evaluating water distribution system performance (USEPA 2015). Each metric provides insights into different aspects of desirable water supply performance, but no single metric provides a complete picture of water supply reliability.

This table and discussion distinguish between technical and fundamental performance metrics. Ecologic or environmental performance objectives are relatively new and are discussed in a later section.

Table 5. Summary of common water supply reliability performance metrics.

Metric Type	Description
Technical	
Averages	Average water delivery, storage, or shortage (e.g., acre-feet per year)
Design drought delivery	Delivery in a particular one-year or multiple-year drought, as is common and required for UWMPs
Firm yield	Highest 100% reliable delivery for historical hydrology (Rippl 1883; Lindsey et al. 1991)
Shortage probability	Probability of water shortage
Delivery probability	Probability distribution of water delivery or storage (Hazen 1914; Hirsch 1978)
Reliability	Probability that delivery is not less than a delivery or storage volume target
Resilience	Time needed for delivery or storage to return to target level after “failure”
Robustness	Range of conditions for which delivery or storage targets are attained
Fundamental	
Public Health	Direct: minimum safe water availability, waterborne illnesses, deaths, or days lost
	Indirect: public health water quality indicators
Economic	Direct: Net economic benefits or costs
	Indirect: costs and/or raw sectoral or economically valued outputs from selected economic sectors (agriculture, urban, recreation, navigation, etc.)
Social	Social objectives are usually in terms of health, prosperity, and well-being of disadvantaged or under-represented groups.
Environmental/ Ecosystem	Direct: Species populations and compositions, numbers or individual health
	Indirect: Flow characteristics desired to support ecosystem characteristics

4.2: Technical Metrics

Technical metrics typically summarize current or forecast water deliveries or storage conditions (Table 5). These metrics are convenient for system operators to assess likely performance, usually in the context of their water management experience, and so help with operational or system design decisions. Some common metrics are:

Average delivery capability is the mean annual or seasonal water volume available for delivery from a water supply system. Although this calculation is straightforward, it is rarely used alone in practice because variability in delivery capability is crucial for the success of a water supply system, particularly in Mediterranean climates like that in California with large annual and seasonal variability.

Design drought delivery is common for water systems designed to accommodate specific design droughts. California's larger urban water suppliers, with more than 3,000 customers, are required to produce Urban Water Management Plans (UWMPs) every 5 years, which describe "the reliability of the water supply and vulnerability to seasonal or climatic shortage" for an average year, a single dry year, and multiple dry years (CWC 10631 (c)(1)). UWMPs also must specify actions to accommodate up to a 50 percent reduction in water supply (CWC 10632 (a)(1)).

Firm yield (sometimes misleadingly called "safe yield") is the amount of water that can be supplied without any shortage for a repeat of the historical hydrologic record (using the critical drought of record as a design drought). It is a classical conservative water supply reliability metric (Rippl 1883; Linsley et al. 1992). Historically, firm yield was the primary metric used for the design and assessment of United States reservoir systems, including major projects in California. The metric remains useful to indicate if water shortages are likely to be a problem. When a system's water use exceeds its "firm yield," drought concerns rise and more elaborate performance metrics and system contingencies and plans are needed.

Probability of shortage is the likelihood that a particular water right or use will experience a shortage in a planning or seasonal timeframe. Figure 5 shows the results of a water rights analysis using historical flow estimates, indicating the probabilities of each of roughly 800 San Joaquin Basin surface water rights being curtailed (Walker 2017). The probability of being curtailed varies greatly with the type and priority of water right and its location in the basin. Upstream tributary users, even those with high priority, are more likely to be curtailed for lack of local water availability, whereas downstream users, even those with lower priority, tend to have more reliable supplies because they can be supplied from several tributaries.

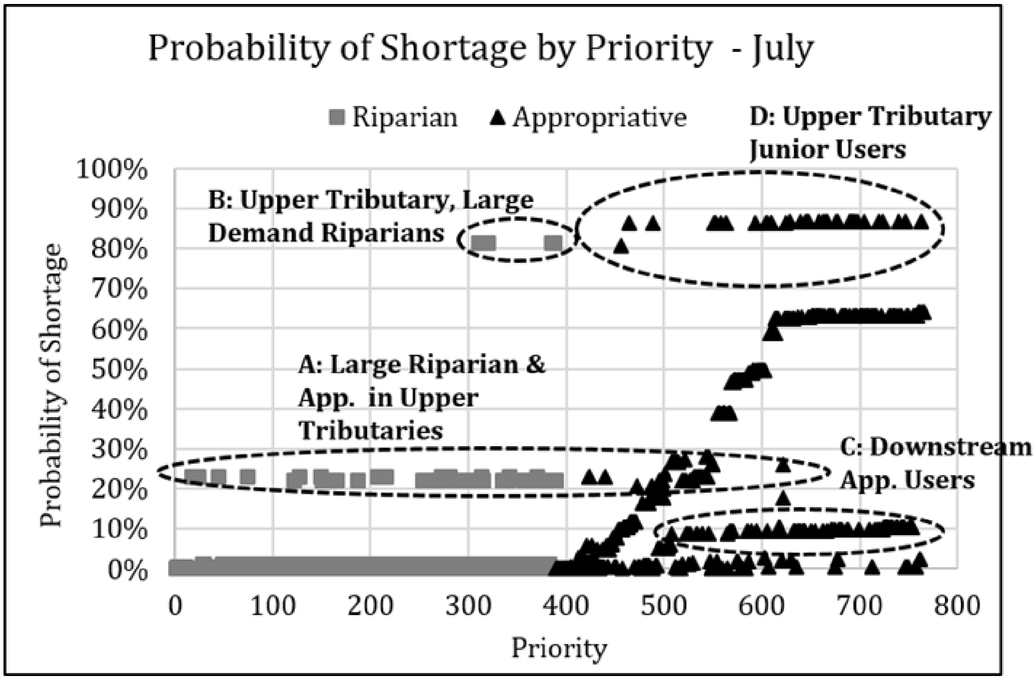


Figure 5. San Joaquin Basin July Water Right Shortage Probabilities (from Walker 2017).

Delivery-reliability distributions (Hazen 1914) arose from a deeper understanding of reliability, particularly the realization that a range of water volumes can be provided with different probabilities or likelihoods. Instead of being a single number (e.g., *firm yield)*, water supply delivery-reliabilities are calculated and presented as a probability distribution. Water supply deliver-reliability distributions are computed for most of California's major water systems today (DWR 1983, 1987). Management targets might be expressed as average probability performance, such as some probability of failure to meet a delivery target (such as a 5 percent annual chance of exceeding a 20 percent shortage). However, the entire distribution of delivery-reliability also can be used for further risk and response analysis for management and evaluation of broader and more complex portfolios of actions.

Figure 6 shows estimated delivery-reliability distributions for the SWP, comparing 2015 and 2017 analysis results (DWR 2017). Various depictions of delivery-reliability include cumulative and density distributions of deliveries or water delivery shortages (Figures Cover, 4, and 5). (Table A water is the amount of water that can be requested by SWP water contractors based on long-term water contracts with SWP.)

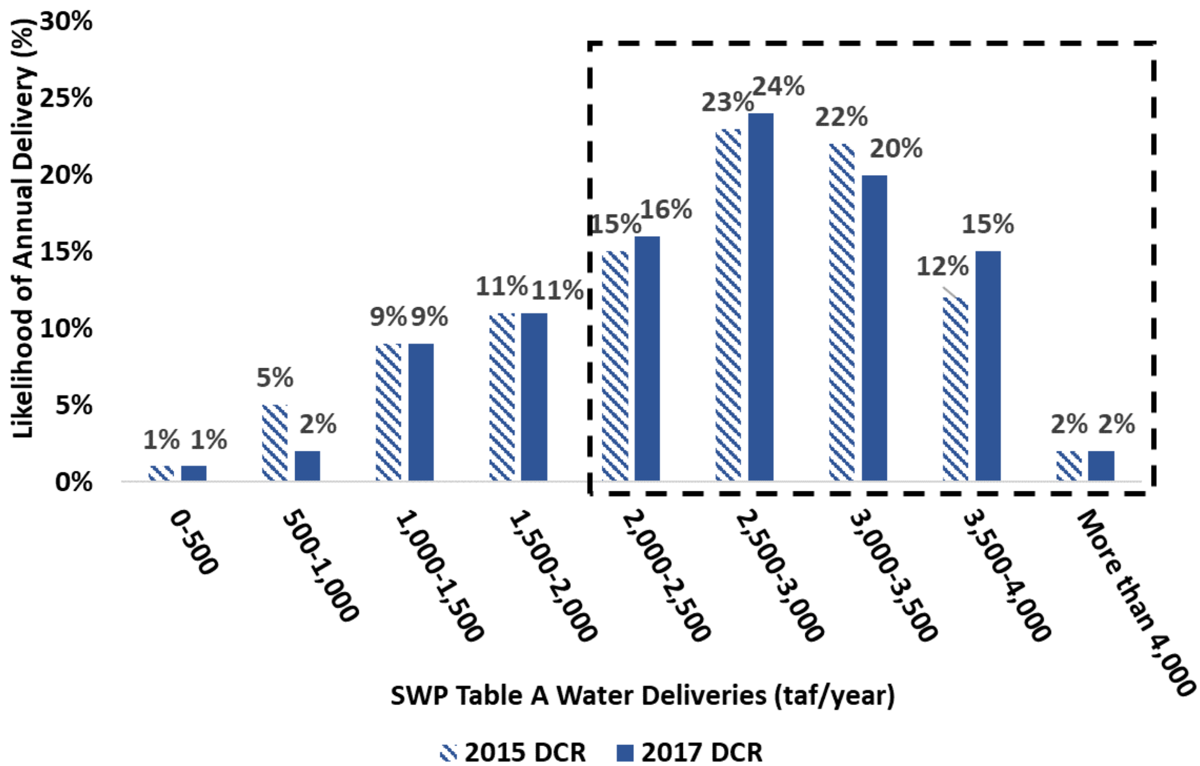


Figure 6. Estimated likelihood of SWP Table A Water Deliveries by increments of 500 taf (excluding Butte County and Yuba City). The dashed box shows there is a 77 percent chance of SWP Table A water delivery of more than 2,000 thousand acre-feet (taf) in 2017 (from DWR 2017 Delivery Capability Report - DCR; modified for accessibility).

Position analyses are a common variant of delivery reliability plots (Hirsch 1978; FitzHugh 2016), which plot and compare operational results from a set of equally-likely input or hydrologic scenarios, e.g., Figure 7. Such plots and analyses are common for seasonal and real-time operation delivery and performance reliability.

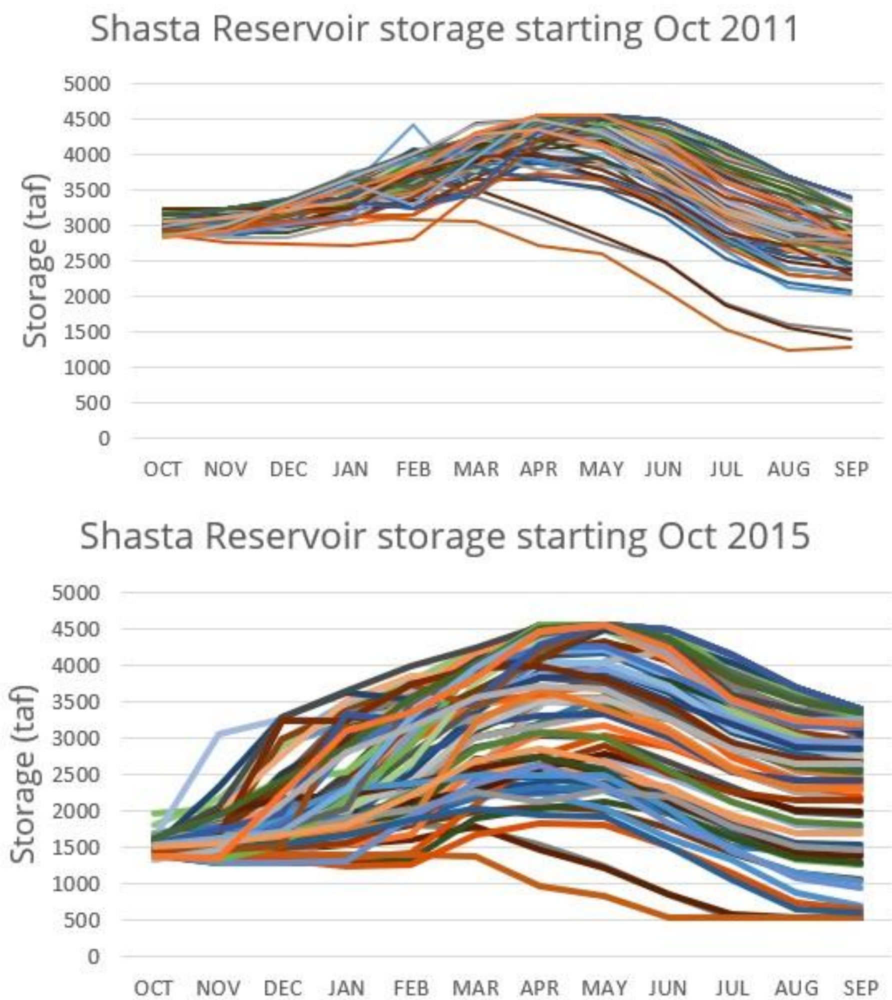


Figure 7. Example of a Position Analysis display of water storage trace results for Shasta Reservoir in 2011 (wet year) and 2015 (dry year). (FitzHugh 2016, modified for accessibility)

Engineering performance indices (Table 5) are a subset of technical metrics that focus on different aspects of water supply reliability performance (Hashimoto, et al. 1982a, b; Shamir and Howard 1981; Vogel and Castellarin 2017; Vogel et al. 2007; Homa et al. 2005; Kuria and Vogel 2015). Management targets might be expressed as average performance or some exceedance probability of an index target (such as no more than a 5 percent annual chance of exceeding a 20 percent shortage). Examples of engineering performance indices include:

- *Reliability* – Percentage of years or time that a water supply system can or cannot meet a target delivery (or other target metric such as storage balance, groundwater elevation, etc.).

- *Vulnerability* – The magnitude of shortage that occurs when a system cannot supply its delivery target, often the average or extreme shortage.
- *Resilience* – The amount of time likely needed for a system to return to supplying a delivery target, after it has failed. A resilient system tends to quickly return to a functioning one after a failure. Recent diverse usage of "resilience" has made this technical metric less useful.
- *Robustness* – The amount of disturbance a system can accommodate before it fails to supply a target delivery (Hashimoto et al. 1982b). More recently, this approach has broadened to take advantage of the surge in computational capabilities, to identify the range of conditions or disturbances for which target deliveries are attained based on hundreds or thousands of future scenarios. Sometimes statistics are calculated on the percentage of scenarios that fail to achieve different levels of performance (Herman et al. 2016, 2020; Erfani et al. 2018).

4.3: Fundamental Performance Metrics

A variety of performance metrics are available to reflect the fundamental societal objectives affected by water management and supply reliability.

Public health indicators can be specific in terms of days of illness, deaths, average annual years-of-life lost, life expectancy, or other terms. However, public health indicators are usually less direct and reflect concentrations or exceedances of standards for water quality constituents or inability to provide minimal water quantities needed for human health.

Economic indicators recognize that not all reliability failures are equally undesirable. Some failures are more economically damaging than others. As water economists have noted, "There is rarely a shortage of water, but often a shortage of cheap water." Economic loss or benefit functions often are employed, or a subsidiary set of economic impact and adaptation models (Howe and Smith 1994; Jenkins et al. 2003; Howitt et al. 2012). Economic indicators can be summarized rigorously as the expected value of net benefits, balancing most of the above considerations in economic terms (Arrow and Lind 1970). Often estimates of variance and extremes of economic losses are useful for assessing economic or financial stability, potential roles for insurance, and more dire effects of drought on vulnerable social groups.

Social indicators for the health, prosperity, and well-being of social groups are sometimes used to characterize effects of decisions and assess equity in the distribution of benefits and risks (USEPA 2021; Teodoro and Saywitz 2020). Environmental justice and social vulnerability indicators can assess equity concerns among socio-demographic groups or places. Social objectives for water management also may be procedural, such as according with principles for the rule of law, property rights, and democratic governance. Metrics can be directly related to resource use by examining the frequency of being unable to meet specific needs or wants.

Environmental indicators represent the environmental and ecological impacts of system performance and reliability. This newer area of water supply reliability metrics is discussed in the next section.

4.4: Metrics for Environmental Water Supply Reliability

Performance metrics for environmental objectives continue to evolve to reflect new information and understanding of species and ecosystem water demands. Quantitative characterization for environmental and ecological performance is still evolving in water planning and management and has less history and methodological development, with sizable uncertainties and ethical quandaries on the ecological effectiveness of specific flow regimes under local conditions. Quantitative characterization is hindered by the many factors affecting many local ecosystems and species, including a wide range of habitats and water qualities affected by seasonal and inter-annual water operations (Arthington 2012; Arthington et al. 2018; Stein et al. 2021; Yarnell, et al. 2020; Bellido-Leiva et al. 2021). Requirements of different species also can conflict. But, but these difficulties do not obviate the value of environmental metrics.

Many metrics of traditional (urban, agricultural, etc.) water supply performance have been applied to environmental water supply performance. The frequency and reliability of a system's ability to deliver instream or wetland flows or water levels are common for assessing if systems have environmentally supportive hydrologic conditions (Singh 2015; Grantham et al. 2014; Stein et al. 2021).

Several approaches have been proposed to represent ecosystem/environmental objectives in water supply reliability analyses (Arthington 2012; Yarnell et al. 2015; Williams et al. 2019). Environmental water objectives usually are represented as constraints on system operations, implying that minimal environmental targets are met first, with remaining water available for non-environmental purposes.

Common approaches to metrics of environmental water system reliability (which can overlap) are summarized in Table 6 and described in the discussion below.

Table 6. Some metrics of environmental water supply reliability.

Metric	Description
Simple flow targets	Usually a fixed instream flow or water delivery target (Tennant 1976)
Composite habitat suitability objectives	Flows based on interactions of flow and habitat selection preference ideas (PHABSIM) (Railsback 2016; Bovee 1982)
Natural flow regime standard	Environmental flow variations based on pre-development natural flows (Poff et al. 2010; Poff 2018)
Environmental flow targets	The *functional flows* approach develops seasonally-varying flow targets to provide particular ecological functions (Yarnell et al. 2020; King; Stein et al 2021; Poff 2017, Poff et al. 2010)
Species and population indicators	Population indicators, usually from integrating population dynamics models with habitat and flow models. (Bellido-Leiva et al. 2021; van Winkle et al. 1998)

Simple environmental flow targets are common as constraints or reliability targets on water supply operations. While preventing complete drying of streams, minimum flows are often insufficient to achieve broader ecological objectives. Simple flow targets can be established systematically (Tennant 1976) but are not always sufficient.

Composite habitat suitability objectives recognize the importance of interactions between flow and habitat in supporting species and ecosystems. A variety of interacting habitat and hydrologic models have been developed and applied to set composite habitat objectives for flow and habitat management (Williams et al. 2019). Flow and habitat specifications often are developed for specialized stream, riparian, wetland, or floodplain habitats preferred by one of more desired species (Whipple 2018; Williams et al. 2019). PHABSIM is a widespread early example of this approach (Bovee 1982). Implementing these approaches can be computationally complex and data-intensive, and may not be particularly successful when they estimate only one component (habitat) of the ecological needs of species. They also often cannot incorporate the benefits of flow variability across seasons (Williams et al. 2019; Whipple and Viers 2019).

Natural flow regime standards usually base environmental flows on a historical pre-development flow regime, allowing some diversions or alterations from these historical flows. The idea is to create an environmentally effective flow regime by setting the percentage of natural flow to remain instream for desirable species (usually native fish, trees, etc.) adapted to the natural variability in flows (Poff et al. 2010; Poff 2018). This approach is simple to understand and implement, but faces many challenges. Historical goals are more difficult, and perhaps impossible or less relevant due to extreme alterations of the physical landscape (e.g., levees, wetland and floodplain development, and channel hardening), composition of species in the local ecosystem, and climate change. Perhaps the most successful development of this approach is the ELOHA (Ecological Limits of Hydrologic Alteration), because its final results ultimately depend on stakeholder inputs (Poff et al. 2010).

Environmental functional flow targets can be expressed as a set of seasonally varying instream flow targets that support a variety of specific ecological functions. These can include minimum instream flows, flow or flow rate change targets to support specific ecological functions (spawning or rearing habitats, fish passage, migration cueing, etc. for specific species or ecosystems), allowable streamflow alterations from unimpaired flow, or allowable water quality conditions (temperature, dissolved oxygen, etc.) assessed empirically or mechanistically (King and Louw 1998; Stein et al. 2021; Yarnell et al. 2015, 2020; Fleenor et al. 2010; CEFF.ucdavis.edu), as shown in Figure 8. Recent functional environmental flow efforts incorporate landscape changes and modification efforts in flow-setting analyses. Functionally-developed, seasonally-varying environmental flow targets have succeeded in improving ecosystem conditions in several applications, and are widely proposed for streams in California (Kiernan et al. 2012; CEFF.ucdavis.edu).

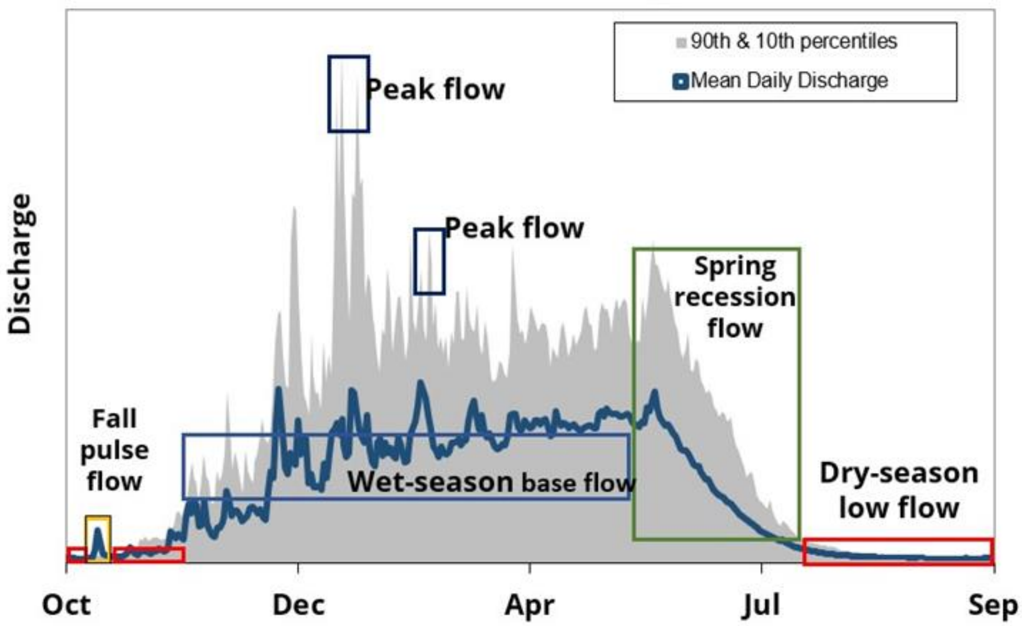


Figure 8. Functional flow components for California depicted on a representative hydrograph. Blue line represents median (50th percentile) daily discharge. Gray shading represents 90th to 10th percentiles of daily discharge over the period of record (Yarnell et al. 2020, modified for accessibility).

Species and population indicators use estimates of species population or biomass dynamics to explicitly represent ecological objectives of flow and habitat management. This is similar to using economic benefit estimates to more directly represent objectives for societal prosperity. These approaches explicitly represent life-cycle continuity and population dynamics of species, such as found in Individual Based Models (van Winkle et al. 1998; Cardwell, et al. 1996; Williams et al. 2019; Adams et al. 2017; Bellido-Leiva et al. 2021). Using more direct population estimates as a metric is less common and requires more mechanistic ecosystem representations but could be combined with a functional environmental flows approach to quantify the ecological functionality of particular seasonal flows.

Representations of environmental flows or their performance may require very short modeling time steps (15-minutes or hourly) when rapid flow or ecological processes need to be captured. For planning purposes, time increments simplified to daily, weekly, or monthly flow requirements often are deemed sufficient to provide water for finer-scale ecological operation decisions. Environmental flow reliability then can be estimated as probability distributions of the likelihood of desired flow, habitat, or population conditions.

Given the approximate, uncertain, and complex relationships between desired environmental objectives and actual ecosystem conditions and lack of monitored experience with environmental flows, there is often uncertainty in the actual ecosystem outcomes from implementation. This imposes a need for adaptive management and field-testing and improvements of models used for environmental flows (Dietze 2017; Davies et al. 2014).

5. Quality Control in Reliability Estimation

"In all hydraulic data the probable error of measurement is considerable. There is, therefore, no justification for the application of extreme refinements in methods of calculation." Allen Hazen (1914, p. 1541)

Water supply reliability estimates are important for project planners, water managers and users, regulators, and a wide variety of decision-makers faced with evaluating and judging the performance and trade-offs of decision alternatives. These important, expensive, and often time-consuming decisions typically involve difficult and complex discussions, multiple proposal iterations, and technical controversies regarding supply reliability for various water uses. Decisions usually are implemented with specific agreements or requirements informed by reliability estimates.

This section reviews and examines unreliability in estimates of water supply reliability, and discusses approaches to quality control in water supply reliability estimation.

5.1: Why Water Supply Reliability Estimates Differ

Analyses to estimate water supply reliability require an organized representation of water sources, water demands, and the water management system (as shown in Figure 2). Each representation usually requires many subsidiary representations and judgements. These representations are approximate, especially when they apply to the future. Thus, any two modelers will likely make different estimates of water supply reliability, even where they agree substantially in their representations (Lund 2016). Future reliability estimates are uncertain and probabilistic. Even with little data, probability distributions can be estimated (for example, with Bayesian and maximum-entropy techniques, Jaynes 2003).

Water supply reliability estimates also can vary from actual experienced water supply reliability, particularly under unusual circumstances, such as droughts, as shown in Figure 9.

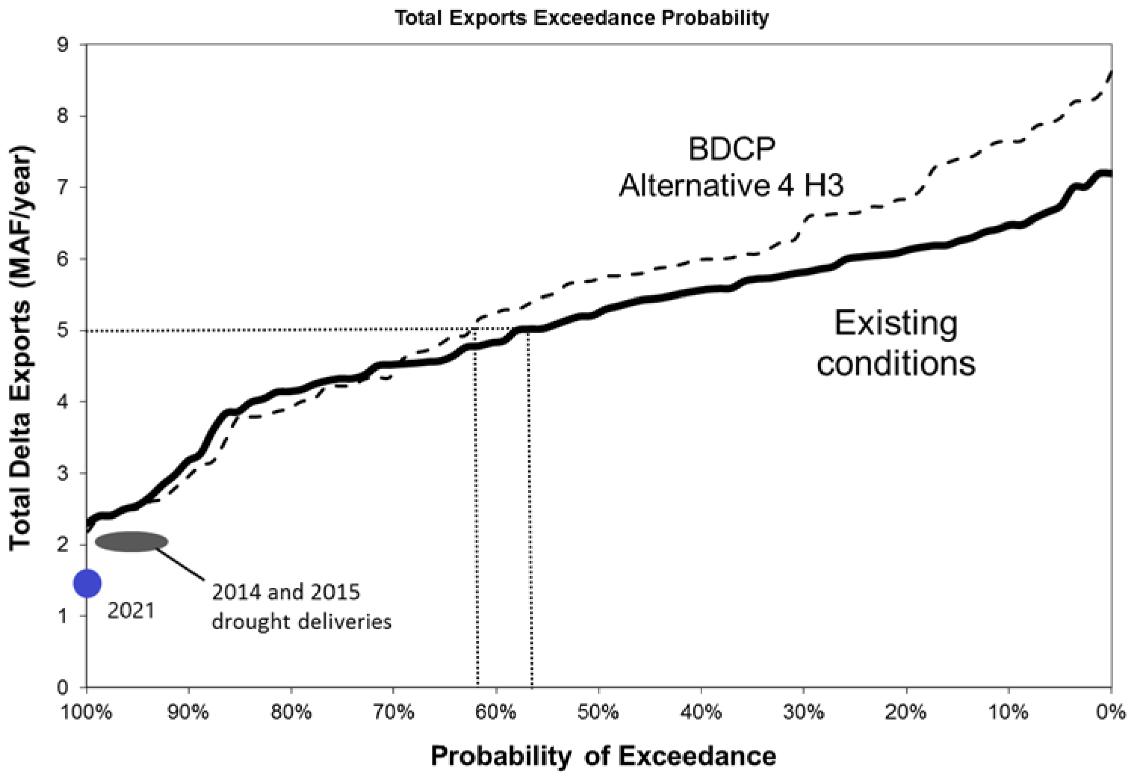


Figure 9. Comparison of Delta water export reliabilities estimated in 2015 with actual severe drought year exports 2014, 2015, and 2021 (after Lund 2016).

The quality and uncertainty of water supply reliability estimates depend on the representation of inputs, infrastructure and its operations, and demand expectations. In California, traditional water delivery reliability estimates employ water system models, e.g., CalSim II, CalSim 3.0, CalLite, WEAP, SACWAM, and CV mod. All these models have some accounting for water demands, regulations, network dynamics, infrastructure, and operating policies (Lund 2016). Because these models and their variants are specialized, a potential vulnerability is that modelers may become preoccupied with learning and running the model without being critical of the broader realism of model outputs for decision-making. Turnover of modelers in agencies has been an annoyance, as has been retaining experienced personnel and developing a cadre of modelers who are at different career-stages.

Estimations of water supply reliability can diverge with representations in the broad components in Figure 2, as summarized in Table 7 and discussed below.

Table 7. Why water supply reliability estimates differ.

Source of differences	Improvements
Hydrology of water sources	Common hydrologic accounting and assumptions, documentation, sensitivity or error analysis, explicit interpretation
Water demands	Documentation of demands, sensitivity or error analysis
Model structure and representation of the water system, infrastructure, operating rules, etc.	System, model, and decision documentation; sensitivity or error analysis; explicit interpretive discussion
Modeler and modeling practices	Documentation of modeling and interpretation of results, external review, sensitivity or error analysis

Hydrology of water sources. Water supply systems can have multiple surface water, groundwater, and reuse sources, which may be represented in different ways, especially when considering different future climate and regulatory scenarios. Water accounting is imperfect with many estimated components (Escriva-Bou et al. 2020b; Ariyama et al. 2019). Quantities, such as precipitation, streamflow and water exports are relatively well measured/estimated and documented for the Delta, and extensive water monitoring networks cover most large watersheds, but even small uncertainties can have high decision value, when the market value of water in drought exceeds $1000/acre-ft (DWR 2018). The hydrology of each source must be represented and estimated, usually as a time series of available streamflow, runoff, aquifer pumpage, or reuse water availability. Estimating these quantities over time is particularly approximate for extreme wet and dry conditions, especially with a changing climate.

Hydrologic inflows usually are based on historical records of unimpaired streamflow or a synthesis from outputs of climate models. Most water supply reliability modeling considers only the historical hydrology with little account of anthropogenic changes in demands, regulations, and operations and other uncertainties in upstream and downstream inflows. An ensemble (e.g., Monte Carlo) approach might better represent a diverse set of dynamic scenarios.

Currently MWDSC runs as many as 17,000 plausible, but not probabilistically representative, future scenarios (MWDSC 2015). MWDSC and Santa Clara Valley Water District also have in the past run probabilistic scenarios based on re-sequencing the historical hydrologic record (MWDSC 2010; SCVWD 2003).

More substantial hydrologic gaps and uncertainties exist for groundwater storage, flows, pumping, basin evapotranspiration, snow cover, melt rates and upstream precipitation (Medellín-Azuara et al. 2018). Water use by surface water rights holders is often poorly reported. Typically, only applied and not consumptive use is reported, and groundwater withdrawal is not reported at all. Return water to the system after usage is sometimes not properly reported (Lund 2016). High frequency (e.g., sub-monthly) data are more prone to error than monthly or annual counterparts. Synthesis between data sources, identification of flaws of measurements leading to divergent data, and stronger error estimations and documentation may help improve input data quality (Kadir 2017; Pasner 2021). The monitoring tool that ESSA developed for Delta Science Program can be useful for some data gaps, duplication, and uncertainty and quality estimates (Alexander et al. 2018). Appendix A further discusses some issues in representing hydrologic inputs for water supply reliability analyses.

Currently federal and state agencies in California maintain multiple computer models, but coordination in their development and use could be improved. Establishing a common or standardized water accounting framework for water (in and outside the Delta) with consistent and contextual monitoring, evaluating and reporting protocols is highly desirable (Escriva-Bou et al. 2020b).

Water demands. Water supply systems for the various urban, agricultural, and environmental uses tend to have fluctuating and changing water demands. Major urban areas are seeing diminishing per-capita water use rates and commonly manage water demands by voluntary or mandatory rationing during drought to shape the frequency and depth of water shortages and use of alternative water sources. Some agricultural water users reduce water use in lower-valued crops differentially across wet and dry years to increase aquifer recharge, shift water to higher valued crops, or sell water (Howitt et al. 2012, 2015).

Water demands are simplified for modeling, but become more complex when water conservation/demand management activities are considered in the reliability analysis. Greater testing and documentation of water demand representations would help in understanding the likely range of model reliability. Water demands in models usually are based on populations, climate, land uses, and other factors, that are frequently considered fixed. Agricultural water demand estimation is hampered by lack of field data at appropriate space-time scales. Remote sensing of land uses and evapotranspiration have been helping greatly here, and has continued future potential (Medellín-Azuara et al. 2018). Appendix A further discusses some issues in representing water demands for water supply reliability analyses.

Model structure and representation of the water supply system. Models used for water supply reliability have structural and detailed differences, often including different portfolio elements and representing their interactions differently. Different modelers also usually apply these models differently. As a result, there can be a significant spread in water supply reliability predictions, despite reasonable differences in modeling assumptions (Lund 2016).

More detailed internal water network reliability assessments are common. Simpler analyses estimate the probability that all users are connected to at least one source, based on combining probabilities of individual network component failures. This topological reliability uses network theory. In more elaborate hydraulic reliability estimates, the probability that a water supply system provides adequate supplies to each user is estimated using stochastic (Monte Carlo) simulations, where random events out of the component reliabilities are generated, and the cumulative performance of the system is summarized with performance statistics. Hybrid methods combine the two approaches (ASCE Task Committee on Risk and Reliability Analysis of Water Distribution Systems 1989; Hossain et al. 2020).

Water supply reliability estimation is challenged by random and non-stationary processes such as population growth, land use change, climate variability and change and unexpected (black swan - surprise) events. Models often need to be nudged to account for these. Climate change effects on the Delta water supplies are likely to be significant, including water export reductions of about half-a-million of acre feet and diminishing north-of-Delta carryover storage (Fleenor et al. 2008; Wang et al. 2018; Knowles et al. 2018; Schwartz et al. 2021). Additional non-hydrologic non-stationarity in operations, regulations, ecosystems, and water demands has potential to change model details, capacities, portfolio structure, and operating rules over time.

Modeler and modeling practices. Historically, model errors have been attributed to error in model structure (formulation), model parameter estimates, model input values, solution method, and results interpretation. All of these are under the domain of the modeler and the modeling culture of the performing organization.

Despite efforts at convergence, water supply reliability modeling organizations have different modeling cultures and individual modelers have different experiences and judgements. Many water supply reliability studies are minimally documented or inaccessible, making it difficult to assess their structure and reliability. Model results rarely include substantial error analysis. Given the sophistication of reliability estimation models, agencies often are reluctant to invest in laborious and expensive efforts to analyze and document model performance and improve models.

The water management community might benefit from some broader expectations and efforts that include quality assurance, error analysis, and evaluation. Quality control for modeling, system analysis, and their applications to California water problems are long-standing topics (Tetratech 2019a, b; CWEMF 2021; DIB 2019; ongoing USBR and DWR efforts for CalSim). Almost all modeling efforts have some quality control. Recent years have seen increasing professional expectations for quality control in model development and applications, with related expectations for documentation of models and data, transparency, reproducibility, accessibility, as presented below.

5.2: Making Analysis Transparent, Documented, Replicable, and Accessible

Desirable modeling practices are well described (Tetratech 2019a, b; CWEMF 2021). Today, most quality controls on water supply reliability modeling are internally facing for the conducting organization, not reflecting explicit external technical expectations. No method is universally accepted to quantify the quality of water supply reliability analyses (Thissen et al. 2017).

Professional expectations for water supply reliability studies, and technical studies in general, tend to be based on the professional culture of individual and collective practices. In fields without a common modelling institution or professional organization where expectations can form and perhaps be codified, divergent quality control efforts often take root.

Expectations for professional practice can be informal, often patterned after templates or exemplars of practice or more formal, but less flexible standards, or regulatory requirements, and contract language. Professional practices often are manifest in model, data, and analysis documentation, testing, and availability. The state-of-practice of quality control for various components of water supply reliability analysis based on our experience is summarized in Table 8 and discussed below.

Table 8. Common quality control efforts for components of water supply reliability analyses.

Quality Control Action	Model	Input data	Model Results	Studies/ reports
Documentation	Sometimes	Usual	Sometimes	Sometimes
Testing	Usual	Usual	Informal	Rare
Interpretation	Sometimes	Informal	Sometimes	Sometimes
External Review	Informal	Informal	Unusual	Unusual
Data and Code Availability	Sometimes	Usual	Sometimes	Sometimes

Documentation. Models dealing with complex coupled natural-human-engineered systems have unavoidable deficiencies, uncertainties and quality of data, so it is useful to have public documentation of modeling methods, assumptions, building blocks, and underlying uncertainties available and, where appropriate, published peer-reviewed results.

The availability of documentation for studies and models in California has improved markedly in recent years, with the posting of such reports on agency web sites becoming a common practice. However, there has been a nearly wholesale removal of such reports and documents from State agency websites because the historical documents did not comply with accessibility requirements for persons using assistive technology (Venteicher 2019). Much of the details of California's water system, history, and analyses are increasingly inaccessible, difficult to discover, and susceptible to becoming lost.

Testing. System models for water supply reliability estimations can be tested in multiple ways. These include model-data comparisons, model code verification, sensitivity studies, and formal error analyses.

Models can be tested against field data and logic. For routine short-term operating purposes, comparisons of field data with model results provide timely insights to assess and improve model accuracy and use. However, for longer-term policy and planning application, comparisons of model and field data are largely unavailable until long after planning decisions must be made. Thus, field data for longer-term planning analyses must be extrapolated from historical or recent conditions, usually for component process models (such as household or crop water demand models).

Models also can be tested based on the logic, theoretical, and literature validity of their structure and parameter values, and assumed inputs. These can be vetted with experts and stakeholders, particularly if they are well documented. Error analyses can propagate presumed or estimated errors in model components to estimate likely errors in model outputs. When models are applied to more distant futures or operating conditions further outside their range of calibration, larger errors should be expected and testing must be based more on logic, error analyses and formal reviews.

The logic and behavior of most models are tested primarily by comparing their assumptions and results against the understanding of the system by the modelers involved, as well as operators, managers, stakeholders, and sometimes external reviewers. Some tests are extensive, prolonged, and iterative processes, with some documentation, culminating in a more accurate and trusted model.

Sensitivity analysis is a process that varies various model assumptions to assess how much model results and conclusions might change. This is a common approach to testing model results and conclusions (Vicuna et al. 2007).

Error analysis is a more formal type of sensitivity analysis, which makes probabilistic assumptions about the likelihood of various model input or parameter conditions (Hazen 1914; Shuang et al. 2014). Error analysis can be done analytically (Hazen 1914) or more flexibly as Monte Carlo studies (Klemes 1987; Nayak et al. 2018). A limitation of both sensitivity and error analysis approaches is how to handle the many (often hundreds or more) assumptions involved in reliability estimation, and how these conditions might be correlated across variables and in space and time.

To better test and compare models and model results, standardization of data and modeling is needed, discouraging the current closed in-house models that are black boxes to outsiders. American Water Works Association (AWWA) and International Water Association (IWA) have developed standardized methods for water audits that assist completing water balances. Periodic audits can be a part of reliability estimates (Sturm et al. 2015). Documenting such results can be helpful.

Expert Interpretation. Initial model testing already employs the scrutiny of model and domain experts. Routine model results, and reliability estimations, also can benefit by adding written interpretations and discussions of results by model and problem experts for problem-oriented managers. The documentation of interpreted results can make their reasoning more explicit and useful for a broader range of interested parties.

Interpretations of well-crafted sensitivity results can be insightful, especially when a wide range of possible future conditions are explored. Such results have been used and developed extensively as "decision-scaling" or "robustness" analyses (Brown et al. 2012; Wilby and Dessai 2010). Most "robustness" planning examines the performance of alternatives based on many possible future scenarios (usually not probabilistic) to assess ranges of unfavorable and favorable future conditions (Wilby and Dessai 2010; Means et al. 2010). The "decision-scaling" approach is especially promising in that it uses fewer, more artfully designed scenarios representing sequentially more dire conditions to assess the range of stable and desirable performance for a system or a proposed alternative (Brown et al. 2012).

Review. Internal technical reviews of water supply reliability studies almost always occur, including the system models used to produce them. Most regard the representation of operations. However, external reviews are less uniformly applied but may be advisable to promote use of current science. For example, in California, the CalSim and CalLite models have been formally reviewed externally for journal publication (Draper et al. 2004; Islam et al. 2011) and sometimes in more depth, sponsored by the California Water and Environment Modeling Forum (CWEMF) (Ford et al. 2006; Close et al. 2003). Local system models are sometimes also reviewed externally (Randall, et al. 1997). Elsewhere, the major water supply reliability modeling system used by New York City recently was reviewed by the US National Academy of Sciences, Engineering, and Medicine (NASEM 2018).

External Replication. Replicability is a staple of testing scientific work. Sometimes replication efforts are made of water supply reliability and other analyses. An example is MBK Engineers and Steiner's (MBK 2014) report on their attempt to repeat several BDCP water supply reliability modeling analyses done for the Department of Water Resources (DWR 2015). Another example is a recent re-analysis of San Diego County Water Authority proposals for a second Colorado River Aqueduct (Elmer 2020). Some recent efforts have been made in the water engineering profession to make replication testing of modeling and technical work less onerous and more common (Stagge et al. 2019; Rosenberg and Watkins 2018). Some comparisons are adversarial reviews intended for regulatory or court proceedings or negotiations.

For long-term planning studies, such re-analyses often give substantially different results, which is not surprising given the many assumptions and uncertainties involved over long-term planning horizons. There is often a tendency to over-interpret reasonable but substantial differences in results in adversarial discussions, rather than using these differences as indications of inherent uncertainties in the estimation problem and the wider range of contingencies that should be prepared for.

Data and Model Codes Availability. Having documentation, data, and models available are important aspects of quality control. These are necessary to directly support other quality control processes (replicability, etc.) and to improve understanding of water supply reliability results and their limitations.

Data availability in California is much better than elsewhere, with streamflow, modeling and other data often being posted by some agency programs. California's Open and Transparent Water Data Act (AB 1755) has furthered these efforts. The broader profession also has devoted some efforts to document and standardize data and data management, which should speed new model development, as well as testing and improvement of existing models and model results (Harou et al. 2010b; Rosenberg and Watkins 2018; Knox et al. 2019; Abdallah and Rosenberg 2019; Stagge et al. 2019).

Although publishing system model codes has not been common, it is becoming a common expectation in California and elsewhere. The modeling software for CalSim (as well as its input data sets) are often available from DWR. The newest Python version of the CALVIN network optimization model for California is available on GitHub (Dogan et al. 2018). Elsewhere in the profession, a generalized water resource network modelling Python library, Pywr, is now available (Tomlinson et al. 2020).

As indicated in Table 7, quality control for technical work has many facets, especially for controversial public policy problems. Considerable progress is being made in quality control for water supply reliability estimation in California, but additional benefits for technical efficiency, understanding, and improved discourse will result from further informal and organized efforts in this direction.

5.3: Common Basis for Water Supply Reliability Estimates

Various agency efforts have been made to support more of a common approach to water supply reliability estimation. Some such efforts are discussed by Jackson (2006, 2005). Several multi-agency efforts in California include:

1. The California Water and Environment Modeling Forum (CWEMF): The Forum meets regularly in annual meetings and workshops to discuss modeling advances and issues. The Forum fosters technical information exchange among agencies, and has organized several modeling reviews for CalSim (Ford et al. 2006; Close et al. 2004). It currently is finalizing modeling guidelines (CWEMF 2021).
2. California's DWR and the federal USBR: These two large state and federal agencies jointly developed the largely open-source CalSim models used in the SWP and CVP water projects. After 20 years, this model is on its third basic revision. They have a joint effort, the CalSim Model Maintenance Management (CM3) group, to coordinate development and documentation of these models.
3. "Common assumptions" efforts: Following development of CalSim II, there was a multi-agency (DWR and USBR) effort for several years that was staffed by consultants, to standardize land use, inflows, groundwater modeling, water demands, and portfolio characterization for modeling. Similar efforts continue informally.

Other efforts to provide a common basis for modeling include:

1. Standard model test data sets: Algorithmic and historical test sets sometimes are developed and used. Several professional efforts have sometimes been proposed or utilized to improve quality control and documentation of water supply reliability estimates.

2. Separation of models from input and parameter data: This is a further extension of the long-standing philosophy of CalSim of avoiding hard-coding of operating parameters and rules as much as possible. Here, data for the model is stored in separate explicit data bases, often including documentation of the data (much like Draper et al. 2003 for CALVIN). This can greatly improve model and data documentation and ease its understandability and ability to upgrade.
3. Software-neutral modeling and data standards: These have been suggested and developed to encourage development, testing, comparison, and documentation of models (Knox et al. 2019; Tomlinsom et al. 2020).
4. Common water accounting: An example is the state of Colorado's maintenance of common water accounting across basins for models for water right and water supply reliability (Escriva-Bou et al. 2020b).
5. Common efforts to estimate uncertainty: Uncertainty analysis is common in water supply reliability estimation, particularly for seasonal (within-year) operations. However, different agencies perform such analyses very differently. More common efforts to estimate uncertainties in reliability might be useful (MWDSC 2015; Hirsch 1978). In some cases, machine learning methods might be helpful (Lingireddy and Brion 2005).

Integration of various models under a unified framework is a possibility, but would be time consuming. Integration needs to be a parallel effort in conjunction with ongoing water supply reliability estimates and modeling upgrades. Integration requires expertise from multiple agencies. Integration itself may produce uncertainties, and an evaluation of return on investment is needed.

5.4: Model Updating and System Learning

Modeling and analyses will need updating as water systems and problems change in California. Classically (Hollings 1978), adaptive management is based on updating models in an organized way to combine scientific efforts, management problems, and solution development.

More transparent, science-based, collaborative, and open-source modeling will help agencies, stakeholders, and the public be more aware of the intricacies, value, and limitations of water supply reliability estimates (Sarofim et al. 2021). Such an approach may help reduce litigation and better support healthy partnerships. Building trust on the quality of water supply reliability estimates should support science-based Delta management in the near-term and long run.

6. Reliability Estimation in Decision-making

"The best-laid schemes of mice and men go often awry." Robert Burns 1785

Although water supply reliability estimation is broadly important for water planning and operations in California, ideas of how to characterize and estimate water supply reliability vary widely. Today it is easy to produce a plethora of numbers and statistics on water supply reliability. It is a challenge institutionally and technically to develop reliability estimates that are insightful for diverse policy-makers, managers, and the public.

Several policy and management questions regarding water supply reliability arose in the course of discussions and presentations for this report, with examples in Box 6. These illustrate the wide range of questions of concern. Formal water supply reliability studies can be designed to formalize and answer such questions.

Box 6. Some Water Supply Reliability Questions Arising in the Course of this Review

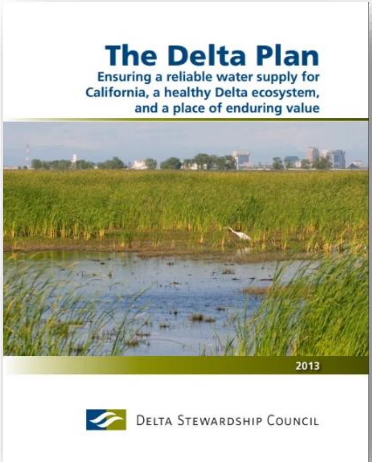
- Could water quality reliability contracts between the State Water Project and various in-Delta water agencies better coordinate in-Delta operations?
- How would a western Delta tunnel diversion location affect Delta export supply reliability?
- What is the reliability of attaining Delta water quality standards under various future and management conditions and Delta water export levels?
- How is Delta water diversion reliability affected by various Shasta operations for winter-run salmon?
- How do alternative out-of-Delta water supply and demand management portfolios affect the frequencies of Delta water demands for various operating, environmental, and climate conditions?
- How do various Delta salinity or fish barriers affect Delta water quality and diversion reliabilities?
- How can California climate change predictions be effectively incorporated into water supply reliability estimation for the Delta?
- What are the implications of California's Sustainable Groundwater Management Act (SGMA) for water supply reliability estimates?

6.1: Organizing the Problem and Solutions

Formal water supply reliability analysis can help structure and organize complex and difficult technical problems for decision-making. Although the problems remain difficult and complex, organizing them and providing decision-relevant analyses can improve policy and management discussions and decisions. Conversely, poor analysis can obscure and obfuscate problems and solutions (Rosenberg and Madani 2014). Scientific and technical work is most effective when the analysis is tailored to the decision-making problem and context. Decision-making also benefits when the institutionalized decision process is tailored to employ scientific and technical information that can be used to meaningfully compare likely outcomes of alternative management strategies.

Formal water supply reliability estimation provides a rough common structure for organizing problems and solutions. Many details, which involve technical and policy assumptions for future conditions must be specified in each model component representation. Some details are based on socio-economic models, designed to maximize benefits. A range of detailed representations can be employed for any system component, providing precision where needed to estimate likely system behavior.

Water supply reliability analyses tend to be more useful when they have co-evolved interactively with structured water management decision-making as is the case with more routine operational decision-making. As operational decisions come to include more environmental objectives, it will be important to adapt reliability analyses to better represent these objectives.



Longer-term planning efforts (such as the Delta Plan and the State Water Resources Control Board's Delta water quality planning) would benefit from a more explicit common foundation for reliability analyses in their broader deliberations, as it would provide a more scientific structure for the development, understanding, and evaluation of solution alternatives.

6.2: Short-term Operation Decisions

Short-term water supply decisions include water diversion, conveyance, storage, and delivery operations. These decisions usually extend from daily to seasonal (within-year) periods, and sometimes extend to limited multi-year planning operations for ongoing or hypothetical droughts. Most short-term operating decisions are routine procedures informed by recent experience and are agreed upon in advance to represent regulatory requirements, daily and seasonal fluctuations in demand, and hydrologic cycles. Both analysts and decision-makers often use modeling estimates to refine and test different management ideas, based on their expertise and experiences. Because the analysts and decision-making users of model results have worked together for some time, they often have adapted their work and deliberations to be mutually-informative.

Water supply reliability analyses for these short-term decisions commonly use some variant of position analysis or other probabilistic representations of how conditions could likely evolve (Figure 3) (Hirsch 1978; FitzHugh 2016). The results embody many likely uncertainties explicitly, and contingencies for unusual extremes are considered with various forms of sensitivity analysis and informed professional judgement.

Sharing techniques and management results through routine reporting could help decision-makers, regulators, and other stakeholders better understand and employ these methods. Retrospective analyses could help refine operations, particularly following extreme events. In addition, more rapid incorporation of short-term forecasts and improved modeling techniques could improve operations for multiple purposes (Nayak et al. 2018; Doering et al. 2021).

6.3: Long-term Planning and Policy Decisions

Decision-making over long time-frames have inherent modeling limitations and must accommodate less accurate modeling forecasts. Although improvements in model reliability may be gained through model refinement and data collection, decisions will necessarily require choosing among options with less certain outcomes. Several approaches to choosing options, despite performance uncertainty, have been advanced. Most approaches are based on various structured decision analysis methods (Keeney and Raiffa 1993), often based on historical experiences, often represented as a range of events with probabilities.

Several Delta problems have been organized and addressed with simple decision analyses (Suddeth et al. 2010; Lund et al. 2010). For instance, Bayesian analyses use historical data to update expectations of future change to estimate probabilities and outcomes with changing conditions (Fletcher et al. 2019).

Some variants on this approach omit probability estimation to assess benefits and contingent regrets under a wide range of future scenarios, while others aim to reduce stranded assets (and sunk costs) by implementing management options in stages that are triggered as risk increases (Marchau et al. 2019). Exploratory sensitivity and robustness analyses of models under creative future scenarios also can be insightful for long-term planning (Brown et al. 2013; Herman et al. 2020).

The discussions and structuring of problems needed for reliability analyses can be more important to resolving policy problems than the numerical results of the analyses. Poorly formulated models tend to solve the wrong problem.

6.4: Long-term Education and Insights for Policymakers

Well-crafted modeling analyses and studies have become important for educating people involved in water management, and for preparing them for operational, planning, and policy challenges. Decision-makers, policymakers, regulators, stakeholders, operators, and modelers often lack deep background in the breadth of water delivery and water management systems. Further, changes over time in these systems and their problems makes it difficult for the many groups and people involved in water management decisions to remain informed and explore solutions.

Well-executed, documented, communicated, and available water supply reliability studies all can help educate these groups and provide a more common understanding and ability to communicate in policy and planning deliberations. Complex analyses including Monte Carlo analyses are most directly useful to decision makers if they are led to actionable advice, but they sometimes have greater indirect value if they increase decision-makers’ understanding of problems, vulnerabilities, and potential solutions. Modelers must do more than represent system variability and interpret findings in terms of how systems and people will be affected. For instance, risk levels can be characterized in terms of ability to manage risk with contingency planning.

Model and model result documentation should serve both detail-oriented audiences (e.g., regulators and analysts interested in replicating and interpreting results) and broader management and policy audiences, who need to easily interpret and act on the policy implications. Documentation for policy makers will need to communicate useful model results, and assure audiences that the understanding and modeling of the system has been appropriately thorough. Research and co-development can be used to design outputs and visual interpretations of results (e.g., color-coded risk levels). More detailed documentation should include all materials needed to replicate the analysis and educate new policy-making staff and modelers.

When addressing uncertainty, it is tempting to include elaborate and complex decision analyses. However, complex decision analyses and analyses at finer geographic scales and shorter time steps are time-consuming to develop, hard to interpret and trust, and subject to high error. Simple decision analyses are often better for developing useful insights for managing a problem and serve as a foundation for additional refinements. Complex analyses, when needed, are often completed more quickly, rigorously, and insightfully when grown from simpler analyses. Much can be learned from parsimonious models tailored for a specific set of problems, but more complex problems and solutions often must be analyzed or tested with advanced modeling.

7. Conclusions and Moving Forward

Most large water systems in California have matured and adapted to include integrated portfolios of water supply and demand management actions to improve their performance. Estimating the reliability of such complex and often-interconnected systems typically requires computer model representations of interacting physical supplies, infrastructure, operations, institutional priorities and regulations, and diverse human and environmental water demands that vary in space and time. Expansion from water source reliability to estimation of integrated water system performance reliability often involves a combination of technical and fundamental performance objectives.

Water supply reliability estimation needs to be better incorporated into decision-making processes. Improved documentation, model testing, multi-agency modeling, and continuous adaptation would facilitate the application of such modeling to decision-making.

Water supply reliability estimation in California and the Sacramento-San Joaquin Delta will have to adapt to many changes including climate, human and ecosystem water demands, infrastructure, environmental regulations, and probably a few surprises. Water supply reliability estimates are vital to prepare, plan, and negotiate for these changes, individually and collectively. These estimates must be done in the context of California's extreme and growing hydrologic variability, complex and extensive infrastructure systems, changing water demands, and decentralized institutions that bless and curse water management in California.

Many questions for estimating water supply reliability confront us today and many new ones will emerge. Some examples are summarized in Boxes 6 and 7. It behooves California to strengthen its comparatively strong capabilities to estimate water supply reliability and to integrate such analyses into its dynamic and evolving systems of policy- and decision-making.

Box 7. Some Common Questions on Water Supply Reliability

Is there potential for long-term seasonal and multi-year forecasting?

Short-term forecasts of a few days often provide the greatest improvements in performance, with longer forecasts generally providing diminishing increments of improvement (Doering et al. 2021). Longer-term forecasts also usually tend to be less accurate. In most of California, precipitation forecasts beyond about two weeks are generally show little predictive skill beyond that of historical climate statistics. Long-term seasonal and multi-year forecasts are usually much less accurate than short-term weather forecasts. Seasonal and multi-year weather patterns for some parts of the world do seem correlated with ocean conditions (Chikamoto et al. 2020). For southern California, annual precipitation is mildly correlated with ENSO ocean conditions (Schonher and Nicholson 1989). Long-term forecast accuracy faces a fundamental problem of the chaotic nature of most weather forecasting (Lorenz 1993, Slingo and Palmer 2011; Cao et al. 2021). All forecasts are imperfect, with potential to mislead and distract, as well as to provide management insights. For the foreseeable future, historical records, perhaps modified statistically to account for a range of climate change estimates, appear to be the most promising basis for developing forecast scenarios.

Does the export or import of water-intensive products affect water supply reliability?

The fate of products produced using water is usually not included in estimates of water supply reliability. ”Virtual water” is the water use embodied in goods which are traded across borders, and is a rough indicator of the amount of water used goods which are exported and imported. The production of water-intensive products does affect water supply reliability, although their export can provide greater economic advantages than producing other products using an equivalent amount of water, particularly in poor rural areas. For economic prosperity in a non-subsistence economy, the economic value of goods produced using water is the same if they are exported or consumed locally (Pfister et al. 2009; Wichelns 2010; Neubert 2008).

How does water storage expansion affect water supply reliability?

Having additional water storage capacity usually requires some, often large, costs for construction, operations, permitting, etc. The additional water supply reliability from these investments varies considerably with the availability of water to fill that capacity, and the conveyance capacities and costs to move water into and out of the storage location to serve water demands. Additional water storage capacity theoretically improves water supply reliability, but not always enough to justify the necessary investment (Hazen 1914; Arnold 2021).

What is the potential for artificial recharge of flood waters for improving water supply reliability?

The recharge of flood waters to aquifers is perhaps the most popular solution for eliminating overdraft in California’s groundwater basins. Several analyses of this source have found that it has some value for this purpose, but that it is unlikely to be able to eliminate most groundwater overdraft in most groundwater basins in California (Alam et al. 2020; Escriva-Bou and Hanak 2018; DWR 2018). Flood waters in California are infrequent, hard to capture, and tend to occur in locations far from areas with the greatest groundwater overdraft.

Appendix A. Some Technical Issues in Estimating Water Supply Reliability

This appendix briefly reviews approaches for representing hydrology, human water demands, time, and decision-making in water supply reliability analysis. The appendix also summarizes approaches to uncertainty analysis in estimating water supply reliability.

A.1: Representing Hydrology in Estimating Water Supply Reliability

Hydrology is the most commonly explored proximate cause of unreliability in water systems. Several approaches are used to representing hydrologic uncertainty and variability in water supply reliability studies.

Future water availability estimates are based on historical records and/or different climate models as summarized in Table 9.

Climate models generally have a course geographic resolution, with results based on a particular global emissions scenario. These coarse spatial results must be downscaled, by one of several approaches, to produce regional and local precipitation and temperature results. These local results are then input into models for estimating stream runoff and groundwater infiltration from precipitation, sometimes with climate-dependent vegetation and land cover. High resolution multi-ensemble models coupled with innovative downscaling techniques to high space-time frequency hydrologic projections can characterize the range and probabilities of future climate results (Pagán et al. 2016; Grantham et al. 2018). Yet high resolution and large ensembles without better process understanding might not be more accurate.

Traditional delivery capabilities reports from the California Department of Water Resources are updated every two years (DWR 2020). Climate change scenarios are being introduced into these studies, having importance for long-term planning. Climate change is affecting current seasonal operations, due to warmer temperatures at least. There is some discussion, and a variety of approaches, on how historical hydrologic flow estimates might be adjusted for observed and likely changes in climate. Long term planning (e.g., decadal) should incorporate the range of reasonable projections of climate change, with consideration that these projections are themselves uncertain. Current seasonal operation plans and policies might benefit from adjusting historical climate estimates for recent changes in climate (Lund 2021).

Several approaches to representing hydrologic extremes and variability are summarized in Table 9 and discussed below.

Table 9. Common approaches to representing hydrology for water supply reliability studies

Approach	Description
For Current Studies	
Design drought	A specific extreme drought hydrology is used.
Historical unimpaired flows	Hydrologic flows are developed from historical records, often with considerable estimation to fill and correct gaps.
Re-sequenced historical flows	Historical flows are re-sampled to create longer synthetic flow records which can include more severe extreme conditions.
Statistically synthesized streamflows	Statistical characteristics of historical flows (means, variance, correlations) are used to create multiple longer representative flow time series.
Broad range of scenarios	A wide range of design droughts, developed to represent a wider range and types of extreme events.
Hydrologic forecasts	Statistical or mechanistic estimates of future flows.
For Climate Change Studies	
Paleohydrology	Paleohydrologic observations are used to estimate hydrology.
Climate model precipitation and runoff	Local hydrologies developed by downscaling climate model results and running through precipitation-runoff models.
Continuous adjustment of historical flows	Historical streamflows are adjusted to reflect major statistical shifts seen from aggregate climate change models.
Parametric climate representation	Essentially inverse-scenarios, increasing climate change characteristics (temperature, seasonal shift, extreme events) until system performance suffers.

"Design drought" – Many water supply systems evaluate their system infrastructure and operations based on a repeat of the most severe drought of record, akin to "firm yield" analysis (Linsley et al. 1992). Many urban areas use design droughts as specified in state law for Urban Water Management Plans, mandated for all large urban water suppliers. East Bay Municipal Utility District (EBMUD) has developed a drought somewhat more severe than that seen historically to assess the ability of their system to weather severe droughts. The EBMUD design drought is a three-year sequence where the first and second years have runoff from years 1976 and 1977 (the driest two-years on record), plus a third year with the average runoff from these two years (EBMUD 2021).

Historical unimpaired flows – In California, most large water supply systems use estimates of historical unimpaired streamflows (and sometimes groundwater inflows) in evaluating water supply reliability. DWR's series of water delivery capability reports (since 2002) mostly takes this approach (DWR 2017, 2020). In early times, such analyses were used to identify system "firm yield" deliveries. Today, most analyses develop water delivery-reliability distributions and curves (Hirsch 1978). DWR has an extensive and formal hydrology development process to adjust historical records for changes in land and water use upstream. Such accretions/depletion adjustments have been developed by DWR-USBR more than 50 years ago as their basis for planning and operation models (DWR 2016). Recent work further refines the calibration of historical unimpaired flows and allows better statistical characterization of likely statistical errors in these flows (Kadir 2017).

***Re-sequenced historical flows* –** Resequencing historical streamflows by varying the starting year or by bootstrapping can, in principle, produce larger statistically representative samples of streamflows that include more extreme events (Tasker and Dunne 1997). Because the historical streamflow record represents only one realization of the many sequences that could occur in the future, MWDSC has used more of combinatorial approach that develops additional hydrologic time series, with each time series beginning in one year from the hydrologic record, followed by the remaining years of record, followed abruptly by the earlier years of record before the starting year (MWDSC 2010; 2015). Santa Clara Valley Water District also had employed a similar approach (SCVWD 2003). This allowed MWDSC and SCVWD to statistically include drought periods more extreme than experienced historically in its water supply reliability estimates. This is probably the most sophisticated routine representation of hydrologic variability in water supply reliability analysis by a California water agency.

Statistically synthesized streamflows – Hydrologic records are often short and under-represent the range of extreme events that water supply systems need to be prepared for. A large literature exists on statistical methods that use local and regional hydrologic observations to develop and calibrate stochastic models for generating large ensembles of long statistically representative scenarios of streamflows or other hydrologic conditions (Tasker and Dunne 1997; Hirsch 1979; Lamontagne 2017).

Broad range of scenarios – Another approach to representing a broader range of hydrologic scenarios than have been experienced historically is to rely on a broader but less statistically careful range of hydrologic events, generated by various means. MWDSC also uses this approach, which has value for stress testing system operations under a wide range of plausible, but not statistically representative, conditions (Herman et al. 2016; MWDSC 2010).

Hydrologic forecasts – Forecast inflows using a combination of NWS, CNRFC, DWR, and other forecasts, and modified historical streamflows are commonly used by local, state, and federal water projects for near-term and seasonal operational reliability analyses. “Position analysis” or similar “spaghetti curve” analyses are commonly fed hydrologically with such inflows (Hirsch 1978; Tasker and Dunne 1997; DWR Bulletin 120, FitzHugh 2016). These often use model-based weather forecasts for a few weeks of foresight and then transition to historical hydrologic estimates (Cao et al. 2021).

A.2: Climate Change and Hydrology

Several decades of many modeling studies almost all agree that California will see higher temperatures, but among the many models, there is a considerable range of results in how much and how fast temperatures will increase, as shown in Figure 10, even for one emissions scenario. California should prepare for a warmer climate with less snow, more rain, and less snowpack, shifting runoff from spring and summer to winter. This seasonal runoff shift can be seen in the hydrologic record in recent decades (Aguado et al. 1992). Higher temperatures also are increasing watershed evapotranspiration, which reduces the amount of rain and snow precipitation which becomes streamflow or aquifer recharge (Albano et al. 2022).

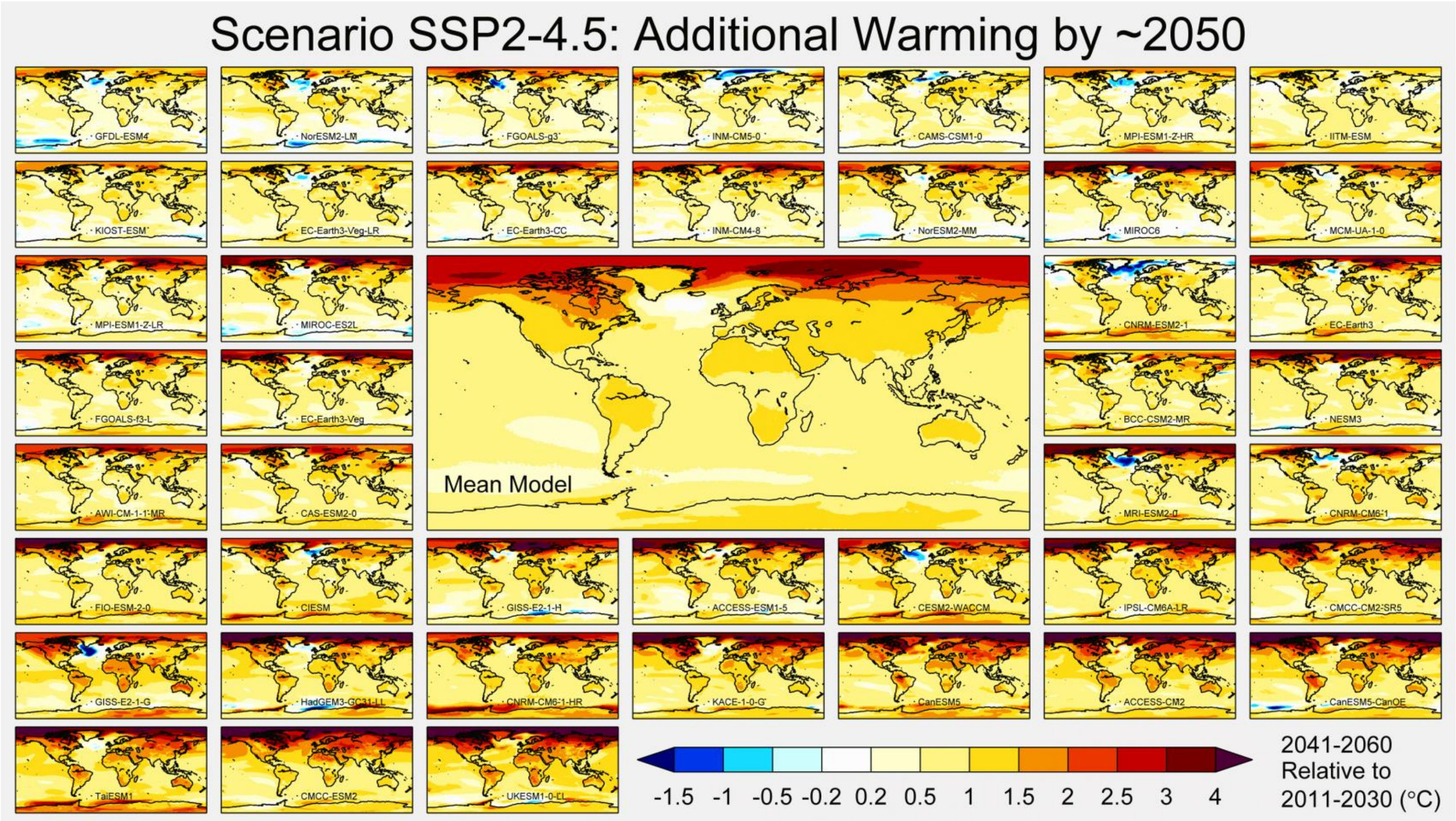


Figure 10. California becomes warmer in all of 43 global climate models with moderate greenhouse gas emissions (IPCC CMIP 6).

There is less modeling consensus on future changes in overall precipitation. For some parts of the world, the consensus of global climate models shows decreasing or increasing overall precipitation. This is not clear for California, as seen in Figure 11. However, the many models of California's future climate do show an increase in precipitation variability, with bigger flood events and deeper droughts (Swain et al. 2020, 2018).

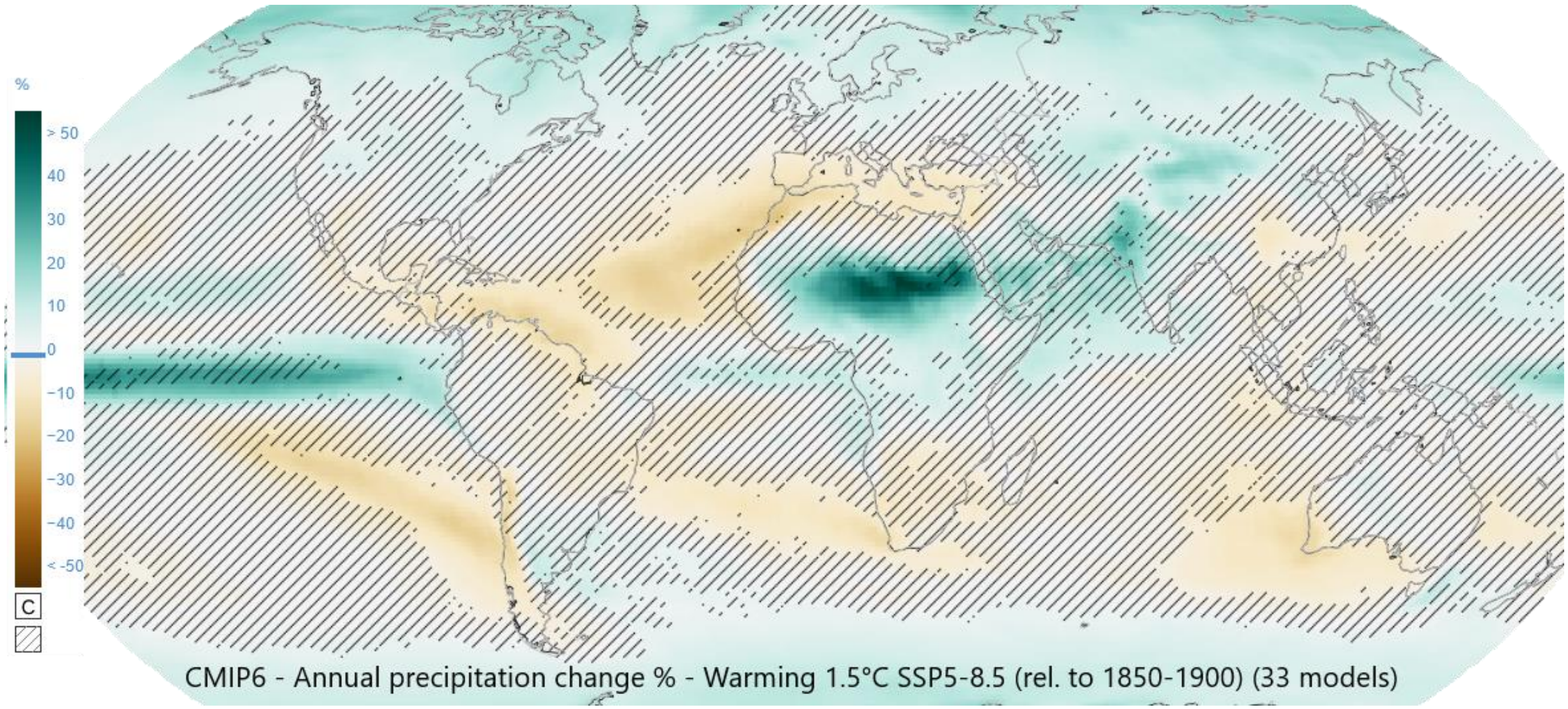


Figure 11. Lack of clear average precipitation trend for California from 33 models with modest warming (IPCC CMIP 6 global precipitation) .

Four approaches have been taken to represent changes in future climate in water supply reliability studies:

Paleohydrology – Several studies have employed representations of severe, prolonged distant past droughts for water supply reliability analysis (Harou et al. 2010a; Woodhouse and Lukas 2006). These paleorecords are usually based on tree-ring studies or records of distant past lake levels and sediments (Adams et al. 2015; Meko et al. 2001; Stine 1994).

Climate model precipitation and runoff – Sometimes hydrologic inflows for water supply analyses are taken from one or more sequential climate change and hydrologic models. This process introduces several sources of uncertainty from the selection and use of:

a) Particular global circulation models
b) Greenhouse gas emission scenarios
c) Bias correction method used to post-process global climate model results,
d) downscaling method used to take coarser climate model results to finer scales needed for water resource studies
e) Hydrologic, snowmelt, and groundwater models needed to develop streamflow and aquifer inflows from precipitation, temperature, and other climate conditions.

These methods are resource-intensive and produce compounded uncertainties which are rarely explored (Mehta et al. 2013; Joyce et al. 2011).

Climate change adjusted historical inflows – Historical inflows are commonly adjusted to match statistical differences with climate change hydrologic outputs from paired climate change and hydrologic models, usually representing changes in seasonal shifts in flow means and variance. This approach better preserves observed spatial and temporal auto-correlations in streamflow and experienced hydrologic persistence in extremes, but also can be limiting in these regards (Zhu et al., 2005; Willis et al. 2011; DWR 2018b, 2019; Lund 2021; Aguado et al. 1992).

Continuous adjustment of historical flows – To represent the likely future evolution of streamflow or conditions with climate change, some authors have represented climate change as a continuous change in the mean and standard deviation of historical conditions or streamflow (Hui et al. 2018). This can efficiently summarize the effects of climate change without more awkward and computationally burdensome use of an ensemble of GCM and derivative results, but limits climate change to a few statistical parameters.

Parametric climate representation – Because climate change is uncertain, it can be insightful to represent major aspects of climate in a few parameters, and then systematically change the parameter values to assess the vulnerability and responses of the water system under a range of conditions. Several such studies for water supply systems have been done in California (Kiparsky et al. 2014; Willis et al. 2011).

A more systematic version of this approach, sometimes called "Decision-scaling" where the performance of particular decisions is assessed to identify the scale of climate and other changes under which a system or decision performs well (Brown et al. 2012; Albano et al. 2021; DWR 2018b, 2019). This is essentially an inverse-scenario approach that requires generating fewer, but smarter, scenarios to assess system performance.

The representation of potential climate changes into the future can be as a single climate change scenario, fixed weighted multiple climate change scenarios, or multiple scenarios with Bayesian updating of their probabilities. Of these, the examination of a single scenario has been most common, and has shown many consistent impacts and insights for policy and management. Recently, reliability results for multiple scenarios have become more common, and better shows where and how reliability results and policies might diverge with future climate.

Over time, observations of changes in climate might narrow the scattering of potential climate futures produced today, and could help in updating water management plans, infrastructure decisions, and policies. Two recent papers have examined the use of Bayes' Theorem to update probabilities of climate scenarios for the future based on future climate observations, and integrated these calculations into reliability optimization studies for long-term water infrastructure (Fletcher et al. 2019; Hui et al. 2018).

A.3: Representing Human Water Demands

Representing humans and their water use decisions is important in water supply reliability estimations and analyses (Madani and Shafiee-Jood 2020). Several approaches are summarized in Table 10 and discussed below.

Table 10. Approaches to representing human water demands for water reliability studies.

Approach	Description
Delivery targets	Fixed desired water deliver volumes, often varying in time
Water demand curves	Economic values of delivered water, often varying in time to better represent the variable values of water delivery
Uncertainties in water demands	Probabilistic or multiple scenario variations on water delivery targets or economic values of delivered water
Climate change and water demands	Modifications of water delivery targets or economic values for changed climate conditions

Delivery targets – Classically, water supply reliability analyses represent water demands as *target delivery quantities*. These will often vary by month (and sometimes by smaller time-steps) and sometimes vary by year-type (dry versus wetter years). Small and large failure to be able to provide these target deliveries are all counted as equally unreliable.

Water demand curves – However, because different amounts of water shortage incur different levels of economic or other losses, economists and engineers have long suggested the use of economic demand curves (Dupuit 1853; Howe and Smith 1994; Harou et al. 2009). Water demand curves often vary seasonally (sometimes with time of day and sometimes by year-type). In modeling, they are often recast as economically-based penalty functions with growing amounts of shortage resulting in greater economic losses.

Uncertainties in water demands – Most representations of water demands in water supply reliability analyses are fixed deterministic. However, particularly in planning time frames, water demands often have considerable uncertainty (Whitford 1972). Sometimes these uncertainties are represented as an ensemble of equally-probable water delivery targets, or potentially as an ensemble of equally-probable water demand curves. San Diego County Water Authority has taken this approach in planning (Kiefer and Porter 2000).

Climate change and water demands – Climate change will affect water demands as well as water availability, particularly for agriculture. Higher temperatures increase evaporation and evapotranspiration rates, and will lengthen growing seasons in some areas, increasing water use, but also decrease the time needed for crops to mature, potentially decreasing irrigation water demands. Higher carbon dioxide concentrations also are likely to affect crop maturity, yields, and selection (Pathak and Stoddard 2018; Pathak et al. 2018; Lee et al. 2011; Lobell et al. 2007). Climate impacts on water use and demands might differ between annual and perennial crops.

A.4: Representing Time

Static future conditions – Most water supply analyses estimate reliability for a particular slice of time, present or future, usually representing water demands expected for a specified time in the future. So, it is common for studies estimating reliability for estimated 2020, 2040, 2050, or 2100 conditions, often referred as a future “level of development.” The system simulation model then examines these estimated future conditions using historical or other hydrologies to estimate the probability distributions of water deliveries for these future conditions.

Continuous simulation – A more elaborate and time-consuming representation of time estimates reliability in each year from the present into the future. This is done by running a system simulation model many times using randomly estimated hydrologic, water demand, and other operating conditions, including how these conditions are thought to change into the future. This requires characterizing the randomness in hydrology/climate, water demands, and other important reliability factors, and how this randomness changes with time. This approach is essentially the “plotting position” approach, common for seasonal water supply reliability analysis, applied to longer-term planning (Hirsch 1978). These results become harder to generate and explain, and can introduce new spurious sources of error. The Bayesian approached described above are a more sophisticated form of continuous modeling (simulation or optimization) (Fletcher et al. 2019; Hui et al. 2018).

A.4.1: Representing Decision-making

System modeling for water supply reliability also requires representation of operational decisions over the course of hydrologic events. These include reservoir releases, water rights administration and curtailments, implementation of drought water conservation actions, changes in crop mix, groundwater recharge, and other decisions that affect the portfolio of management activities available for the water system. Because these operating decisions usually vary each year with hydrologic, water demand, and other conditions, some representation of decision-making must be included in system models. Several approaches are common.

Some models represent operating decisions during their simulations with a series of rules, representing established or expected policies for operating each element of water management portfolios included in the model over the range of hydrologic and other conditions. Such fixed operating rules could include reservoir releases as a function of water stored in the reservoir, groundwater pumping as a function of the difference between water demands and surface water availability, or the implementation of water conservation actions based on the amount of water stored in reservoirs. Although there is a vast and insightful literature on water system operating rules (Macian-Sorribes and Pulido-Velazques 2019), such rules can prove inflexible and difficult to adapt to new conditions, such as climate change.

More recent water supply simulation models embed an optimization algorithm that makes such operational decisions based on prioritized technical objectives, such as implementation of seniority-based water rights or contractual obligations, within capacity, water availability, and other constraints. This approach is much more flexible and adaptable, and usually easier to implement in software, than direct rule-based simulations. CalSim, WEAP, and many other contemporary water system simulation models take this priority optimization approach, which is usually implemented for each time-step individually (including New York City's Operation Support Tool (NASEM 2018, using OASIS software) and ModSIM (CSU 2017).

A third approach to representing decision-making is explicit optimization of technical or fundamental objectives, within constraints (Lefkoff and Kendall 1996). Some such models minimize overall economic costs (or maximize overall economic value) within other physical and policy constraints. Optimization-based operations are the most flexible and adaptable operations for scenarios which diverge from current operating experiences, but can be over-optimistic in terms of actual decisions made (Harou et al. 2009; Tanaka et al. 2006).

A fourth approach, sometimes used in decision-making exercises, is to have actual or surrogate human decision-makers make decisions during each time step, or at crucial time-steps (say, during drought) (Werick et al. 1994). This can help decision-makers think through decisions in a simulated context. Although this is perhaps the most adaptable way to represent decision-making in system models, model run-times are much slower when humans must make decisions, greatly restricting the range of conditions which can be examined in this way. It is also possible, and perhaps likely, that human decision-makers would make different decisions if presented with the same conditions a second time, perhaps reducing the replicability and transparency of the modeling results. Although this approach is rarely used, and even more rarely documented, it can be useful for integrating modeling and decision-making.

Sometimes hybrid approaches are used to represent decision-making. There is no perfect representation of decision-making in system modeling.

Appendix B. Questionnaire Responses and Interviews

To help inform its review of water supply reliability estimation (see prospectus) the Delta ISB released a questionnaire to survey applications and issues with water supply reliability estimation and to develop an inventory of water supply reliability estimation efforts. The board also conducted a series of 30-minute interviews with multiple practitioners of water supply reliability estimation.

The questionnaire was released to the e-mailing lists of the California Water Environmental Modeling Forum and California Water Quality Monitoring Council on December 13, 2018, the California Water Plan eNews on December 19, 2018, and the Integrated Modeling Steering Committee on December 21, 2018, and the Delta Stewardship Council on December 31, 2018.

Responses to the questionnaire that were received through January 25, 2019, are compiled and analyzed in appendix sections, B.1 and B.2. Section B.1 is a summary of data from completed questionnaires. The section consists of two parts. Part 1 lists the organizations of the individuals who responded to the questionnaire and compiles responses to questions about applications of and issues with water supply reliability estimation. Part 2 inventories water supply reliability estimation efforts. Section B.2 presents an analysis of the responses in Section B.1. It includes discussions of potential bias in the responses to the questions caused by the small sample size.

Section B.3 summarizes responses to interviews conducted after the workshop on September 13, 2019, by Delta ISB members with a diverse variety of practitioners. Interviewees were asked the same set of questions and responses are compiled without attribution.

B.1: Data Summary

B.1.1 (Part 1): Applications and Issues with Water Supply Reliability Estimation

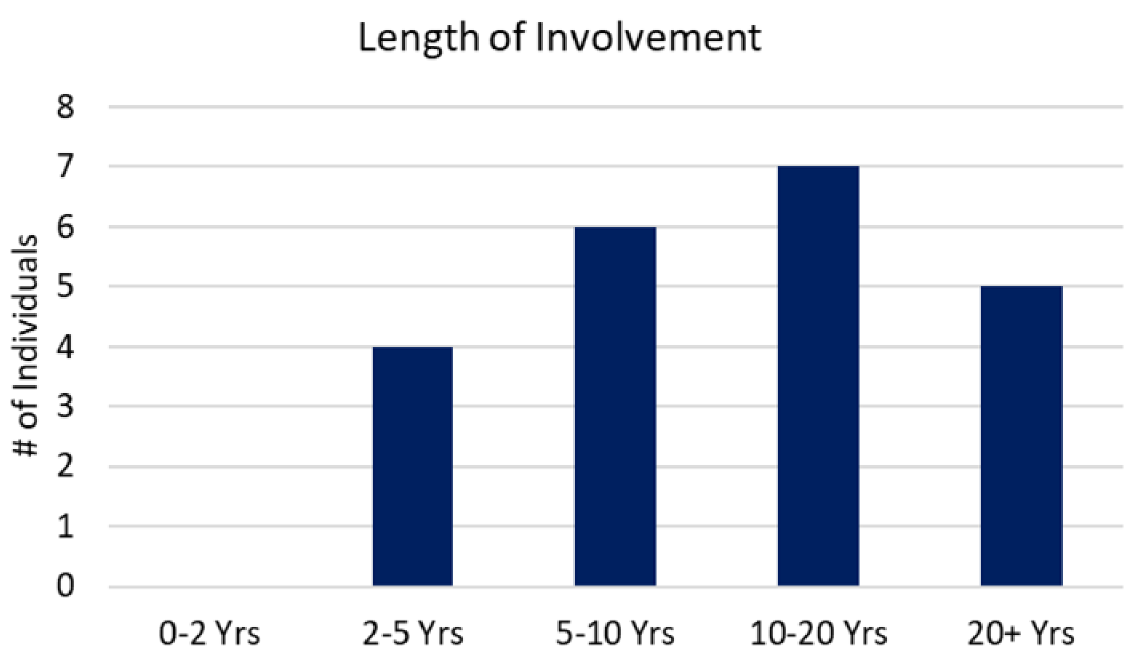
Twenty-two individuals responded to the questionnaire from a range of organizations:

- Berkeley National Laboratory
- California Department of Water Resources (DWR; N=3)
- Central Delta Water Agency
- California Water Research

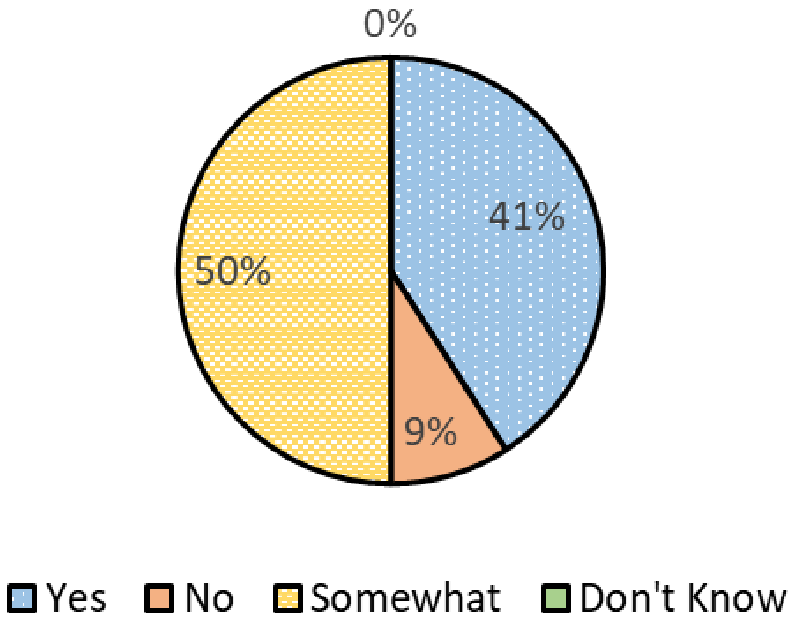
- East Bay Municipal Utility District
- GEI Consultants
- Metropolitan Water District of Southern California
- MBK Engineers
- North Delta Water Agency
- One-Water Hydrologic
- San Francisco Bay Chapter of the Sierra Club
- Santa Clara Valley Water District
- Stantec
- State Water Resources Control Board (SWRCB; N=2)
- Watercourse Engineering, Inc.
- Westlands Water District
- United States Geological Survey (USGS)
- UC Davis
- UC Merced

Individuals were not asked to respond on behalf of their organizations. The respondent's length of involvement with water supply reliability estimation is documented in the figure below.

All responses are included, and no edits were made to the responses.



1. In general, are water supply reliability estimates and studies done in a rigorous technical way (N=17)?

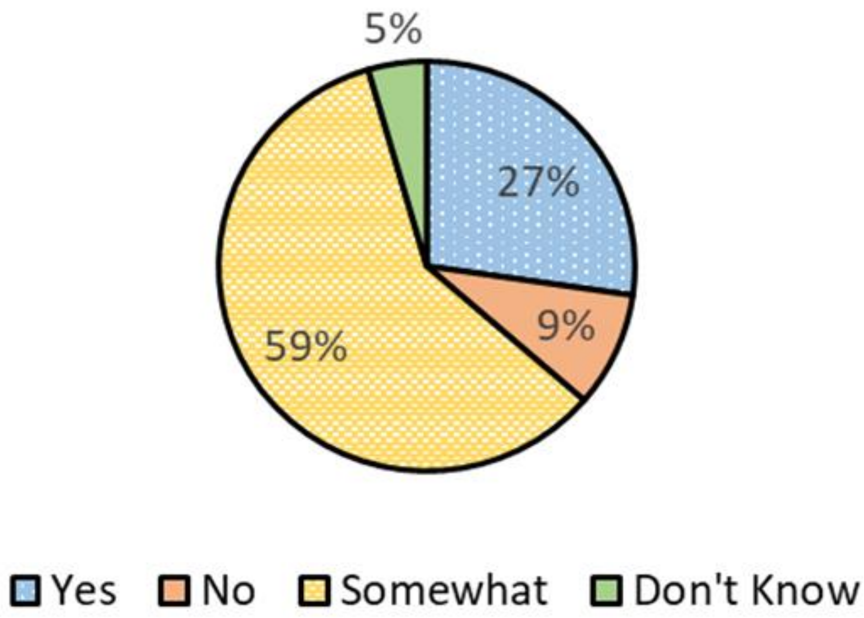


Respondent #	Response (Please Explain)	Rating
1	Reported results are useful, but often incomparable due to lack of standardization. Still, even variable results give a hint of how actual results can vary from those estimated.	Somewhat
2	Difficult to accommodate the multiple uses of water when assessing reliability. A few challenges include (a) reliability is measured/defined differently among uses (finding a common metric can be difficult) or objectives, (b) reliability can (and probably should) change with space and time, (c) there is often no common "rigorous technical" methodology or approach to estimate or study reliability.	Somewhat
3	That depends on the group that is doing and the level of funding.	Somewhat

Respondent #	Response (Please Explain)	Rating
6	There is a long history of monthly forecasts, which become more reliable as the wet season progresses. Future precipitation and snow from the time of forecast are highly variable but this becomes a smaller factor as the wet season progresses.	Yes
8	Delta consumptive use estimates could be refined by actual land use and satellite technology	Somewhat
9	We use a linear programming-based model to portray operations, supplies, and demands on a monthly timestep. We run a range of scenarios to understand uncertainty.	Yes
10	There are wide range of methods employed to estimate water supply reliability because term “reliability” can have different meanings based on the perspective of the water user. In general, these studies are very important for organizations that deliver water because if demands are not met there can be large costs incurred, the scientific basis for the Bay-Delta Plan amendments as well as the tools used to estimate water supply reliability go through peer review.	Yes
13	Subjectivity and professional judgment are required to interpret Level of Development / demand data and simulating operational decision rationales. Consistent published estimates would help (common assumptions framework, etc.)	Somewhat
15	There are uncertainties in the estimates of available water in the surface, actual water demand from agriculture and cities and environment and also water allocation decisions.	Somewhat
16	Typically, based on simulation models of water resources that explore reliability under a range if hydrologic conditions.	Somewhat

Respondent #	Response (Please Explain)	Rating
17	Fairly comprehensive integration across many different departments and divisions, intensive technical components to understand demand and project demand as well as raw water system modeling of supplies and infrastructure components with regulatory and contractual constraints. Typically includes additional sensitivity analysis of key components to understand their effect on the outcome and develop a manageable range of likely outcomes.	Yes
18	CalSim 2 provided "big picture" estimates.	Somewhat
19	These are all computer models	Yes
20	Integrating regional or statewide data into a trend analysis for the basins supplying a particular water agency is a broad-brush approach but probably suitable for a 20- 40- or 60-year planning horizon.	No
21	More detail needed as is being developed in CVHM-2	Somewhat
22	There have been some significant recent improvements in analysis of shifts in hydrology due to climate change and drought impacts. But the lack of validation of the CalSim modeling of reservoir operations remains a major issue for all reliability studies with the model. Calibration data and error estimates for the model are also unavailable. The impacts of high sea level rise due to accelerated disintegration of the polar ice sheets have also not been considered and will have major impacts on the SWP and CVP.	Somewhat

2. In general, are reliability estimates sufficiently understood, communicated to, and applied by managers and decision-makers (N=17)?

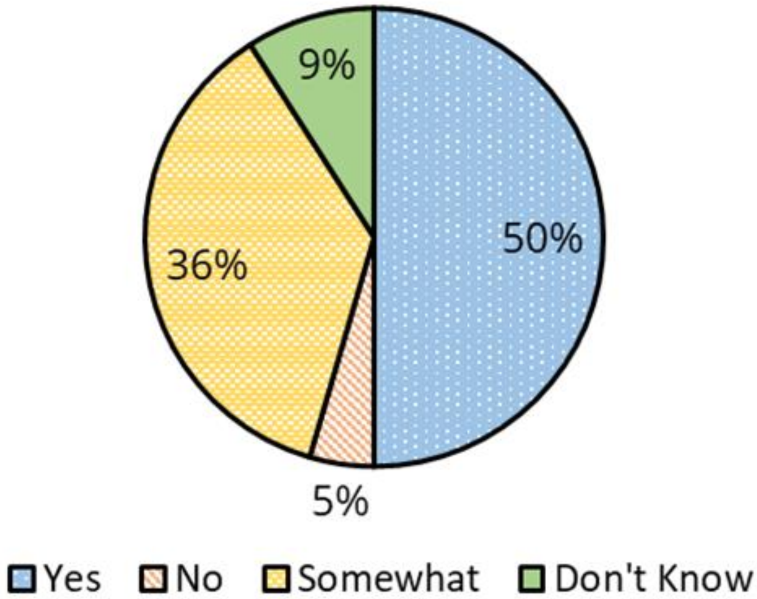


Respondent #	Response (Please Explain/How Can Communication be Improved?)	Rating
1	Reliability results are probably taken too seriously by negotiators taking their numbers too seriously. Some standardization and more interpretation might be helpful.	Somewhat
2	Same reason as above. Item (c), above would be a place to start.	Somewhat
3	More engagement with stakeholders and general public	Somewhat
5	Improved visualization as aid to understanding	Somewhat
6	Provide opportunities for forecasters and users to huddle and review how things went at the end of the season; also make sure of access of users to forecasters, via telephone and computer.	Yes
7	Requirement of Monterrey agreement that results are easily understandable. However, other groups use results beyond intention of studies.	Yes

Respondent #	Response (Please Explain/How Can Communication be Improved?)	Rating
9	It can be difficult to clearly explain study results, especially when they have interest groups making contradictory claims or a misunderstanding of the background science or data.	Somewhat
10	The term “reliability” can have different meanings to different people. I think a clear definition of the goal of “increasing water supply reliability” would be helpful.	Somewhat
11	Understanding among decision-makers varies significantly. Some decision makers with the most decision making power have the least understanding and this has led to wrong decisions.	Somewhat
13	Need to develop linguistic proficiency in reliability concepts for both analysts and decision-makers so that reliability concepts can be understood in terms of effective tradeoffs, more so than just exceedance plots.	Somewhat
14	Water supply estimates provided to the SWRCB and other State agencies are skewed to only identify impacts to SWP and CVP water users and omit/ignore the impacts to in-Delta water rights holders or other beneficial uses such as habitat projects and other environmental purposes.	No
15	Most managers would understand probabilities for water shortage yet tradeoffs associated with these shortages and system operation decisions may use some improvements.	Somewhat
16	Better communication of limitations of models	Somewhat

Respondent #	Response (Please Explain/How Can Communication be Improved?)	Rating
17	Formal planning studies are completed every 5 years as part of the update process. Estimates are revisited frequently-at least annually-and assumptions or possible portfolio changes are constantly revisited, revised, and reanalyzed. Due to close coordination between technical staff and management/decision makers, there is a good flow of communication and good understanding on both sides with respect to reliability outcomes and context of the estimates provided. The challenge sometimes is scenario management or prioritizing scenarios where there are multiple-often competing-objectives as well as working through assumptions in planning study design to avoid arriving at unrealistic or infeasible outcomes through compounded "conservative" assumptions. Sometimes dual time bases that is a feature of the fixed level-of-development approach can be a source of confusion for new managers or stakeholders not familiar with the approach.	Yes
19	I think communication can be improved by creating a clearinghouse (webpage) for estimates.	Yes
20	Water agency managers tend to follow what consultants advise and consultants and managers tend to repeat past practices to minimize change and avoid "selling" new ideas or solutions. Water agencies should be "ordered" to focus on managing demand rather than planning to increase supply by draining ever more from streams, rivers, deltas and bays. Increasing the salinity of coastal shores is also not the best solution.	No
21	Use estimates beyond those developed by DWR	Somewhat
22	Limitations of the estimates need to be clearly understood and communicated.	Somewhat

3. In general, are water supply reliability estimates and studies employed in policy and management discussions and decisions (N=17)?



Respondent #	Response (Please Explain)	Rating
1	So I hear.	Yes
2	The overall answer is yes. However, they are often incomplete because of challenges listed above. (I guess I could answer "see question 1" to all these questions...I will try to do better below).	Somewhat
6	We do provide a range of outlooks, basically median and 90 and 10 percent likely.	Yes
7	Used in Urban Water Management Plans.	Yes
9	Management and the Board of Directors listens to the results of the water supply modeling.	Yes
13	Water supply reliability has been a central metric for the SWRCB Bay-Delta Basin Plan revision SED impacts analysis.	Yes

Respondent #	Response (Please Explain)	Rating
14	Studies presented to State agencies (WaterFix EIR, CVP/SWP water rights petition, drought plans, etc) appear to only analyze water supply impacts to CVP/SWP water contractor or whether D-1641 standards are being met and modeling conducted ignores whether the the year-round and daily variations in salinity levels affect agricultural or other water users in the Delta.	No
15	It is my impression that water districts and utilities follow water management plans that indicate the procedure to follow in the event of water shortages. However, it is also my understanding that water curtailments at the state level during droughts would use some improvements.	Yes
16	Not responsible for policy-level decisions within water agencies.	Don't Know
17	Water supply reliability is one of a handful of core duties that integrate a lot of internal and external information. Conditions are always changing, such as new partnerships or new regulatory requirements that were not anticipated a few years ago and there is always interest at management and policy levels to understand how these changes affect the water supply picture. These analyses are used to inform further action, advocacy, and/or significant investments.	Yes
19	see #5	Yes

Respondent #	Response (Please Explain)	Rating
20	Typically water agencies react by planning to expand storage or sharing rights to storage of making connections to adjacent basins. This addresses short -term impacts. A more useful approach, in the face of climate change, would be to enhance local groundwater management and plan and build for recycling for non-potable and potable use. If managers really believe the population growth numbers they put in their 5-year plans, they should plan how to reduce per capita demand. This would include tiered water rates (say 10 steps, each one with a rate X% higher than the rate for the tier below), no fixed charge, develop customer expectations that rates will rise each year. As population grows, if population grows, rates will rise to keep demand in the bounds of reliable supply. Strict adherence to development limit lines will keep the value of land in the service area high. People won't be building houses that take up a lot of land for irrigated lawns. Land will be used for dense housing, efficient employment and politely shared green spaces. Tiered rates for residences might be set at a tier size of 1 CCF per month per resident. Commercial and institutional rates might be set based on a tier size of 0.35 CCF per FTE employee or student. Rates for non-potable water would be lower - for irrigation use - making shared green spaces affordable.	Somewhat
21	Need to broaden the analysis of drivers that could affect water-supply reliability such as climate change, land subsidence, saline-water intrusion of Delta, and tunnel projects.	Somewhat

4. What major technical and application problems and uncertainties do you see in water supply reliability estimation that limit their utility for management and decision-making?

Respondent #	Response
1	Non-standardized or absent documentation and reporting of model inputs; lack of explicit model testing and error analysis.
2	Technical/application: • information availability • coordination/communication • transparency • Buy-in. I mean real buy-in, where entities are not just going through the motions, but have some real commitment to the outcome and to making clear progress.
3	Lack of consistent approach, lack of open and accessible data, lack of trust in data and methods among stakeholders.
5	Increased frequency of catastrophic events creates a new "normal" and can throw off reliability estimation activities.
6	Raw input variable access, including mountain wilderness areas; data sharing between a multitude of users and forecasters.
7	Water supply reliability estimates are used for different purposes with different assumptions. Communicating those assumptions/purposes of the different applications would help in understanding the larger picture. This workshop hopefully will provide a way to do that. It doesn't necessarily mean that one method is wrong or better than another. It depends on the application. Additionally, some of the agreements or legal requirements for reliability estimates do not include Climate change or Paleo data. That data/information will provide additional uncertainties in reliability estimation. The difficulty is in how to bracket that uncertainty for near- and longer-term decisions.

Respondent #	Response
9	1. Clear and succinct communication of complex results to a diverse audience. 2. Data uncertainties due to unknowns related to climate change, population growth, environmental regulations, and future innovations. 3. Determining commonly agreed upon metrics that identify potential future water supply shortages
13	Reliability depends a lot on operational decisions and demand estimation. Further standardization of model operations decision envelope and levels of demand met (changing effects with increasing shortage) would contribute to analytical consistency (and not just decisions that suit USBR or DWR).
14	Modeling results presented to the SWRCB and other State agencies only analyze impacts to CVP/SWP water exporters and fail to analyze degradation of water quality for in-Delta water users/diversions or determine whether compliance with water rights contracts such as the NDWA 1981 Contract can be maintained under existing CVP/SWP operations or expansion of SWP with construction of WaterFix intakes and tunnels. D-1641 is only April thru August 15th and therefore is not relevant to year-round salinity criteria contained in the 1981 NDWA-DWR Contract.
15	While there are some good estimates of the potential water supply for a given month or a year, net water use in cities and agriculture is often a big unknown. This makes it difficult to properly plan and reconfigure system operations especially during droughts.
16	Climate change and population growth.

Respondent #	Response
17	I will provide a list of about six that I came up with in preparation for the workshop: (1) Climate change and non-stationarity of hydrologic distribution where the hydrology of the past is less reliable for representing hydrology of the future; (2) Regulatory uncertainty such as SWRCB curtailments that were a feature of the recent drought that are inherently unpredictable; (3) Policy "off-ramps" such as public health and safety and unanticipated yet legally valid deviations from defined policies; (4) Scenario management can become a problem with so many components to the process where the number of scenarios or alternatives can easily grow large resulting in making decisions more difficult and/or finding common ground between disparate views more of a challenge; (5) Compounded uncertainty where there can, again, be several components to the analysis where information from the different sources can be correlated or synergistic; (6) Variability in risk tolerance either because of changes in circumstance over time or as a function of changes in decision makers or agency objectives in the short or long term.
18	Not as useful for project-specific analysis. sometimes not enough detail (nodes).
19	People need to understand that CalSim and other models are used for comparative purposes to generally evaluate the differences between proposals and may not be effective for real time evaluation.
20	Supply reliability is challenged by seasonal variations (in which month will it rain?), by cyclical fluctuation based on our less than 150 year window of history, political transformation as we see the human impact on the water cycles at and below the ground level, political transformation as we react to the impact of climate change on the evaporation-transpiration-precipitation cycles over every region and every basin. The failure of political animals - Future Farmers of America, voters, politicians and scientists to think long means that we are usually working today to solve yesterday's problem, not tomorrow's. We need to make sure we are ready to do more with less - water.
21	Future changes in land use and climate change.

Respondent #	Response
22	Interannual water supply reliability is closely tied to reservoir operations. Reservoir operations are changed regularly in ways which are non-transparent, and may not be optimal for all beneficial uses. River reaches often have significant losses to groundwater in critically dry years or extended droughts, which may not be reflected in hydrologic models based on average flows.

5. What are some major technical or institutional innovations that would improve the use of water supply reliability studies in the future?

Respondent #	Response
1	Documentation expectation standards for models and applications.
2	Technical • higher resolution data (spatially and temporally) so that water use studies could directly address demand and use, both critical elements in determining reliability. • data management and visualization tools - both on the front and back end of analyses. This would allow better understanding and quality control of data (front end), as well as interpreting output and analysis results, and ease conveying approaches and results to managers and decision makers Institutional is this a trap? There are so many points here. Coordination among and within institutions is a huge challenge. Funding is likewise a constraint for institutions. There is also a tendency for institutions and institutional processes to lack flexibility, to be nimble, and to evolve - not all institutions, but these elements are common. This is kind of vanilla pudding and probably not much help. However, developing and maintaining in-house expertise is remarkably effective when and where it happens
3	High resolution data that is federated. Open source models.
5	Better estimates of groundwater contribution to annual water supply. Modeling capability has lagged surface water modeling. Integrated models needed.

Respondent #	Response
6	Funds and technical training, and ability to attend technical conferences, and opportunities for staff participation in technical discussions with researchers, sometimes out of state.
7	Hard to say. Continued improvement in data and modeling studies. Better communication. Ways to present uncertainty or ranges of estimates that are understandable to managers. Normally it is difficult to get beyond a "one answer" approach for decision makers.
8	Opportunities for reservoir reoperation in conjunction with ground water recharge methodologies can stabilize the supply/demand equation
9	1. Improved certainty of the local climate model projections for precipitation timing, precipitation volume, and temperature. 2. Improved understanding of how different types of water supply projects may help (or not help) with climate change. 3. Improved approaches for water demand modeling 4. Improved communication and/or collaboration across agencies (i.e., through institutional support and funding for Integrated Regional Water Management)
11	Common sense!!!! Also, political agendas and egos often override technical information
13	1. Standardization of demands and operations as above, 2. development of the language/vernacular of major reliability dynamics and causal relationships, and 3. further examples of "objective" basin wide analysis or a trusted entity to conduct unbiased analysis that can withstand cross-examination in evidentiary proceedings.
14	Independent modeling conducted separate from the one-sided SWP/CVP affects conducted by DWR/USBR is necessary to show the impacts to the other hundreds of smaller agricultural diversion pipes in the Delta (25 cfs and less) that pre-exist the CVP and SWP water rights.

Respondent #	Response
15	A coherent and standardized water accounting system, that identifies major elements in regional water balance, and uncertainties. In the case of agriculture, a comprehensive land use survey program would also be beneficial.
16	Accessibility of models to a broader water community.
17	Big data analysis methods such as machine learning that may be helpful in identifying important patterns in large data sets that ultimately may reduce uncertainty or improve precision of demand estimates or consumption patterns. Building in flexibility into existing or proposed/future regulations. Perhaps obvious would be improving both short term and long term forecasting to reduce water supply uncertainty inter- and intra-annually.
19	Continued refinement of CalSim and groundwater models. Needs to be better short-term modeling. Efficient dissemination of results and in a manner that does not require modeling expertise.
20	The institutional innovation needed is to recognize that raising the marginal price is the best way to reign in demand. Tier pricing can be used to make wasted water - that "unnecessary" drop - expensive, whoever you are, even while complying with the need to avoid surplus income.
21	Continued refinement of CVHM-2 such as projections in land-use changes and climate change.
22	Machine learning techniques could significantly improve mid-range forecasts of water supply. Temporal and spatial distribution of snowpack is also changing with climate change, and mid-range forecasts need to be adjusted accordingly.

6. Science needs. What are some research directions that might support improvements in water supply reliability estimates and the use of such estimates for management and decision-making?

Respondent #	Response
1	Error analysis templates regarding demand, inflow, and regulatory uncertainties.

Respondent #	Response
2	Quantitative tools of all types. This includes data (see above). Also, effective methods to quantify uncertainty in estimates AND guidance for decision makers on using those uncertainty estimates. This uncertainty quantification and guidance may be specific to projects, certain analysis approaches, etc. Include an "expiration date." Water reliability analyses have a shelf life. Develop approaches to assess performance and provide direction on when to update water supply reliability plans and analyses.
3	Quantification of managed aquifer recharge potential, supporting science to show that recharge is a beneficial use.
5	Publicly accessible monitoring networks - data updates to models in real-time.
6	New and simpler remote measuring devices or tools, possibly from space via satellites; better long range weather forecasting.
7	Improved data, data management, transparency of data. Continued development of better hydrologic, water system, and Climate modeling. Ways to manage to a range of uncertainty.
8	See response to question 5
9	1. Research on water conservation technologies and effectiveness 2. Research on how to improve community water conservation 3. Research on maximizing stormwater capture and recharge in a Mediterranean climate 4. Research on how and to what extent new water supply technologies may help with adapting to climate change 5. Research on emerging water supply technologies and an assessment of their potential for meeting future demands
13	There are glaring gaps in existing streamflow data collection networks, and for temperature. Construction of next-generation basin wide models with common-assumptions frameworks for LOD/demand and operational prioritization could help.

Respondent #	Response
14	DWR modeling on WaterFix, drought plans presented to SWRCB, and others venues only analyzes water supply impacts to CVP/SWP water contractors and ignores water supply and quality impacts to in-Delta water users. Independent modeling is necessary to provide more comprehensive impacts to other water users besides SWP/CVP water contractors. Research should also determine the amount of water that is used, excess put back into the rivers and then re-used downstream in order to get a better handle on consumptive use in watersheds. In other words, the amount of diverted is not the same as the final amount used because a portion is put back into the rivers/channels.
15	Surface water supply information has improved substantially over the past few decades, also the SGMA will improve groundwater information and planning as the state achieves sustainability. Further studies on net water use from all sectors including environmental flows would greatly improve the demand side water needs estimates which conform the other side of the reliability estimates. Standardization and transparency of some of this information would be also beneficial.
16	Agricultural water use under increased temperature and CO2 scenarios. Changes in reservoir flood control operations under climate change scenarios.
17	Continued multi-disciplinary research of climate change and improvements in scientific understanding of our climate system. Retrospective studies to show water supply effects-both intentional and unintentional-of past regulations and regulatory interactions using models. Continued research to continue developing scientific understanding to the Sacramento San-Joaquin ecosystem. Exploring possible policy tweaks to the California water rights system. More monitoring and scientific studies to advance understanding of a range of water quality effects on water systems and ecosystems.
18	fish flow modeling
19	There needs to be a shift in focus away from flow based solutions to environmental concerns.

Respondent #	Response
20	There is no improvement in weather forecasting that really matters. Better science around groundwater resources and making aquifer protection more important than oil and gas production would be useful. Learning to price a product to reduce consumption requires a psychological transformation from the goal being to lower prices to maximize sales. Water was never in the Sears Roebuck Catalog.
21	Water reuse, drains, and flood flow capture for recharge
22	Complete and accurate streamflow gage data is critical, as are fully calibrated models. Decision-making research is also needed. 1. Economic research on optimization of reservoir carryover storage rules for avoidance of direct and indirect economic loss. 2. For retail water agencies, research on optimal balancing of revenue loss from delivery curtailments vs. risk of running out of water during extended droughts.

7. Please add any other comments or suggestions you would like to make on water supply reliability estimation.

Respondent #	Response
1	Gosh, this is a messy topic. But if they could do a good job with water quality, we should be able to do something useful here too.
2	See question 1 (just joking:)). I think my reliability thinking is quite different than what this questionnaire has in mind. I am looking at (a) minimum flows in streams to ensure discharge reliability, (b) flow reliability for hydropower production under water quality constraints (regulatory), (c) minimum instream flows for a specific life stage of anadromous fish (which may include how flow and quality impact habitat), (d) water quality reliability to maintain or reduce treatment costs for drinking water. These are different than: is City A or Farmer B going to get the desired water quantity in 8 out of 10 years? That is why I think this is a challenging problem - nothing like a good challenge though!

Respondent #	Response
14	Water supply reliability in the Delta is affected not only by water quality but by changes in water elevations because most local agricultural diversions are siphons that rely on gravity and "head" dynamics that affect the volume of water that can be diverted and may necessitate installation of electrical pumps that increase GHG emissions for water supply deliveries. To avoid increased GHG emissions from installation of water pumps, the water surface elevations must not be lowered by water management decisions.
15	Have a group of experts to come up with a framework to estimate water supply reliability that is relevant over a wide range of planning stances (local, regional, statewide) and uses (agricultural, urban, environmental). As part of it develop a platform that can host this information and that can be accessible to water managers, academics, and stakeholders at various temporal scales (eg, daily, monthly, annually).
16	Better integration of surface and groundwater resources.
20	We can't really manage water supply, we can only manage water use.
21	Better estimates of land use and application of water for agriculture as well as better estimates of climate change with 6-month to one-year forecasts could help refine operational decisions.

B.1.2 (Part 2): Inventory of Water Supply Reliability Estimation Efforts

The table below is an inventory of water supply reliability estimation efforts in California. The inventory was compiled based on what was provided in the questionnaire responses with limited modifications. The order of the inventory is based on the alphabetical order of the group conducting or employing the estimation efforts. It does not correspond to respondent number in Part 1 of Section B.1. Because of the amount of information presented, the State Water Resources Control Board's inventory information is presented as a fact sheet (see end of table) and is not in the table below.

#	Group	Purpose of Underlying Estimates	Frequency Estimates are Updated	Computer Models or Modeling Groups Used	Key References	Application of Estimates	Best Use of Estimates
1	Berkeley National Laboratory	Agency contractor water supply deliveries	Annually and updated monthly	CalSim, integrated groundwater models WESTSIM, CVHM	No journal articles specifically related to water supply reliability. Reliability assessment is a secondary output of the analysis performed.	N/A	N/A
2	California Water Research	History of CVP and SWP water supply reliability, impacts of climate change and climate shifts on CVP and SWP water supply reliability, reliability of meeting Bay-Delta WQCP requirements & environmental needs, reservoir carryover target effects	As needed	Primarily CalSim	Testimony for Friends of the River / Sierra Club in WaterFix Water Right Change Petition Hearing on SWP Water Supply History & Water Supply Reliability Letter -- Changes to SWP operational criteria appear to have greatly increased risks of draining Oroville reservoir in droughts, and greatly diminished the ability of the State Water Project to meet water quality and ecosystem flow obligations in dry and critically dry years. August 2012 Recommendations to DWR Incorporating Drought Risk From Climate Change Into California Water Planning	Analyses for NGOs, Delta, and fishing groups for comments on new infrastructure and regulatory processes Recommended that DWR's Climate Change Adaptation Strategy use all available information about increased drought risk due to climate change, reevaluate prior studies on climate impacts to the State Water Project and Central Valley Project to incorporate this information, and consider strategies for reducing risk of interruption of water supplies. (Recommendations were ignored at the time.)	Better incorporation of climate change into water resources planning, better understanding of climate shift impacts on water supply, better planning to meet all beneficial use needs

#	Group	Purpose of Underlying Estimates	Frequency Estimates are Updated	Computer Models or Modeling Groups Used	Key References	Application of Estimates	Best Use of Estimates
3	DWR Bay-Delta Office	To satisfy a contractual obligation	Every 2 years	CalSim/WRIMS	Delivery Capability Report and Studies	They are used by our contractors to provide estimated supply for planning purposes	Planning
4	DWR Division of Flood Management	Estimate how much water can be delivered yearly for some historic period of record. Historic dry periods provide an important measure of supply dependability. Also, annually forecast during the wet season the expected natural runoff of major rivers in the Snow Surveys program, with the better forecasting beginning February 1.	Yearly at about the halfway point in the wet season; monthly and weekly, continuing into early summer.	Various models; the workhorse is regression models based on precipitation, snow. last year's runoff and current year runoff to date. The challenge is to obtain an accurate measure and evaluation of parameters for the watershed.	Bulletin 120 and weekly updates during the season	They provide guidance for reservoir and water agency managers and operators, and in some cases, criteria for project and in-stream requirements.	Water and power project operations and setting criteria for instream and Delta environmental needs

#	Group	Purpose of Underlying Estimates	Frequency Estimates are Updated	Computer Models or Modeling Groups Used	Key References	Application of Estimates	Best Use of Estimates
5	GEI Consultants	Estimate benefits for water infrastructure projects that our clients design and build. Support grant funding benefit determination and operations analysis.	Annually	CalSim 2	Willow Springs and Chino Basin Prop 1 Grants	Determination of project benefits and avoidance of potential impacts. Support water transfer agreements.	Supporting grant proposals. Showing public benefit.
6	MBK Engineers	There are numerous purposes. Agricultural, M&I, ecosystem, hydropower, groundwater sustainability, recreation, and more.	Estimates are made for every operating season for all purposes. Long-term planning estimates are made whenever key operating/regulation criteria changes (this seems to happen on a continual basis) for all purposes.	Customized models are used for all proposes. Industry standard models are also used, CalSim is often used. When CalSim is used other models and analysis are ALWAYS used to check/verify results. Historical operations data are used to support all reliability analysis.	None provided	Supply estimates are used in multiple ways. • Determining crop acreage each year • Estimating water transfer volumes (buying and selling) • Temperature compliance estimates • Reservoir operation strategies • Conjunctive management strategies • Water right curtailment forecasting Flood forecasting and management Many others	See "Applications of Best Estimates"

#	Group	Purpose of Underlying Estimates	Frequency Estimates are Updated	Computer Models or Modeling Groups Used	Key References	Application of Estimates	Best Use of Estimates
7	MWD Water Surplus and Drought Management Planning	Provides intra-year support for short-term seasonal water operations and water management decision making.	Estimates are produced weekly or more frequently during the winter and spring runoff season.	The short-term decision-making process is supported by a number of analytical tools: • SWP Runoff Model – Regression model that estimates current water-year runoff for the Northern Sierra watersheds. • System Router Model – Spreadsheet model that evaluates impacts of potential water operations on Metropolitan's distribution system. • Resource Simulation Model – Indexed-sequential mass-balance model that simulates annual water supply and demand, resource and storage operation and produces estimates of surplus and shortage.	1998 WSDM Plan (upon request) Metropolitan 2015 UWMP Chapter 2.4	Shorter term water supply availability (including conveyance and distribution constraints, water quality issues) are compared to water demand projections to determine resource operation plans and storage use.	Establishing preferred water resource management strategies to be carried out over the course of a year.
8	MWD Drought Contingency Planning	Provides inter-year support for water management decision making and indicates water resource, demand management and program development needs.	Estimates are produced annually or more frequently during actual drought events.	The Drought Contingency Planning Process is supported by analytical tools used for both Water Surplus and Drought Management Planning and Long-term Water Supply Reliability Planning.	Metropolitan 2015 UWMP Chapter 2.4 Ongoing SWRCB reporting	Water supply availability estimates for single and extended-year drought conditions (including conveyance and distribution constraints) are compared to water demand projections over periods of extended drought to determine resource development needs and to inform resource operation strategies and storage use.	Developing drought contingency plans and water resource and operational strategies for use during deep or extended drought.

#	Group	Purpose of Underlying Estimates	Frequency Estimates are Updated	Computer Models or Modeling Groups Used	Key References	Application of Estimates	Best Use of Estimates
9	MWD Emergency Planning	Provides planning for dedicated water supply and system resiliency under emergency/ seismic events	System reliability and storage needs are reevaluated every few years or with planned new facilities	The Emergency Planning Process is supported by analytical tools used for both Water Surplus and Drought Management Planning and Long-term Water Supply Reliability Planning.	Seismic Resilience Report Metropolitan 2015 UWMP Chapter 2.5	Estimates of water supplies limited by emergency/seismic planning scenarios are compared to water demand projections to determine the duration and extent of potential water shortages and the need for dedicated emergency storage	Establishing dedicated emergency storage requirements. Determining resiliency and recovery plans for distribution system and facilities
10	MWD Robust Decision Making	Applies a wide range of additional uncertainty to test long-term water supply reliability strategies.	The impacts of additional uncertainties are evaluated every 5 years following the IRP Update/UWMP process	Robust Decision Making utilizes Long-term Water Supply Reliability Planning analytical tools and a process and tools developed by RAND that integrates and runs long-term planning models, creates a database of scenario results, and applies a statistical algorithm to identify vulnerabilities within scenario results.	Groves et al. (2014) Lempert et al. (2011)	Water supply estimates under a wide range of uncertainties (climate change, development risk, losses in yields) are compared to ranges of water demand projections under similar or additional uncertainties to develop estimates of vulnerability and risk.	Determine areas of uncertainty that pose the largest risk and vulnerability to long-term water supply reliability.

#	Group	Purpose of Underlying Estimates	Frequency Estimates are Updated	Computer Models or Modeling Groups Used	Key References	Application of Estimates	Best Use of Estimates
11	MWD Long-term Water Supply Reliability Planning	Provides forecasts of water supplies and demands to support long-term planning processes and guide water resource, demand management and program development needs.	Individual model assumptions and input data are updated as available. Reliability estimates are produced to inform water resource management decisions as needed, and every 5 years for the Integrated Water Resource Plan (IRP) Update/ UWMP development process.	Long-term planning processes are supported by a number of analytical tools: • Conservation Savings Model – Spreadsheet model that produces annual estimates of future savings from active (conservation incentives) and code-based (plumbing/landscape codes) conservation. • Local Supply Forecast – Regression model that produces annual estimates of supplies from groundwater recovery, recycling, and sea water desalination produced Metropolitan's member agencies. Local groundwater and Los Angeles Aqueduct supply forecasts are produced through a survey of Metropolitan's member agencies and groundwater basin managers. • Retail Demand Model – Econometric model that produces estimates of future demands for Metropolitan's service area and price-based conservation. • Sales Model – Indexed sequential mass-balance model that produces estimates of demand for Metropolitan supplies, applies a range of hydrologic impacts to retail demand estimates, and provides a forecast of service area distribution of demands. Resource Simulation Model – Indexed-sequential mass-balance model that simulates annual water supply and demand, resource and storage operation and produces estimates of surplus and shortage.	IRPSIM Reference Manual (upon request) 2015 IRP Update Technical Appendices: • Appendix 7: Methodology for Generating MWDSC Water Demand Forecasts • Appendix 8: Demand Forecasting • Appendix 9: Metropolitan Conservation Savings Model • Appendix 10: Imported Supply Forecasts • Appendix 11: IRPSIM (upon request)	Ranges of water supply estimates under varying hydrologic and climatic conditions are compared to ranges of water demand projections to determine the need for water resource, demand management and program development.	Determining preferred water resource, demand management and program development strategies to guide long-term regional investments.

#	Group	Purpose of Underlying Estimates	Frequency Estimates are Updated	Computer Models or Modeling Groups Used	Key References	Application of Estimates	Best Use of Estimates
12	One-Water Hydrologic	Helped develop CVHM model at USGS	Annually	CVHM-1 and CVHM-2	USGS professional paper on Central Valley	Used for Valley-wide analysis	Climate change analysis, subsidence analysis, agricultural water-supply analysis
13	North Delta Water Agency (NDWA)	The NDWA does not delivery water, but monitors DWR's compliance with water quality standards specified in the NDWA-DWR 1981 Contract. Therefore, we do not collect or maintain any records on estimates or water delivery records relates to water supply reliability.	NDWA engineer monitors water quality at seven monitoring stations specified in the NDWA 1981 Contract, but we do not collect or maintain any data on the amount of water diverted or used by individual water users within the Agency's jurisdiction.	No response	No response	No response	No response

#	Group	Purpose of Underlying Estimates	Frequency Estimates are Updated	Computer Models or Modeling Groups Used	Key References	Application of Estimates	Best Use of Estimates
14	Westlands Water District (WWD)	To provide information to customers/growers for their crop planning, to assess shortages and how to fill them, to assess capital projects, to set water rates and land assessments.	Annually and whenever there is a proposed regulatory change or capital project under consideration.	WWD relies on CalSim modeling for comparative analyses of those items listed in question 2. It also relies on shorter term operational projections from Reclamation and DWR for those items listed in question 1.	WWD has relied on data provided in the EIS on Long Term Operations of the CVP and SWP and on Reclamation's operational forecasts when posted	The supply estimates are used by the WWD management and Board to make decisions about projects and water transfers to pursue and how to set rates. The estimates are also used to inform WWD growers so that they can make cropping decisions. Most recently, they have been used to evaluate changes under the COA addendum and we anticipate referring to them when the LTO re-consultation is complete. WWD also uses them to develop a computer model for its groundwater basin.	All of the above.
15	San Francisco Bay Chapter Sierra Club	Understanding appropriate water agency adjustments for cyclical and non-cyclical water supply change.	Review of statewide and regional data collected by others.	Simple charting of data to visualize trends.	Western Region Climate Center Tracker	Encouraging water agencies to shift from fixed charges and shallow tiered water pricing wholly to adjustable, more-steeply tiered water pricing for all customer classes.	Long-term thinking.

#	Group	Purpose of Underlying Estimates	Frequency Estimates are Updated	Computer Models or Modeling Groups Used	Key References	Application of Estimates	Best Use of Estimates
16	Santa Clara Valley Water District	The purpose of the water supply reliability estimates that the Santa Clara Valley Water District (District) conducts is to ensure a reliable water supply in the future. The water reliability estimates are used to help plan for investments in new infrastructure and the maintenance of existing infrastructure. The estimates also inform the level of service the District aims to meet through investments and the risk of water supply shortages during droughts.	The water supply estimates for the purposes explained above are made every 3-5 years. However, demands and supplies are tracked throughout each year to ensure our operations allow us to meet water supply demands.	The District uses the Water Evaluation and Planning (WEAP) software, the Department of Water Resources CalSim II modeling, the Alliance for Water Efficiency Conservation Tracking Tool, and numerical models in excel.	The Water Supply and Infrastructure Master Plan Urban Water Management Plan General Link	The District applies water supply estimates to determine when, what type, and how many future investments will be necessary to meet demands through the mid-century. The District also uses water supply estimates to determine the range of potential impacts related to the uncertainty in future supplies owing to climate change and changing environmental regulations.	The two best uses are: 1. To determine how future uncertainties in supplies (e.g., climate change, changing regulations) may impact the District's ability to meet future demands. 2. To determine investment approaches for meeting future demands.

#	Group	Purpose of Underlying Estimates	Frequency Estimates are Updated	Computer Models or Modeling Groups Used	Key References	Application of Estimates	Best Use of Estimates
18	UC Merced	In my group and through collaboration with other academics, water professionals and agency staff, I conduct research on water supply for agriculture, cities and the environment. A good portion of my research is devoted to economic analysis of water supply for these main users, to estimate water shortage and water supply operating costs.	I do not conduct these water supply reliability analyses or research on a routine basis. Rather I employ existing hydrologic models to economically assess costs and benefits of specific policies or water supply conditions such as droughts, or environmental flow regulations.	I often use the CALVIN model, the SWAP model for agricultural production and other regional models publicly available.	UC Davis CALVIN Website UC Davis SWAP Website UC Davis Drought Impacts Website UC Davis Integrated Modeling Website	Studies I have participated in provide some insights for water management and planning. As such, these are not directly employed in day-to-day operations but are rather used for long term system management. In particular, these provide a quantification of potential shortages and costs of systemwide decisions.	Long term planning, identification of promising water infrastructure, and trade among users.
17	UC Davis	Policy and public insights, theoretical and methodological insights, graduate and undergraduate education.	Sometimes several times a year, depending on the number of graduate student theses and projects needing such analyses. Sometimes less often.	CALVIN, Excel, sometimes post-processing of CALSim or other results	UC Davis CALVIN Website Far too many to read	Graduate theses, academic journal papers, PPIC reports to enliven policy discussions	Enlivening policy discussions and graduate and undergraduate education.

#	Group	Purpose of Underlying Estimates	Frequency Estimates are Updated	Computer Models or Modeling Groups Used	Key References	Application of Estimates	Best Use of Estimates
19	USGS California Water Science Center	Groundwater overdraft, climate variability and change	Current projects evaluate both at monthly scale and another project is forecasting to 2100	GSFLOW, MODFLOW-OWHM, HSPF, PRMS	Total Management Website Plan of Study: Salina and Carmerl Rivers Basin Hanson et al. (2010) Hanson et al. (2014)	Used in decision making	Water supply reliability forecasting

State Water Resources Control Board

Division of Water Rights

Purpose Underlying Estimates

The State Water Resources Control Board and 9 Regional Water Quality Control Boards (Water Boards) are tasked with protecting the quality of California's water resources and drinking water for the protection of the environment, public health, and all beneficial uses, including public trust uses. The Water Boards are also tasked with administering the State's water rights system. In doing this work, the Water Boards employ water supply reliability estimates when: developing and implementing regulatory requirements related to flows, including in flow dependent water quality control plans like the Bay-Delta Plan and associated environmental analyses; in determining water availability for new water rights; in determining when water is not available for diversion during times of shortage; and in the regulation of drinking water systems.

Water supply reliability estimates are specifically used by Water Boards staff in updating the Bay-Delta Plan to understand the range of potential effects from changes in flows and flow dependent water quality requirements. The Water Board considers the benefits of proposed regulations and the water supply costs when it makes decisions regarding the reasonable protection of all beneficial uses.

When making decisions about whether to grant new water rights, the Water Boards also consider water supply reliability in determining whether to grant new water rights, the season of diversion, and other conditions. During times of water scarcity, the Water Board must also determine when water is not available for water users based on their water right priority. While these analyses do not incorporate water supply reliability explicitly, they do incorporate the same information; water supply estimates and demand estimates.

Water supply reliability is generally defined as the fraction of time that a specified level of demand can be met. Water supply reliability depends on available supply, demand, and reservoir management choices that are based on the risks and rewards of short-term and future use. Typically, water users make decisions based on these factors in how to allocate water use to meet demands. In planning scenarios, Water Board staff are tasked to develop sufficiently accurate representations of baseline water use patterns and operational decisions in order to evaluate likely changes in reliability for certain policy alternatives. This reliability manifests in fractions of baseline water demand that can be met for municipal, agricultural, and fish and wildlife beneficial uses, and subsequent potential economic and environmental impacts.

Reservoirs improve reliability for consumptive uses by storing natural supply that exceeds demand for use later in the season or in future years. Reservoir operators balance the need to release water from the reservoir to fulfill seasonal water demand with the need to retain water in the reservoir to be available for future demand, considering the uncertainty of future inflows and the risk of drought. Multiple, successive dry years present difficult choices between releasing reservoir water to meet a portion of immediate demand or storing reservoir water for a future year with the risk of additional shortage. The Water Board's authority primarily affects users' available supply through conditions on the exercise of water rights, while reservoir operational decisions and demand management are typically controlled by water users.

Water supply reliability is also a consideration in the regulation of drinking water systems, including decisions about regulatory requirements that are needed to protect public health and ensure the efficient use of water resources.

Frequency Estimates are Updated

Time periods for the above water supply estimates vary based on the circumstances. For the Bay-Delta Plan they coincide with the planning cycles which can be from 3 to 10 years. For water right applications they occur once per application. During times of drought, for short term planning and enforcement purposes, water supply estimates are employed monthly or more frequently.

Computer Models or Modeling Groups Used

In Bay-Delta planning, the Water Supply Effects (WSE) model (based on the CalSim II water balance framework) was used for the San Joaquin update of the Bay-Delta Plan, and the Sacramento Water Allocation Model (SacWAM), an application of the WEAP model (see below), is being used for the Sacramento/Delta update of the Bay-Delta Plan. For water supply shortage analyses spreadsheet models have been employed.

Key References

- Lower San Joaquin River and Southern Delta Update of the Bay-Delta Basin Plan: 2018 Amendments and Substitute Environmental Document (See Chapters 4 & 5 for general hydrologic overview; Appendix F.1 and Master Response 3.2 for documentation and details of modeling approach and responses to frequent comments)
- Sacramento/Delta Update of the Bay-Delta Plan: Framework Document (See section 3.3): SacWAM Website
- State Water Board: Drought Year Watershed Analysis
- Drought Water Right Curtailment and Analysis Tool (DWRAT)

Application of Estimates

They are applied in regulatory and planning processes as discussed above. Historically, the State Water Resources Control Board has relied on other organizations such as USGS, NOAA and DWR to produce real-time and historical water supply estimates. These estimates of streamflow forecasts (e.g. DWR Bulletin 120 and Water Supply Indices) and unimpaired flow (DWR 2016) are used to inform instream flow requirements and water quality objectives.

Best Use of Estimates

The uses of water supply reliability estimates depend upon the context in which they are being applied. They can be used for planning or regulatory purposes. For planning purposes, they are best used in a comparative sense. (e.g., WSE and SacWAM).

B.2: Analysis of Responses

This section analyzes the 22 responses to the questionnaire that were completed in conjunction with the January 10, 2019, Delta ISB Workshop on Water Supply Reliability Estimation. Respondents from State and Federal agencies, local agencies, and consulting organizations dominated the responses with six in each of the three categories. Only four individuals, two each, respectively, responded from academic and nongovernmental institutions. The respondents were an experienced cadre, with 12 of the 22 having 10 or more years involvement in the field. The names of the organizations represented by the respondents are listed in Section B.1. The analysis here compiles and identifies general trends.

Because of the small sample size and professional diversity of responders, potential bias in the response are evaluated particularly for the first three questions. The reader is referred to Appendix B.1 for individual comments numbered in order of their submittal. The Appendix does not identify responders, but their identity was used for the analysis of potential bias in Section B.2.

Question 1: *In general, are water-supply reliability studies done in a rigorous technical way?*

Seventeen of the 22 respondents answered this question. The bottom line is that 59% of the respondents did not answer yes with most (50%) of the respondents answering somewhat. *Evaluation of potential bias:* Of the 17 respondents, five were consultants and six represented government agencies. Four of the five consultants and three of the six government employees answered somewhat or no, which is probably not a significant difference. Thus, the 59% based on all 17 respondents seems to reflect the opinions of engineers on the front line.

Written responses: The negative tone of the overall response is reflected in the comments. Absence of standards, need for competence and judgement in model operation, and inadequate estimates of uncertainty were the most common comments.

Question 2: *In general, are reliability estimates sufficiently understood, communicated to, and applied by managers and decisionmakers?*

Seventeen of the 22 respondents answered this question, but the 17 respondents did not completely overlap with those answering question 1. The bottom line is that 73% of the respondents did not answer yes. *Evaluation of potential bias:* Of the 17 respondents, five were consultants and eight represented government agencies. All five consultants and four of the eight government employees answered somewhat or no. Thus, the 73% overall response roughly reflects the opinions of engineers on the front line although there may be a difference of opinion between consultants and employees of government agencies, with the consultants being more skeptical.

Written Responses: Lack of understanding and the communication challenge were overwhelmingly cited as the basis for the negative tone of the overall response. Standardization and decreased bias were proposed as partial solutions.

__Question 3:__ In general, are water supply reliability estimates and studies employed in policy and management discussions and decisions?

Seventeen of the 22 respondents answered this question, but as noted previously, the respondents do not completely overlap with respondents in questions 1 and 2. <u>The bottom line is that 50% of the respondents answered yes with an additional 36% answering somewhat.</u> This yields 86% with a positive response. Only 5% answered no. *Evaluation of potential bias:* Of the 17 respondents, only three were consultants and seven represented government agencies. Two of the three consultants answered somewhat with third not expressing an opinion. Six of the seven responders from government agencies answered yes. Thus, the 86% overall response roughly reflects the opinions of consultants and engineers on the front line.

Written Responses: Despite the positive tone of the responses, there seemed to be some detachment from technical findings and the application or decision-making process; both parties are not in the room together.

__Question 4:__ What major technical and application problems and uncertainties do you see in water supply reliability estimation that limit their utility for management and decision-making?

Climate change was the most cited limitation by the 17 respondents, being referenced seven times. Standardization and transparency were also cited, but less frequently. There were a few references to uncertainty and they included both input data and regulatory uncertainty. A potential bias caused by sampling was not evaluated because individual respondents commonly identified multiple limiting factors. Thirteen of the respondents were either consultants or employees of government agencies.

__Question 5:__ What are some major technical or institutional innovations that would improve the use of water supply reliability studies in the future?

This question produced a variety of suggestions by 18 respondents. Innovations mentioned by multiple respondents included:

- Standards
- Inclusion of groundwater
- Improved models with more transparency, and
- Acquisition of hi-resolution data.

__Question 6:__ Science needs. What are some research directions that might support improvements in water supply reliability estimate and use of such estimates for management and decision-making?

A variety of scientific research directions were proposed by the 18 respondents. Data was the only theme that stood out, being mentioned by five respondents. It included a range of aspects including improved data collection, management and transparency, and uncertainty analyses. Other directions mentioned two or more times included:

- How to incorporate groundwater resources in models
- Water conservation
- Better estimates of uncertainty, and
- Accounting for climate change.

__Question 7:__ Other comments or suggestions on water supply reliability estimation.

Only seven respondents contributed to this section. Two of the respondents commented on the wide range of application of models for water supply reliability estimation and one of these recommended that experts provide a framework that is applicable at all scales. Better management of water use (conservation), documentation of land use, prediction of climate change, and inclusion of water quality were all referenced.

Inventory of water supply reliability estimation efforts

Nineteen respondents completed the inventory of purpose, frequency of estimates, and application of water supply reliability estimates. Only the purpose of the estimation effort and frequency are compiled here.

The predominant (11 respondents) purpose of most efforts is to support planning or policy development. Only three respondents mentioned that they were used directly for delivery decisions.

The frequency of updates is dominated (11 respondents) by annual or longer (typically five years) time periods. Three respondents indicated updates were performed monthly or weekly.

B.3: Interview Responses

As part of its information gathering process for this review, Delta ISB members conducted interviews with a broad spectrum of scientists and engineers engaged in water supply reliability estimation. This section summarizes comments and observations gleaned from those interviews. The comments and observations are not verbatim, but have been edited for clarity and terseness.

B.3.1: Interviewee Selection Criteria

Participants who were invited for 30-minute-long interviews were selected to reflect a variety of perspectives based on their experience with water supply reliability estimation and their employer. General categories of interviewees included State and federal regulators, regional and state water agencies, and consultants. Interviewees were informed that they would be identified as participants in the interview process, but that specific comments would not be attributed.

B.3.2: Interviewees and Affiliations (Alphabetical Order):

Ben Bray, Ph.D., East Bay Municipal Utility District
Andy Draper, Ph.D., Stantec Consulting
Tina Leahy, State Water Resources Control Board
Scott Ligare, State Water Resources Control Board
Jennifer Nevills, Metropolitan Water District of Southern California
Nancy Parker, U.S. Bureau of Reclamation
Nicky Sandhu, Ph.D., Department of Water Resources
Robert Tull, Jacobs Engineering
Julie Zimmerman, Ph.D., The Nature Conservancy

B.3.3: Questions and Responses

All interviewees were asked the same questions during the course of their interviews. The following interview comments are paraphrased from automated transcripts and notes of interviewers. They are not sorted in alphabetical order by author.

***Question 1**. How do you use water supply reliability estimation?*

Used on a 15-year cycle to plan and manage utility water supply and to fulfill state mandated water management plans on an approximately 5-year cycle.

We use water resource reliability estimation for all sorts of resource simulation modeling, data management, and demand forecasting. It also is used to develop the state's mandated water management plan.

Large scale system models for the Delta, the Central Valley, and Southern California. These have looked at reservoir operations, stream flows, deliveries, and groundwater pumping. We look at scenarios under different regulatory conditions. There might be new facilities or re operation of existing facilities. There might be climate change scenarios. There might be scenarios based on future land use and population.

***Question 2**. What are your major concerns with water supply reliability estimates? What shortcomings to water supply reliability estimates limit or affect their use by managers and decision-makers? How much of the problem is communication/ understanding and how much is model deficiency? How can these concerns be addressed?*

The more robust the methodology, the more challenging it is to communicate implications to decision makers. A limited number of scenarios that are risk based can be educational.

In California, annual variability is a major challenge. Droughts are stress tests for both plans and the water supply system itself.

The questions that come from the water policy makers are usually straightforward and simple. They want a number on which to base a decision. The big question is how do you communicate that? When we do that, there are a lot of assumptions that we make and a lot of things that we kind of gloss over. That is fine until the point comes where they actually apply that in some way that doesn't, doesn't match up to the assumptions we made.

It's not an integrative and integrated look at the whole system, but we do have counseling which is another part of our branch.

Upstream effects are in both the hydrology and institutional policies, regulatory policies, and environmental flows.

We tend to look at things in isolation and we tend to focus on the things that we understand and have data for. We really analyze those in great detail and tend to either ignore or dismiss the things that we really can't get our hands around because we don't have the ability to analyze.

The major concern is defining long-term reliability. We do a really good job at is looking at metropolitan supplies versus demands and the range of future conditions and defining future reliability under those of conditions. The limitations have more to do with the inputs including supply estimates from other agencies and for other water sources. Just maintaining existing supplies can be challenging, e.g., groundwater estimates have gone down.

Just to keep maintaining existing supplies and then to keep building new supplies on top is very challenging. In addition, water quality concerns and regulation changes can knock out entire supplies very abruptly. So that's a lot of effort for us is to assess risk in local supplies. We've also learned a lot about the transfer market (or the lack of a transfer market) that was a big piece of our portfolio.

It's really just kind of repeated exposure to get our management and board comfortable. They need to repeatedly see outputs and the tools. They used to be really uncomfortable with exceedance curves, but we showed them enough times that they got comfortable with them.

Environmental water supply reliability is not adequately represented in analyses and policy discussions.

My major concern with water supply reliability estimates in the broad context of my long career doing nothing but river system modeling is that there's this ever increasing conflict over water supply in California. And that is coupled with an ever broadening range of stakeholder interest. There are more people that are more concerned about water supply reliability. From my perspective as a modeler, I see that there's intense scrutiny of model results and what seems to be more and more required is an intense need for personalized results of modeling.

From the modelers point of view, I believe that we work pretty diligently on ongoing updates and upgrades. The solutions to a lot of these needs are not fundamentally technically difficult. In California where I do most of my work these days, it's the size of the system and how complex it is that makes implementing solutions slow. Modeling hydrology to represent one small corner of a watershed is not a daunting task, but doing it at a scale that responds to the very picky specific question that every single person who's concerned about what is playing in California has over the entire state is a very big problem. My fundamental response to all this is we just need more people.

There is a dearth of skilled modelers. It's also a double edge sword. Not many of us (modelers) right now are taking the time to train people. This is a really big problem. People move around and nobody stays and does the same thing for more than five years anymore. The mobility challenge exists around the country. We're a lot more mobile as a society. It's not a unique problem to California or water resources in general by any stretch, but we need to either just keep training more people so that out of the hundred people that you train, maybe five actually stick around for the long term.

The other part of the question, how much of the problem is communication and how much is model deficiency, is really interesting. My answer is kind of the same as to the technical side of things. Understanding is a huge problem. Stakeholders sometimes propose solutions that are infeasible because they either don't understand how complicated the system is or they don't understand or don't trust the models that produced results that they don't agree with or they don't like. If people just understood the system and modeling better, then maybe that would alleviate some problems with communication. Addressing this means more time and more people to do outreach and really reach into all of the communities of interest and stakeholder concern. We've talked about for years having monthly counseling appreciation days, where information about the model is pitched to perhaps a nontechnical audience or an environmental audience or something like that. It would be great, but again, there is only so much time. It's another area where having additional people would, would really help.

What are my major concerns about supply reliability? One of the difficult things is to actually express reliability. How do you take the results of a model and turn it into a number or several numbers to communicate in a report to managers? Impact assessment? Typically our models produce monthly water supply estimates over a range of water supply conditions or hydrologic conditions. Hydrologic conditions might be based on a cold start, or they might be based on historical conditions transformed to take into effect climate change. My main concern is how we quantify our model results, what should they be measured against? How do you take results and express them in a way that is meaningful to water managers? We need to think about how water agencies and irrigation districts react in the face of supply reductions during dry conditions rather than thinking of them staying at a fixed level.

When most people think about water supply reliability estimation, they tend to think of it as really focused on water supply for agriculture and for general human use. That gets to what I think is missing, which is really a broader definition and understanding of the concept of the ecosystem. When most people talk about water supply reliability, they're really thinking about one particular piece. And I think that we need to think more collectively about all uses for water.

We need to develop flow criteria for all streams and rivers in California based on the concept of functional flows. Try to come up with a way to define what's needed for nature, either to be broadly ecologically protective or defining first cut recommendations for specific management objectives, either ecological or to meet specific needs for species. That part hasn't been adequately incorporated into the water rely water reliability estimation. A lot of modeling just incorporates the regulatory requirements for the environmental policy and they're treated as constraints. Everything else is designed to meet contracts and supply. It's really difficult in any process to have flexibility for ecosystem purposes.

Water supply reliability estimates are typically single sided. They focus on human needs. We need a paradigm shifts so that we're thinking about it more holistically. Regulatory constraints are a big part of it. We need to manage for an idea of ecological sustainability rather than avoiding jeopardy. And I think that's something that's really gotten us into, into problems in the past. When we model human needs, they tend to be synonymous with, with contracted amounts of water. There's no analysis of tradeoffs of different uses.

There's very little discussion of using conserved water for other purposes. We currently have a hardened demand for water. This pops up in negotiations all of the time including voluntary agreement discussions and collaborative discussions about water management. There's this idea that there's a defined amount of water that's needed for human use and that can't be changed or shouldn't be changed.

We need to take a step back to really look at what the tradeoffs should be. Another issue with current estimates is that we don't know how much water is needed to support ecological function.

The demand side is a really big piece that is often left out of the discussions because it's politically a difficult one to discuss.

My main concern is that models seem to sometimes or frequently overestimate reliability. What happens then is that in times of shortage, the environment is often the user that gets shorted. I think that way suppliers get away from better long term planning and being explicit about assumptions. It's both a communication and understanding problem. Sometimes it's model deficiency. An example is water temperature planning during the drought.

In the grand scheme of things, e.g., a statewide water project like CVP operations, it is more assumptions that go into a model before we enter drought, i.e., water that was allocated before the drought. It is a lack of carry over storage and long term planning for such a scenario. It's kind of a combination of all of those things. How can the concerns be addressed? It's a tough one because of the scale at which many of these decisions are made. It gets political and in a lot of these cases, there's a lot of short term gain that is weighed over long term planning.

There's a lot of pressure from contractors if they see declining reservoirs to increase their allocations. And you know where those pleas go, all the way up to the upper echelon of government. Then the pressure comes back down to increase the allocations where we really need to be thinking on a much longer scale than. Contractors are just thinking one year where long term planning is what really needs to happen. It's difficult to identify the best way to get there. One way to do it would be to impose additional regulations and requirements within water rights that require certain carryover storage levels for major droughts because it doesn't seem like in the past they have been able to do it properly.

Different groups have different models doing their own analysis separately, which can be useful by highlighting the range of, of results that can come out of these models. It illustrates how we should not rely on one number coming out of these models. Maybe that's the value we should expect from this modeling. There are reductions here and there's an increase here and this is the approximate range, these increases and decreases. We've been focused on the number. Instead, we need to be focused on what does this number mean and does this number make sense?

Having a common model might be a benefit, particularly if it is transparent and usable for most applications. I don't think that we have that yet.

__Question 3.__ Are you comfortable using water supply reliability estimates to develop portfolios that include surface water, groundwater, reuse, and demand management? How could these studies be improved?

Our approach is like that in the financial world, not to have all of our eggs in one basket. A portfolio, however, can be challenging to develop because components of a water supply involve more than traditional water supply sources. For example, conservation and recycled water are now important. Incorporating elasticity of water demand in planning for demand management also can be beneficial and needs to be included.

Modelers do what is asked of them, but they usually try to improve integration of various models as well as seek improvements in specific models and data.

There has to be some willingness on all sides to take a little bit of risk in terms of operating things to try to provide a, a greater overall benefit even though it may provide some are risk and need some assurances to any particular entity that is participating in. By drawing hard lines in terms of silos, it makes it much more difficult to do that. In the projects that we are doing, everybody talks about multi-benefit projects and how wonderful they are, but they're actually hard to implement. How can we release the water or leave the water in the river to provide flow benefits to habitat?

Groundwater is always a challenge. The capabilities are getting better. If we ever see a CalSim3 with better integrated surface water and groundwater modelling, I think that would be a benefit versus what we're doing now. There could be improvement in terms of understanding the constraints that are associated with the complex relationships between North and South and different agencies relative to groundwater banking, how you move water around and the frequency of being able to move that water into storage and get it out when you need it. And I think more parties would be interested in participating in some of those projects if they better understood the constraints and potential benefits.

We have learned a lot on the local supply side. Some of the supplies that we thought were drought proof were not as drought proof as we thought. Recycling is easy to sell in droughts.

It's very difficult to estimate the demand responses during droughts and economic recessions and to include the likes of emergency declaration. We've been collecting data to try and better understand how demands come back or don't come back from those conditions. The behavioral aspect is really hard to capture, it is really hard to know how behavior will or won't persist beyond a drought or a recession.

You don't really put probabilities on the scenarios themselves. You put it on, for example, how many of the scenarios are vulnerable.

The portfolio approach is a no-brainer and should be considered in the environmental balance.

In terms of our sophistication and how we deal with that, portfolios reveal shortcomings and where there is resilience. You can develop portfolios which we would consider different strategies and they might see how components like groundwater recharge interact. The conjunctive use itself or from groundwater may be structural parts of the portfolio and reuse and water conservation nonstructural. Put all these kinds of elements into a portfolio and you can evaluate resilience and identify the promising portfolio. And that's the nice thing about looking at resilience is your, your less focused on coming up with a precise or accurate estimate of both climate change and adverse conditions. We know we're going to be wrong. We may be wrong by everything. That's the margin. So rather than trying to come up with the best projection of future water supplies and conditions, we just look at as a large range as possible of future conditions. We can look for portfolios that are resilient.

To incorporate resilience, I don’t think you're really building anything. Well, you've got to build your management actions into the model. So there may be physical facilitates or maybe new facilities and maybe reoperation of existing facilities such as active groundwater management, you may be building in additional reviews. They might, instead of assuming that title water coming off agricultural lands or wastewater discharges to the river system, you're going to recapture those and reuse and reuse that water. So that part is all that is big that's going to be built into our operational models. But that I think what differentiates it is how you treat results. You identify a threshold under which when the performance if exceeded, your system is broken down, it hasn't provided the surface water reliability that you want. Then you look at the number of times that model results exceed a certain threshold and you've run say hundreds of future possible conditions, under different scenarios of climate change, sea level rise, population, and land use. And what you're really looking at is a system that will have the smallest number of exceedance of those thresholds. So you're not saying anything about the likelihood of one. It just saying for all these possible scenarios, this particular portfolio of water management actions results in only exceeding my critical threshold, let's say at 25% shortage to an open moderation fee and only occurs one year in 94 years or, or one month in how many months. It's more how we interpret the model results.

A portfolio approach would be a big improvement. Conjunctively using ground water and surface water is important. SGMA will lessen the availability of groundwater and increase the demand for surface water which will further stress riverine ecosystems.

There is also two sides of it, supply and demand. Portfolios should include both. Sources should be considered holistically rather than managed separately. And I think demand should be considered holistically as well. That would give us a better sense of what the tradeoffs are between different types of uses and, and maybe encourage switching between sources as well. Without integration, you're just kind of addressing these separate needs in a vacuum.

We need to support the ability of water systems, which we between broadly defined as rivers and streams as well as human infrastructure, to support native biodiversity and ecosystems while meeting the needs of people. Part of that is to have an understanding of whether our water system can meet needs into the future under climate change scenarios. That includes periods of stress, such as drought and flood and, fire and additional regulatory actions. Are we considering all those things? Are we able to still meet a broad suite of needs? No way.

Maybe we're not inviting all the right people to be a part of the discussion. We focus a lot on the water users and the agencies, and a little bit on the NGOs. Water users are going to dominate the conversation. I think that's part of why we end up in the same place most of the time, the same people who built the system to provide for human supply and to maximize are in charge. Those people have the strongest voice and it's not going to change because it's designed to meet their needs.

I think it would be really helpful if models were more holistic. Perhaps decision analysis where you have a structure and often a structure and collaborative process where you would build a model that can look at competing objectives. You can have more than one model and use them structure uncertainty in your view of the system. If we took that kind of approach, it, it would help a lot because then we would have models that would be built explicitly to meet the objectives of the group rather than just a water supply for human objectives.

Question 4. *Are environmental and ecological flows treated adequately by water supply reliability estimation? If not, how can environmental water reliability be better addressed?*

In our own planning, environmental flows are paramount. We try to meet both flow and water quality requirements before any diversions can occur. If I put an academic hat on for just a minute, I understand the issue around the question: fish don't have water rights per se. Maybe California needs a steward like a Delta water master for environmental rights or for the entire system.

Anything we do going forward has tradeoffs and risk. In order to increase water supply reliability in terms of knowing that we are putting water to best use in terms of priorities relative to agriculture and the environment, we really need better information on those tradeoffs and risks. One of our, our biggest dilemmas is on the environmental side. We don't understand well enough from fisheries, ecosystems, and habitat standpoints what the water tradeoffs are in terms of trying to increase supply reliability to agriculture. At the same time we are trying to improve the environment. How do we strike the balance and how do we understand the risks to both sides in terms of changing operations with new projects?

Generally, the challenging part of reliability estimation is on the habitat and ecosystem side. That is where it's very hard to identify the risk and to convince agents to participate in something a little more creative that might lead to a larger good and higher priority use of a block of water that they have available. They're just not geared to thinking that way. If they did, it's a different mindset versus a regulatory mindset or an impact mitigation mindset that they're used to dealing with. We have to move the whole discussion into a different arena in terms of what agencies are allowed to do and, and how they can participate. I know that's all kind of a high level, but in terms of moving forward in a meaningful way to improve reliability and protect the environment and enhancing the environment, those are the sorts of things that really have to happen because the current regulatory structure and the current operational structure is just not conducive to that sort of support for multi-benefit projects that really could have a larger benefit if there was enough collaboration to put the pieces together and make it happen.

There's kind of two different questions here. Estimates reflect the current regulatory regime and demand for that water first and then they produce the estimates of supply that come after them. In the modeling, I think they treat those flows adequately. The other question, which is a different question, is are those existing flows adequate by themselves? I think that's a different question which I cannot answer. But as far as the modeling, yes, I think they had a mechanism to sort of account for those flows, if that makes sense.

Water supply reliability is a promising idea to encourage water suppliers to diversify. But the "dark side" is that it often means "how much can I extract as often as possible." This perspective sees environmental water demand as antagonistic to the whole concept of water supply reliability.

Environmental regulations are needed to show that society values the environment – to make sure that water supply reliability is viewed holistically.

A daily model could certainly be appropriate for environmental. Environmental and ecological flows are challenging. We do have temperature models, habitat models, water quality, and salinity models, but the suite of modeling tools needs to be able to talk to each other. There are daily variability components that we can build into our monthly decisions, but for now, the lift that it would take to make this a daily tool is beyond possible. But that's just my personal opinion. Maybe the answer is that we build some kind of a daily operational tool that literally is used on a one-year basis.

So typically, system or management models have 30 calls times steps in one month. It just the first building block in a, in a heated analysis in which the upstream model provides information to a downstream model. The problem with our current analysis is with monthly times model times you are trying to say something about fishing fish survival. A colleague once noted that if you took the air out of the room you're in for 15 minutes, it would not be good for your survival. But if we average the air condition where you know the conditions on a monthly basis, there is no problem. I think we have both temporal and spatial resolution issues in our temporal analysis. In our management models, we're not looking at what might be best for the environment. Where will we impose the current regulatory requirement? And there is, there is no sort of flexibility.

The Delta is a large portfolio. A huge portion of the portfolio for one user might be the only one for others. Keeping that in mind in the planning, framing some of the impacts within those portfolios is one way to help mitigate conflicts. That's different than what was done in the past. Portfolios of environmental management actions are a little bit more tricky. There may be multiple ways we can meet the same environmental goals. Whether it is habitat or flow, for example, we can acknowledge that there might be different ways to meet these same goals. And so potentially there could be this trade off. If a certain habitat is still there then, there could be a reduction in flows. They can meet the same objectives.

It is really difficult to model and to do it accurately. It's really important to have a discussion of climate change. With climate change and SGMA there is potential increased environmental flows. These will have a huge impact on the water supply available for diversion.

Question 5. *Is climate change treated adequately by water supply reliability estimation? If not, how can water supply reliability estimation address climate change?*

Climate change is layered on top of a portfolio that includes many components and presents a complexity challenge for decision makers. We formerly used the droughts of historic record to build robustness into our planning, but it appears that is no longer adequate with climate change. Climate change is an area where the DISB water supply reliability review might add value by sharing how new methods approach this problem.

Hard to integrate changes in climate on decadal scale, with operations at a monthly level and water quality and flood responses on an hourly or shorter scales.

The first challenge is understanding what the climate change models are predicting, what is the range of variation in them, and why is that variation there?

If you look at climate change, which is one of the big driving factors for future water supply reliability estimation, models are coming. What is not clear to me is how those models and their assumptions play into what we are looking at. Because we are so far downstream in our modeling, we can certainly address certain issues of operations and how to do operations at a monthly timescale. But I believe the longer time scales are really important to assess effects of climate change. The upstream effects are not understood in terms of what assumptions are in the models.

With things changing under future climate change conditions and different scenarios of the future may look like, I think it is going to be more and more important in terms of how do we do this. It is not just the water supply side, but also on the flood side, which is of course tied to water supply and groundwater management. We're just not structured to really facilitate, support and develop these multi-benefit projects. In terms of the way the agencies review things, they are focused on regulations. We need to step back from things and look at what is the best ways to use water and ask how do we get different agencies in water resources management to cooperate with environmental agencies and take a little bit of risk for the greater good.

Climate change is huge in terms of changes in precipitation, timing of runoff and sea level rise. We include a climate change component in everything we do these days and you're not sure exactly where things are going to go in the future. Some of the climate change estimates, especially on the flood side, are kind of extreme and we are trying to better understand what that really means. From water supply and ecosystem standpoints, water temperature management strategies are a practical concern. We have also looked at lots of different climate scenarios.

We pretty much work with the historical hydrology because that seems to be what folks are most comfortable with. We do look at design conditions in terms of the historical seven-year droughts in 1976 and 1977 and, and those sorts of things in terms of looking at the historical hydrology and, and extracting pieces of it. We have not gotten into a lot of stochastic stuff or Monte Carlo stuff. There just don't seem to be accepted although I personally think they are needed as we go forward. And understanding that simply looks at the last 82 years of our hydrology or a climate perturbed 82 years is not going to be adequate because there is uncertainty in the future and we need to take alternative approaches in terms of what is needed for design and, and planning and understanding, potential envelopes of future reliability relative to where things are going to be going. It's kind of amazing where we are now and kind of the traditional approaches we're still using and how hard it is to convince folks to move outside that and do things that are a little more unconventional. There seems to be a resistance there.

Is climate change treated adequately? I think not. We have a lot to learn about how climate change is impacting groundwater and surface water and how to incorporate it into our models.

Most people have one climate projection or one central tendency climate projection to work with. Trying to get people more comfortable with that space as multiple futures is a challenge. We have been doing this with portfolio planning since the early nineties.

Concerned that climate change is being used to ignore ecosystems.

We've been working with climate change scenarios for well over a decade in a variety of studies. There have been a number of climate scenario development efforts by different agencies too. All have used completely different perspectives to develop climate projections. What emissions scenarios? What future pathways and adaptation strategies might be in place? I think these are at least partially policy calls.

We already are challenged when we try to model extremes. Then you want to address impacts caused by climate change on water supply reliability. Over the last 10 years we've taken two approaches. We take downscaled results from a particular GCM model and apply that as one particular scenario or we take a different approach and use a collection of GCM’s and downscaled results, which approximately tell the same story. We take groups of model results to represent different climate warmings or changes in precipitation. We're not only present water supply reliability for the natural hydrologic variation, but we're also saying this is the water supply reliability under different projections of the future. Those aren't disentangled very well when we look at water supply reliability, but we get from model the variability under changing climate conditions.

Climate change is a tough one. Addressing ecosystem needs has become even more crucial when we consider climate change. There will be a whole different suite of stressors. Well not necessarily different but more intensive. One insight from the recent drought that is when we think about climate change under drought conditions, we think of water scarcity. But what shows up in the data is that drought removes natural variability from a hydrograph. So as the drought continued, we were managing straight line flows.

Question 6. *How can unreliability be addressed in water supply reliability estimation? How can estimates of variability and uncertainty be improved.*

Uncertainties from upstream models (hydrology, etc.) are neglected in water supply reliability estimation. Estimating uncertainties for climate change and adaptations to climate change are a challenge. A Monte Carlo approach might give a different result. Currently we rely more on historical hydrology and rely less on distributions of what could happen.

Common standards.

We definitely need better data to support the tools, and consistency of application between tools and things. Monthly models are wonderful for some applications, but we need to look at other applications from a daily basis when, especially when we're looking at various and different flow regimes and the frequency and duration of diversions into bypasses. Diversions do provide the fisheries folks and other biologists with information to help them assess the impact of diversions. Would this be beneficial or impactful?

Our model are monthly models. You hear a lot of talk about these big atmospheric rivers and short time periods where you're having a lot of runoff. Those are things that are not captured. A lot of work needs to be done to improve how the state water project captures climate change and uncertainty.

A major concern is how to best capture uncertainty in all of the inputs. We use a process called robust decision making, which is a way to get at uncertainty (Mankin et al. 2020). For example, we know that there are a lot of different climate models and a lot of assumptions go into them. And then they are down-scaled and create uncertainty in space and how that will impact our supplies from the Colorado River, the State Water Project, and locally. Robust decision-making aggregates and considers the impacts of all the components of climate change. You can separate precipitation effects, temperature effects, and expand the range of climate impact beyond the model sets that currently exist. That takes a lot of computing power.

The way that we have approached uncertainty with robust decision making is a little bit different. You actually sort the uncertainty space by defining a range of temperature and precipitation changes. So for instance, for the Colorado River basin, we might look at a temperature increase ranging from zero to four degrees Celsius. And we would look at a precipitation change of plus or minus 20%.

Sometimes it's not appreciated how sensitive model outputs can be to subjective model inputs. The trouble is the models do well on the initial range of hydrologic conditions. They do well in a normal year. As you stress the system, such as in extreme droughts, they do not do as well. That is precisely the condition when water managers are most interested.

Reliability is a major limitation for extreme conditions. That makes a lot of sense because a model is a simplification of all operating worlds. We assume a set of operating rules that apply under most conditions.

Appendix C. Acronyms / Glossary

CalSim – California Simulation model, DWR-USBR model of Central Valley, CVP, and SWP water supply operations and planning

CalLite – simplified CalSim model, DWR and USBR have separate versions

CALVIN – California Value Integrated Network (UC Davis – UC Merced system optimization model)

CCWD – Contra Costa Water District

CEFF – California Environmental Flows Framework

CRSS – Colorado River Simulation System (USBR)

CVP – Central Valley Project (federal)

DCO – Delta Coordinated Operations

DSM2 – Delta Simulation Model 2 – DWR hydrodynamics and water quality model of the Delta

DWR – Department of Water Resources, California

EBMUD – East Bay Municipal Utility District

EDF – Environmental Defense Fund

IRPSIM – Integrated Regional Planning Simulation (MWDSC model)

LCPSIM – Least-Cost Planning Simulation (DWR model of urban water service area economics and decisions)

MWDOC – Municipal Water District of Orange County

MWDSC – Metropolitan Water District of Southern California

MWQI – Municipal Water Quality Investigations (DWR program)

SacWAM – SWRCB simulation model for Sacramento Valley and Delta

SCVWD – Santa Clara Valley Water District

SDCWA – San Diego Country Water Authority

SFPUC – San Francisco Public Utility Commission

SGMA – Sustainable Groundwater Management Act, California's 2014 legislation on groundwater overdraft

SWAP – Statewide Agricultural Production Model

SWP – State Water Project

SWRCB – State Water Resources Control Board

TNC – The Nature Conservancy

USBR – US Bureau of Reclamation

UWMP – Urban Water Management Plan

WEAP – Water Evaluation And Planning water supply simulation model

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Other Reviews

A review of water supply reliability estimation related to the Sacramento-San Joaquin Delta is just one of the themes/topic areas that the Delta ISB has reviewed to meet its legislative mandate of providing oversight of the scientific research, monitoring, and assessment programs that support adaptive management in the Delta. Completed reviews are below.

Restoration (2013)
Habitat Restoration in the Sacramento-San Joaquin Delta and Suisun Marsh: A Review of Science Programs

Flows and Fishes (2015)
Flows and Fishes in the Sacramento-San Joaquin Delta. Research Needs in Support of Adaptive Management

Adaptive Management (2016)
Improving Adaptive Management in the Sacramento-San Joaquin Delta

Levees (2016)
Workshop Report – Earthquakes and High Water as Levee Hazards in the Sacramento-San Joaquin Delta.

Delta as an Evolving Place
Review of Research on the Sacramento-San Joaquin Delta as an Evolving Place.

Water Quality
Water Quality Science in the Sacramento and San Joaquin Delta. Chemical Contaminants and Nutrients

Interagency Ecological Program
A Review of the Interagency Ecological Program's Ability to Provide Science Supporting Management of the Delta

Non-Native Species
The Science of Non-native Species in a Dynamic Delta

Monitoring
Review of the Monitoring Enterprise of the Sacramento-San Joaquin Delta

Delta Independent Science Board
(916) 445-5511
disb@deltacouncil.ca.gov