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Scenarios, Sustainability, and Critical Infrastructure Risk Mitigation in Water Planning

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Abstract

This paper examines the state of water supply planning facing unprecedented challenges for ensuring reliable, resilient, safe, and affordable water supplies in Texas and throughout the US. Analysis of water planning methods and practices reveals a robustly sophisticated quantitative modeling capability. Its focus is on both near-term and long-term capital investment requirements and managing operating costs. Water planning focuses on drought mitigation and flood risk management as predominant concerns. But climate change is impacting whole watersheds as well as water systems subject to sea level rise incursions that disrupt wastewater systems. Significant cross-impacts between energy and water add new risks to both energy and water infrastructure, with uncertainties still difficult to robustly quantify. Energy-water nexus issues reflect deeper planning challenges concerning critical infrastructures. Critical infrastructure planning tends to be sectoral-specific even though interdependencies and cross impacts can create broadly impactful cascade effects. Future-state water planning should be done in the context of critical infrastructure planning. Both will benefit from integrating qualitative scenario planning into established quantitative planning models. Doing so expands the complexity that can be captured in planning while providing narratives and using decision-making and public communications tools.

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Any errors in this report are the responsibility of the author.

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1.0 Introduction

Weather patterns drift year-to-year. Water supplies generally mirror weather patterns. Hot and dry years can mean water supply challenges, e.g., droughts and requirements to conserve. Cooler and wetter years enable water supplies to be replenished. The impacts of weather patterns vary according to population concentrations, land use practices, and many other factors. Loss of water supply reliability can contribute to significant human migration patterns, which disrupt local areas, regions, and national economies.

Critical infrastructure (CI) in the US has significant interdependencies between electricity, water, communications, transportation and other sectors. In today's world, separating these interdependencies risks overlooking critical cross-impacts. Neglect of CI interdependencies results in more costly critical service delivery because risk reduction and cost efficiencies come from managing interdependencies.

It is why long-term water planning merits enhancements to address the implications of CI interdependencies. That is, the scope of water planning is challenged to adapt to interdependencies stemming from (but not limited to), (a) the *increasing* interdependencies amongst multiple critical infrastructures, (b) weather patterns exhibiting more pronounced drifts and attendant consequences from year to year, and (c) the digitalization of the US economy.

This paper examines the present state of water planning in the US. Its conclusions point to the need for enhancements in CI planning to recognize and manage interdependencies, which can turn a single sector disaster or hazard event into a broad economic and social crisis. The role of scenario planning as both an add-on to existing CI plans, such as water, and as an integrating enhancement that helps sectoral CIs function more systemically is considered. Systemic management is deemed a new form of essential service that is relevant, but only when comprehensive CI plans and platforms become as vital in planning as they are critical to service delivery.

Recently, the Water Resources Foundation (WRF) prepared a report aiming to identify critical challenges facing water utilities, which cross-impacts other CIs. WRF identified seven main challenges:¹

- (1) ***Politics and competing interests*** – a perennial underlying consideration, which necessitates that stakeholder engagement is ongoing
- (2) ***Funding*** – allocations amongst competing interests and prioritization between multiple critical infrastructures as ongoing friction points
- (3) ***Water rights (direct and indirect) and regulatory hurdles*** – function as barriers to change and reinforcers of the “as-is”
- (4) ***Utility cooperation and coordination*** – essential to executing changes, but can limit expeditious change management
- (5) ***Public perception*** – an essential force that can drive change or resist it
- (6) ***Insufficient implementation tools*** – including practices that enable quick responses across two or more CIs as needed
- (7) ***Insufficient experience*** with how to apply new water and CI management tools (to be discussed throughout this paper)

These main challenges reflect issues that policymakers and decision-takers must navigate. They are both reminders and guides for how water and CI planning pathways must enhance management of shared challenges.

2.0 Methodology

Research findings for this paper came from several sources. First, a sustained period of work in Texas with local water utilities gave ISE staff access to people, processes, and technologies used in planning for water supply reliability and resilience in towns outside of the Austin metropolitan area.

Insights from hands-on working relationships with local water planners in Texas helped ISE staff in its review of a complex and deep literature on water planning methods and practices, especially quantitative modeling tools used for water planning. Literature reviews were used to identify key issues of concern to water planners. Many that were identified were aligned with local water planning efforts; however, some issues pertaining to cross impacts under critical infrastructure planning emerged, which were not evident from hands-on work with local town and city staffs.

¹ Available at: <https://www.waterrf.org/sites/default/files/file/2019-09/4949-IntegratedPlanning.pdf>

ISE used hands-on experience and literature reviews to develop an issue and policy map for water planning in an age of change. This process was informed by other work underway at the ISE. Collaborative work with the Sustainable Energy Division of the United Nations Economic Commission on Europe introduced next generation scenario planning methods, which integrated with quantitative modeling to create rich decision perspectives for member nations of the UNECE. These scenarios, referred to as pathways, painted pictures of possible futures based on policy decisions that had to be made in the near-term. These decisions were contextualized as policy choices tied to meeting Paris Agreement commitments.

ISE staff with experience working at the Department of Energy on critical infrastructure cross impacts, especially between energy and water, brought to the research and analysis for this paper a framework crafted by the Department of Defense (DOD), Department of Homeland Security (DHS), and the Department of Energy (DOE) for mapping institutional divergences and congruences that were at the heart of necessary but somewhat ineffective efforts to integrate CI sectoral plans into an integrated systemic CI planning and management platform.

These research vectors became inputs to the crafting of an approach for enhancing rather than transforming well established water planning processes and practices. Scenario planning was analyzed and became an important element in an adapted framework that composes the main body of this paper.

3.0 Analysis and Findings

Robust quantitative water supply planning methods are widely applied. These models include water demand and tools for assessing the conservation potential of various water supply, demand management, and pricing tactics. Water supply planning models are particularly focused on drought, extreme weather, and conservation practices. Climate change related factors are included but do not appear to be widely applied.

There are important additions to contemporary water supply planning that promise to enhance resiliency planning, risk and uncertainty identification and mitigation, and managing cross impacts of CI interdependencies. The main CI consideration for water is the complex interdependency with energy; but communications and information infrastructure are becoming equally important.

Scenario planning practices are tangentially used in water planning — the focus being bounding forecasts using Monte Carlo and other simulation methods. Making more integrated use of scenario planning, especially at the interface of single CI sectors with other CI sectors, increases the fan of possible risks and uncertainties that can be modeled. Also, it enhances communication with decision-makers and stakeholders by making situations, outcomes, and complex options more clearly understandable.

3.1 *The Case of Texas*

Water for Texas is the statewide water plan for 2017, updated in 2019.² Its composition is comprehensive. Its focus leans toward water conservation and drought management. Elements of the plan include drought and drought response — including evaluation of prior droughts and how the state handled them, costs of the state water plan discussed as financial requirements, future population and water demand. Water demand considerations span projects for demand by region, demand for municipal services, demand for manufacturing, mining, power generation, irrigation, and livestock, as well as discussion of uncertainties of water supply and demand forecasting. Water supply considerations cover surface water availability within river basins, future surface water availability, groundwater availability within aquifers, future groundwater availability within aquifers, other sources and existing supplies, as well as discussion of uncertainties specific to assessing existing and future water supplies. The plan also discusses issues related to not meeting needs, uncertainty about future needs, implications of needs that exceed those within the plan, and water management strategies, which focus on strategy design and framework and discusses options in general terms.

The city of Austin's recent 100-year water plan is arguably a breakout contribution to water strategy and supply planning. The rationale for and design of Austin's water planning effort is quoted below.

“The recommendation to develop an integrated water resource plan emerged from the historic drought Central Texas endured from 2008-2016. During the drought, the lakes that supply Austin's drinking water fell to historically low levels. While Austin successfully weathered the drought, the event highlighted the need to increase the sustainability, reliability, and diversity of Austin's water supplies through an integrated

² Available at: <http://www.twdb.texas.gov/waterplanning/swp/2017/doc/SWP17-Water-for-Texas.pdf>

water resource plan. Water Forward addresses these issues by modeling potential climate change effects on Austin's water supplies and evaluating multiple future scenarios to plan for droughts worse than what we have experienced in the past. The recommended plan is the culmination of a robust effort that involved the Austin community, the Water Forward Task Force, an outside consultant team, City staff, and others.”³

Austin's 100-year water plan focused on major water supply projects and incremental demand management and reuse solutions, to augment Austin's access to water during drought conditions when core surface water supplies are severely limited. The plan, as noted, was born of severe drought for 2008-2016, which drove home the need to address resilience in the face of changing climate conditions and significant population growth.

3.2 *Principal Planning Methodologies and Planning Execution Challenges*

Hart and Halden found that across the US almost universally (94%) of water management was reactive, focused on emergency responses. As such, proactive mitigation management was not a priority.⁴

Nevertheless, water supply planning consistently occurs with operating costs and budgets emanating therefrom, and capital programs being specified and financed accordingly. Limitations of planning inputs coupled with a predominant focus on reactive processes serve to constrain the range of planning horizons and options. Because they are meaningful influences on longer term pathways for ensuring water supply reliability and resilience, enhanced planning tools offer significant value to be added.

The main limitations to contemporary planning processes and models include outdated data, the misalignment of data and guidance, effects of inelastic demand that cannot be moved, and climate change impacts not fully included in contemporary planning practices throughout the US.

A persistent challenge for water planners is the chronically outdated state of floodplain mapping data used to meet program requirements of the Federal Emergency Management Agency (FEMA). FEMA drought planning guidance was outdated 84% of the time over the last five years, and 82% of the time over the last 10 years. Regarding state-level guidance supplementing Federally mandated flood mitigation requiring programs to be updated regularly — this actually occurs regularly only 54% of the time amongst the sample population of cities and states in the five years from 2013-2018, but 84% of the time over a ten year horizon. Further, although 79–94% of states provide some level of water supply and demand guidance, projections themselves tend to significantly predate guidance. About 70% of US states still lack climate change impact guidance, particularly non-coastal states and those impacted by increased water scarcity rather than flooding concerns. Strategies are rare (4%) for addressing the impacts of increased variability and uncertainty in meeting inelastic demands.⁵

The above limitations obviate other factors that influence how water planning is executed. Specifically, there are seven main clusters of issues that emerged from ISE's literature review (2018-2020). They are noted below.

1. ***Supply planning***, including water storage, quality, reuse, and water-energy tradeoffs, as well as energy-water-food interdependencies, complicate the easy exercise of contemporary water planning, particularly when quantitative models are the key planning platform. The parameters, scope and scale, as well as cross impacts, present a different mix of challenges depending on water utility priorities, municipal policies, and socio-economic changes caused by urban growth and climate change.

2. ***Decision-making challenges***, including endogenous interlinked (e.g., how functions within a water utility coordinate and ration capacity) and exogenous interdependent influences. For example, the impact of energy supply, reliability, and costs on water supply and delivery, or necessary tradeoffs between water conservation as a sustainable solution to water scarcity or significant new capital investments to garner new water supplies from reused or desalinated water necessitate new resource allocation and capital investment prioritization practices.

Allocation and prioritization practices will be investing more in answering what is the value water reliability? How much lead time is required for conservation to mitigate shortages compared to new recycled

³ Available at: www.austintexas.gov/department/water-forward

⁴ Olga E. Hart, Rolf U. Halden, “On the need to integrate uncertainty into U.S. water resource planning,” *Science of the Total Environment*, 691 (2019) 1262–1270.

⁵ Hart & Haden, *Ibid.*

or desalinated water infrastructure? These and many other questions will impact conventional water supply planning and decision-making in the years ahead.

3. **Physical infrastructure challenges**, including aging infrastructure as well as operations and maintenance costs continue to rise as priorities. This point is further amplified when the energy-water nexus is included as an interdependent slate of relationships. Electric power supply and delivery infrastructure also are aging out faster than replacement and upgrading investments can be made and deployed.

4. **Safety and security planning concerns**, in particular related to cyber infrastructure, such as smart water meters and SCADA (Supervisory Control and Data Acquisition) on water lines is both an aging infrastructure issue as well as a CI challenge. Information infrastructure, which enables smart meter and SCADA use-value, is costly and tends to require ongoing O&M. Ongoing O&M includes upgrades to software platforms, such as CRM, ERP, workflow management, and web-based engagement channels. That is, once capital costs are incurred, a fast cycle of capital upgrades (computing power) and operating system versions leads to a higher ongoing operating cost than the pre-digitalization era.

5. **Planning information quality, accessibility, use-value, and privacy matters** are important to keep up to date, especially related to population growth; and how and where its clusters within an urban landscape. Existing water planning tools capture data but in some cases the data is old and the gap between the old and actual is significant enough to distort planning choices.

6. **Processes**, which include planning activities related to resilience, reliability, and adaptation to changing circumstances, are mature for most water utilities. Inclusion of non-conventional processes may be necessary if a deeper integration of uncertain outcomes is required. For example, what would water planning look like if there was a surprising recession that reduced demand? What if population growth suddenly surged? What if aging infrastructure failed, disrupting service to parts of the system for sustained periods of time? These examples are intentionally simplified, but each case has cross-impacts that can have ripple effects on city processes and regional economies.

7. **Strategies to manage a stressed system** are dominant considerations for decision-makers, especially in locations where water supply already is insufficient and urban population growth continues. The demographics and psychographics of population migration and settlement are important to map and track for many reasons. Consumer market segments use water differently, where pricing may or may not be effective at regulating use or allocating supply.

For example, high income segments tend to use more water but also tend to be more aware of costs of water, so tiered, time-of-use, or real-time pricing regimes can influence consumption of higher income segments. By contrast, pricing regimes that exploit elasticity of demand tend to be quality of life choices for low income segments compared to higher income segments, i.e., pay the water bill, or the electricity bill, or the medical bill this month?

Rising complexity, greater uncertainty (or ambiguity), and enhanced scope of impacts point to more emphasis on systems dynamics (SD) modeling. It is designed from the ground up to integrate a complex mix of interacting variables. When applied to water supply planning, variables such as population patterns, diminishing water supplies, variable climatic conditions, and regional characteristics (such as aridity, “tropicality,” or seasonality) can be integrated in both stochastic and nonlinear modalities. Systems dynamics based simulation analysis can help to shape workable water management strategies to cope with present and/or future water demand changes, as well as supply changes. SD models also help drive allocation decisions between competing water needs, and achieving consensus among users for proposed near-term water supply plans.

SD models include water sources, users, recharge facilities, water and wastewater treatment plants. Simulations help planners understand the structural interdependencies of various elements in an end-to-end water supply and delivery system. It enables relatively realistic hypothetical system outcome simulations over long planning horizons.⁶

⁶ “Simulations” are different from “Scenarios.” Simulations are model runs that product outcomes based on how assumptions and interdependencies are set for a particular run. Scenarios are narratives that describe possible futures and the factors that yield them. When articulated as a storyline, scenarios provide context for simulations and guidance on how to shape them. The difference between a simulation and a scenario helps to differentiate quantitative and qualitative planning processes; where the interaction of scenarios and simulations

Contemporary SD simulations are yielding new results that have implications for longer term water supply planning for all water utilities. For example, construction of small-cluster decentralized wastewater treatment systems appear to be more economical than centralized plants when communities are spatially scattered or located in geographies with steep areas, where pumping costs may be challenging.⁷

In addition to systems dynamics modeling, linear programming, regression models, and various forms of sensitivity analysis applied to them afford water planners a robust array of tools. One of the challenges stemming from this robust array is how to maximize use-value of a portfolio of analytical tools. Models for addressing hydrological challenges, wastewater, storm water, and drinking water can be complementary but cumbersome to run in parallel. This is why contemporary SD tools merit increased attention.

Further, location and geography play an important role in water supply analysis and related modeling tools. For example, city expansion often advances into rural areas creating dispersed and fragmented delivery patterns, which make providing water, gas, and electricity services more costly and often more difficult.

The economic costs needed to meet service demand and the environmental costs associated therewith for dispersed towns and small cities are higher than in large cities. Urban locations experiencing expansion of dispersed locations often seek integration with higher density places for critical infrastructure services. Uncertainties in the planning of infrastructure investments can lead to mis-sized actual delivery systems to meet dispersed demands for service. Careful estimates of the optimal location of infrastructure investments helps to guarantee not only economic savings but also reduce the environmental costs. Creating links between infrastructure planning and overall urban planning can help to minimize inefficient capital deployment. Modeling robustness helps to inform investment decisions, but does not necessarily contribute to an end-to-end water supply/demand management plan.⁸

Capital investments in water supplies are a dominant consideration for water utilities. Financial models must absorb results from systems models, infrastructure planning models, and in some cases urban planning inputs, which are policy-based, not necessarily computationally articulated.

3.3 *The Water-Energy Nexus and its Implications for Water Planning*

One particularly important “out of the box” consideration for water supply planning is the relationship between electric power and water supply. For example, optimal strategic and operational decisions for desalination-based water supply systems present more cost-effective outcomes when integrated with hybrid energy systems (wind, solar, battery combined with small gas-fired generators). In Perth, Australia, needs for desalination to secure water supplies for the city and its surrounding areas serve to enhance sustainable energy deployments. In combination, both desalination and renewable energy cost less than pursuing each separately.⁹

Water-electricity tradeoffs are emerging as new critical planning challenges. New modeling tools are emerging to support planning for and investment decisions pertaining to optimizing water-energy tradeoffs. For example, a two-level mixed integer linear programming model serves to highlight best fit hybrid energy-water pathways. Use of this model showed analytical results that helped to maximize operational flexibility through decentralized deployment of infrastructure assets. An integrated water supply system emerged from analysis, leading to a reduction in desalination costs of over AU \$215 million.¹⁰

The mutually reinforcing water and energy needs in this Perth, Australia case produced a 42 MW increase in solar cell uptake capacity on average in each year within the planning horizon for Perth’s desalination initiatives. Still, the determination of the best path depended on the selection of this particular option (scenario) as the preferred alternative. Proceeding forward was highly dependent on the values associated with subjective criteria and operational and maintenance costs of flexible operating modes, which were challenges for conventional water utility modalities. In other words, qualitative assessments were an important element in water supply capital investments.

illustrates how qualitative and quantitative tools both compliment and reinforce each other. The result is a more robust set of planning process and decision choices.

⁷ G. Chung, K. Lansey, P. Blowers, P. Brooks, W. Ela, S. Stewart, P. Wilson, “A general water supply planning model: Evaluation of decentralized treatment,” *Environmental Modelling & Software* 23 May (2008).

⁸ Michele Grimaldi, Vincenzo Pellecchia, and Isidoro Fasolino, “Urban Plan and Water Infrastructures Planning: A Methodology Based on Spatial ANP,” *Sustainability*, May 2017. Available at: [sustainability 2017, 771; www.mdpi.com/journal/sustainability](https://doi.org/10.3390/sustainability2017050771)

⁹ Negar Vakilifard, Parisa A. Bahri, Martin Anda, Goen Ho, “An interactive planning model for sustainable urban water and energy supply,” *Applied Energy*, 235, 2019, 332-345.

¹⁰ Vakilifard, et.al., *Ibid.*

The predominant focus of water planning is supply and how to ensure water is available to meet existing and growing needs. Thus, water supply planning robustly considers storage options, quality assurance and control, methods and techniques for recycling water, and some energy-water tradeoffs.

Water utilities and agencies have not aggressively intervened with regulators or municipal utility boards to make the case that water for energy versus water for public use is becoming an unequivocal zero-sum game.¹¹ However, the time for such intervention is just over the horizon in many locations facing water shortages from climate changes, in particular California, Arizona, and Texas.

Today's water planning for tomorrow's needs must examine water supply from a much richer palette. Certainly, conventional water supply modeling can identify and explore various innovations for meeting forecasted water needs. But innovative solutions invite innovative resistance. In Texas (and California), desalination is far from being a consensus solution to worrisome water shortage possibilities. Robust scenario planning tools can help to clarify the implications of various choices for how to meet water needs in coming years.

Stresses on water supply systems intensify the difficulty of related decision choices. They can determine the allocation of water services for commercial, industrial, agricultural, and public water consumption purposes. Water allocation processes differ based on whether pricing, auction and trading, or needs-based criteria serve as the optimization function. Water rights and supply control complicate shifts in allocation processes and status quo use patterns.

Particularly important reallocation requirements just over the horizon concern the significant volumes of water used by power plants for cooling and other purposes. Coal-fired and natural gas-fired generation are especially vulnerable to water reallocation requirements based on supply reserves.

Carbon-fueled electric power production is under siege from parties determined to end their operations as part of large-scale decarbonization requirements for mitigating climate change. Water supply shortages and supply risk management may well overtake decarbonization advocacy as the primary driver of carbon-based generation asset closures in the coming years.

For locations where power plants and fuel sources reside in the US, carbon-based generating assets may close, in turn liberating dedicated water supplies for other uses, e.g., agriculture and industrial requirements. Water planning in an uncertain world is significantly impacted by the potential for surprising causes of either increased water supply or intensified water scarcity from interdependencies not generally included in integrated water planning methods.

Core water planning focuses on operational integrity for maintaining reliable, resilient, and clean water services for end-users of all types. Meeting growing demand is a prime focus, which involves both operational and capital planning for near-term and longer-term efforts to avoid shortages. Today's water planning processes in many US states recognize mutual dependence on the same water resources for both power production and water services. However, organizational barriers, differences in planning cycles, differences in geographic jurisdiction, and limited joint planning tools, yield power and water interdependency planning that is rudimentary compared to the scope of the present and impending challenges related to both power and water.¹²

The institutional differences between power and water planning, i.e., jurisdictional misalignments at the local level, point to state level planning processes as integrators of multiple CI sector plans. Execution of such responsibilities could occur through state level functions or a distinctly purposed entity addressing CI interdependencies and their impact on state and local level CI sector planning.

For example, the use of water for power generation involves both withdrawals and consumption. Withdrawal means water is passed through a steam condenser and returned to its source as heated water. Consumption means the water is used for cooling and other purposes, ultimately being discharged in waste streams or evaporated to the atmosphere.¹³ When power and water CIs are treated as components of one system — and their respective components are looked at individually — a complex interdependent system is revealed as a continuously adapting collinear vital service system for communities. Circumstances can change the delivery capabilities of essential services (e.g., meeting demand volumes, or ensuring water availability). When triggered, interdependent components of CI sectors can react in different, often unexpected, ways. New forms of agent-based modeling (with both quantitative and qualitative aspects) offer tools for capturing cross impacting CI sector behaviors.¹⁴

¹¹These are findings of the authors based on review of city and state water plans as well as academic literature and trade press.

¹²James R. Thompson, Damon Frezza, Burhan Necioglu, Michael L. Cohen, Kenneth Hoffman, Kristine Rosfjord, "Interdependent Critical Infrastructure Model (ICIM): An agent-based model of power and water infrastructure," *International Journal of Critical Infrastructure Protection*, 24 (2019) 144-165.

¹³Thompson, et.al., Ibid.

¹⁴Thompson, et.al., Ibid.

Overriding all water management decisions is a physical, hydrologic constraint that is a function of watershed supply and water system sourcing and delivery conditions. Investment tradeoffs and policy gaps at the interface of water and energy span two additional dimensions. First, there is an *unprecedented optimization challenge* in balancing water supply needs against the criticality of electricity supplies literally on a minute-to-minute basis. Second, there is a *tradeoff matrix to be developed that considers environmental impacts and potential electricity supplies at the power plant and watershed levels*, respectively. Policy parameters for addressing such tradeoffs are focused on combinations of environmental regulations and economic penalties during a drought event.¹⁵

While quantification of new challenges is vital for understanding their scope, scale, and implications, quantification is not the primary engine of policy decision-making under conditions of uncertainty. Certainly, it is an essential input; but policies are shaped qualitatively as a function of the proclivities of leaders and their agendas. If for no other reason than this, contemporary uses of scenario design and planning are important add-ons to the multiplicity of quantitative planning and modeling tools that drive water supply planning.

3.4 The Use of Scenario Planning for Risk Mitigation in Water and Cross Impacts with Other CIs

In water management, scenarios are used, for the most part, to account for uncertainties associated with climatic, socio-economic, and management conditions that affect the performance of water resource systems. These uncertainties can impact future water supply reliability, delivery, and water demand management, typically examined within the framework of contemporary modeling and analytical tools used by water planners.

Two limitations of applied quantitative techniques merit consideration in the context of scenario planning for water infrastructure. First, contemporary water scenario practices are discrete stories that map prospective futures directly impacting water system management. An adjustment to craft them as continuous scenarios enables covering future conditions more thoroughly, e.g., providing a more robust consideration of critical infrastructure interdependency impacts as ongoing and shifting challenges for water supply management.

Second, contemporary water planning tends to qualitatively depict possible outcomes based on quantitative model runs. Scenarios enable present-state water supply models to improve assumptions that drive model runs. Probabilistic scenarios can explicitly articulate uncertainties. This enhances the analytical and forecasting value of contemporary water supply planning methods and practices.

A review of water policy issues brings to the foreground the significance of “unknowns” that potentially seriously impact future water service development. Policy issues are primarily socio-economic and climate impact concerns, which bear on whether water supply sources are inevitably bound for scarcity as demand continues to grow. For instance, with the growth of population and economy, water demand from domestic, industrial and agricultural sectors will increase, resulting in more stress on limited, shared water resources. Human caused greenhouse gas emissions are causing increased global temperatures, which alter precipitation patterns that directly impact specific water resource availability and irrigation water demand. Water quality and ecosystem stability issues are part of this constellation, as well.¹⁶

Assessing future impacts of climate change is subject to significant uncertainty, due to knowledge and data gaps in climate system behavior and its interaction with water systems. Water supply models projecting future precipitation and water supply are beginning to diverge on impacts and outcomes against water reliability and service delivery as objective functions.¹⁷

Divergence in water planning modeling platforms has inspired deeper dives into the significance of uncertainties at the root of modeling output divergence. These deeper dives help water managers and decision-makers make more robust decisions, which drive more relevant management strategies.

For example a Water World Vision study focused on water availability and demand driven by population growth and GDP as critical underlying uncertainty factors.¹⁸ A global water outlook study focused on precipitation and temperature changes as root causes of uncertain outcomes in availability of food, water, and

¹⁵ Mengfei Mu, Zhenxing Zhang, Ximing Cai, Qihong Tang, “A water-electricity nexus model to analyze thermoelectricity supply reliability under environmental regulations and economic penalties during drought events,” *Environmental Modeling and Software*, 123 (2020).

¹⁶ Congli Dong, Gerrit Schoups, Nick van de Giesen, “Scenario development for water resource planning and management: A review,” *Technological Forecasting and Social Change*, 80 (2013) 749-761.

¹⁷ Congli Dong, et.al., *Ibid*

¹⁸ W.J. Cosgrove, F.R. Rijsberman, in: *World Water Vision: Making Water Everybody's Business*, Earthscan Publications, London, 2000, Available at: <http://www.worldwatercouncil.org>.

agriculture supplies.¹⁹ A study of water withdrawals and the effect on climate focused on foundational effects inherently amplifying critical uncertainties, including birth/death rates, GDP, water use efficiency, population growth, and land use.²⁰ Water availability and use, with impacts on aquatic biodiversity impacting water supply, focused on population growth and water use efficiency as underlying concerns is another example.²¹ Several additional studies are profiled by Dong, et.al., demonstrating the key uncertainties of critical water supply impacting variables.²²

Another aspect of appropriately shaping scenarios for water planning is how planning processes themselves can influence, or bias, the value of adding scenario analysis to contemporary water planning models.

Achieving useful, appropriately shaped scenarios for water planning requires (a) understanding the development process, (b) recognizing key flaws in it, and (c) implementing tactics to increase the value and integrity of scenario development directly tied to specific water supply planning cases.

Scenarios are used in water planning to capture issues and challenges that may impact water planning but are not easily integrated into existing methods, models, and practices. For example, critical infrastructure interdependencies such as energy and water tradeoffs noted above may be only tangentially considered in core water planning methods.

The increasing interest in this nexus bears on water delivery reliability, among many other considerations. The requirement that water delivery continue during forced outages of electric power, backup and/or primary onsite power sources must be integrated into ongoing water supply management and operations. Doing so requires expert judgment on the extent of redundancy and resilience. It impacts scale and scope, and hence investment requirements for ensuring high level water supply reliability in these changing times.

Scenarios are often applied as extrapolations from core quantitative models, for instance using Monte Carlo techniques for generating a wide array of best- and worst-case outcomes. These techniques benefit core planning by increasing the sophistication of and risk adjustments to water planning results. However, extrapolations by definition are locked into the underlying assumptions and limits of any modeling method. Scenarios need not be similarly constrained.

Scenarios are descriptions of one or more future situations; they articulate possible events and outcomes; they serve as foils for assessing how the handling of present risks can lead to future consequences.²³ The transition from the present state of water supply and delivery in the US to a future state that is resilient and able to sustain quality water service is arguably an unprecedented challenge.

Water system models represent the complexity of interactions in combined processes from water sourcing to the delivery of water for end-use purposes. Water supply models focus on cost, reliability and affordability. Climate change and conventional use patterns require the consideration of a broader range of decision-relevant aspects of continuing to muddle through.

Scenario planning and multi-criteria decision-making can complement established water system analysis. Integrating scenario development, properly executed with methodology that fits existing water supply planning, allows for better problem structuring. It does so by focusing on relevant alternatives, external uncertainties, and appropriately configured evaluation criteria. Integrating appropriately shaped scenario development allows for a more thorough investigation of critical external uncertainties and diseconomies.

The key words are “appropriately shaped scenario development.” There are many scenario development methods, each tailored for specific uses. For water planning, adding scenarios helps planners avoid stress testing particular assumptions in core quantitative water planning models for uncertainty parameters. Finally, combining core quantitative planning models with appropriately shaped scenarios allows for a more balanced and objective evaluation of alternative water supply reliability pathways, in turn informing discussions among stakeholders that help increase acceptance of possible future investment and operational practices in service to continued high quality and reliability of service.²⁴

Scenario development and use must be shaped to appropriately fit into core water planning analyses and modeling practices in order to be beneficial. Use of scenarios has been part of risk-aware planning for decades. Over the arc of its use, its greatest strength also is its greatest weakness. Scenario development cannot be

¹⁹ M.W. Rosegrant, X.M. Cai, S.A. Cline, “Global water outlook to 2025: averting an impending crisis,” *A 2020 Vision for Food, Agriculture, and the Environment*, Initiative, International Food Policy Research Institute, Washington, D.C., U.S.A, 2002

²⁰ G. Gallopín, “Five stylized scenarios,” United Nations Educational, Scientific and Cultural Organization, Paris, France, 2012.

²¹ S.R. Carpenter, P.L. Pingali, E.M. Bennett, M.B. Zurek, in: *Ecosystems and Human Well-being: Volume 2 Scenarios: Findings of the Scenarios Working Group* (Millennium Ecosystem Assessment Series), Island Press, Washington, 2005, Available online at: <http://www.watercouncil.org>.

²² Dong, et.al., Ibid.

²³ Muhammad Amer, Tugrul U. Daim, Antonie Jetter, “A Review of Scenario Planning,” *Futures*, 46 (2013) 23-46

²⁴ Tobias Witt, Marcel Dumeier, Jutta Geldermann, “Combining scenario planning, energy system analysis, and multi-criteria analysis to develop and evaluate energy scenarios,” *Journal of Cleaner Production*, 242 (2020).

standardized and produce relevant recommendations for inherently non-standardized planning circumstances; i.e., unique planning challenges of specific local, regional, and/or state level water supply reliability. Appropriately shaped scenario-development must be evidence based; where the evidence is resident in existing planning models and practices of specific water utilities and policy-making bodies. It must explicitly map “contextual factors” that contribute to how engagement in scenario development itself can change perspectives of participating stakeholders.²⁵

The scenario development process itself is designed to be malleable. Scenario integrity depends on the quality of inputs, i.e., the subject matter experts (SMEs) and other participants in the story development effort such as local stakeholders, decision-makers, artists, and scientists. However, scenario relevance depends on the definition of the situation that frames the overall effort. For example, when a reservoir has to be designed in order to alleviate an unevenly distributed water resource, storylines to describe water shortage situations in dry years and water abundance in wet years are not sufficient to identify an optimal design for the reservoir. It requires integrating quantitative and qualitative planning tools.

Misconstruing scenario integrity for scenario relevance is a key flaw in the way scenarios generally have been applied. That is, using scenarios for reservoir design is misplaced. A more appropriate framing would elevate the scenario process to framing choices based on future outcome storylines at the city, region, or state level encompassing water planning from end-to-end of its supply chain.

Other flaws in scenario planning that warrant attention when using this approach as a compliment or enhancement to contemporary quantitative water planning include (a) limitations in the number of quantitative scenarios that can be considered, (b) implicit or incomplete characterization of uncertainties, and (c) lack of transparency when implementing expert judgment procedures. However, each of these flaws also can be the basis for sound scenario development when recognized and incorporated into the generic process.

First, scenario configurations can bias outcomes. For example, conventional modes typically include three scenarios — one each for the outer extremes of upside potential and downside risk with the third scenario balancing the extremes, and looking like the present-state. Structuring scenario planning thus more or less guarantees a default to the as-is. Contemporary practices insist on at least four scenarios where one each brackets the upside and downside extremes and two differentiate more likely divergences from the present-state. In other words, the present state is captured for reference but is not included in configured scenarios.

Second, scenarios can be disadvantaged by having incompletely articulated or implicitly assumed uncertainty characterizations. The use of SMEs helps to mitigate incompleteness or implicit characterizations, if the number of SMEs is sufficient to offset for individual biases. Probabilities depend upon the experience and expertise of individuals contributing to scenario design. Whether using one SME or several, probabilities invariably are inexact because valuation is implicitly a compromise, if not explicitly so noted. Of course, there are tools to shore up the integrity of probability estimates, e.g., axiom-based practices that check and limit subjectivity, or Bayesian probabilities that drive people to explicitly explain the judgments they make help to enhance integrity.

Third, essentially a corollary of the second issue, is the risk of insufficient transparency around SME judgments. There is a complicating factor when integrating quantitative and qualitative planning tools. If the integration process is not transparent, it leaves the integrity of analytical outcomes subject to question. What protocols were used in scenario design that guided the conversion of qualitative stories into quantitative modeling? Documenting as explicitly as possible the techniques that were used in scenario design helps with stakeholders and decision-makers who may question the integrity of scenarios designed and used.

Nevertheless, the proof of value is not in the precision of subjective judgments but rather in the integrity of judgments, which guide the design of stories that capture both extreme possibilities and intermediate cases where alternative futures may be more likely to occur. Contemporary practices acknowledge the risks of bias and offset it through a number of practices, including (a) ensuring a large population of diverse SMEs, (b) an effective process that keeps SME judgements from drifting outside the definition of the situation, which frames the scenario design effort and (c) its interconnection with water supply planning models used by specific locations, whether cities, regions, or at the state level.

3.5 *Water Supply Models and Narrow Casting Effects*

²⁵ David Firth, Efstathios Tapinos, “Opening the black box of scenario planning through realist synthesis,” *Technological Forecasting and Social Change*, 151 (2020).

At the present time, tools for water planning include conventional budgeting processes enabled by well-established quantitative water supply models. Supply models extend into out-years where an array of scenarios can be assessed to guide city, regional, and state water supply decision-making.

Out-year forecasts leverage core water supply models, which form the foundation of relatively narrow casted scenarios, i.e., extrapolations based on supply and demand assumptions, which drive water supply models and produce gaps requiring changes in supply management (e.g., drought mitigation) and/or demand management (e.g., conservation) practices. Such narrow cast scenario planning helps to enhance the robustness of quantitative forecasts, which support more thorough articulation of needs for infrastructure changes and related financing requirements.

3.6 Risk and Uncertainty Requirements to Enhance Water Planning Processes and Practices

Water planning literature distinguishes between risk and uncertainty. Risk may be generally characterized as probabilistic assessments of possible outcomes stemming from a change in operating practices or specific investments, e.g., a new trunk line or tunnel for water distribution. Probabilities may be articulated based on distinct definitions of success or failure. For example, the probability of investment loss offers a different risk assessment than the probability of asset failure within a wastewater treatment facility.

Risk is a vector-based calculation of outcome probabilities where numerous modeling tools are used to increase the robustness, or confidence, in the assessment of probable outcomes. Some methodologies include qualitative assessments from appropriate SMEs to enhance understanding of how models should be configured; then run to achieve the most robust findings, which support management and/or investment decision-making.

One promising novel approach for enriching the understanding of uncertainty in water planning is to use a combination of “preference elicitation” and “predictive modeling” to support core water supply planning models. A two-step elicitation process using online surveys and face-to-face interviews is followed by an extensive uncertainty analysis prior to integration with core water supply planning models.²⁶

Uncertainty is a broader consideration of multiple risk profiles and cumulative impacts under various operational scenarios. For instance, uncertainty in water supply planning uses models to identify plans that either perform well under a wide range of plausible future conditions (via robust decision-making) or reflect adaptive management practices that rely on progressively adjusting plans as new information becomes available. The first approach is oriented around investment decision sensitivities that are indifferent to the actual source of uncertainties. Adaptive methods are optimally activated, delayed, and/or replaced to meet supply and demand gaps that emerge.²⁷

Water planners use both frameworks when considering water supply investments and/or operational changes; where staged water infrastructure capacity expansion optimization drives plan flexibility shaped by uncertainty.²⁸ But it is important to appreciate the emphasis with respect to how uncertainty is characterized, analyzed, and incorporated into water management decision-making.

- It is primarily model driven, i.e., starting with models rather than upfront articulation of risks as discrete or multi-attribute phenomena.
- It is focused primarily on water supplies, their acquisition, storage, treatment, and delivery infrastructure.
- It is rooted in technical engineering platforms that provide extraordinary detail on how water assets are intended to perform against how they actually perform.

Thus, uncertainty can be said to be more narrowly focused and imminently understandable through a diverse array of modeling platforms. Recent platform innovations include interval-fuzzy information associated with flexible constraints and integrated interval joint probabilistic stochastic programs.²⁹

Preference elicitation with water planning SMEs works well for covering uncertainties related to marginal value changes amongst various supply investment options. Also, skillful use of preference elicitation can

²⁶ Lisa Sholten, et.al., “Tackling uncertainty in multi-criteria decision analysis – An application to water supply infrastructure planning,” *European Journal of Operational Research*, Volume 242, Issue 1, 1 April 2015.

²⁷ Erfania, et.al., *Ibid.*

²⁸ Erfania, et.al., *Ibid.*

²⁹ X.X. Ma, et.al., “An interval joint-probabilistic stochastic flexible programming method for planning municipal-scale energy-water nexus system under uncertainty,” *Energy Conservation and Management*, Volume 208, 15 March 2020.

increase the robustness of (economic) utility functions, which do influence decision choices with respect to prioritizing water supply investments.

Predictive modeling is enriched by preference elicitation regarding future socio-economic development scenarios. Scenarios in this case mean rigorous sensitivity analyses within water supply modeling platforms.

Sholten, et.al., analyzed eleven water supply alternatives ranging from conventional water supply systems to novel technologies and management schemes for sustainable water infrastructure planning in Switzerland. Four future scenarios were derived from eleven water supply alternatives. Ten diverse stakeholders were engaged to assess scenarios and recommend decisions. Results showed that preference elicitation integrated into predictive modeling helped identify best and worst case solutions.³⁰

Water resource planning and design problems, such as sequencing water supply infrastructure deployment, are influenced by what is defined as “deep uncertainties.” These are less technical factors with outcome fans that have much broader implications. For example, incorporating population dynamics and the impact of climate change are deep uncertainties that can influence more narrowly modeled capital and operations planning.³¹

To handle such uncertainties, robustness can be used to assess system performance, but its calculation typically involves many scenarios and hence is computationally expensive. Consequently, robustness tends not to be included as a formal component of water planning models. However, there are new modeling techniques, i.e., “meta-models” which are lower cost and faster to use by essentially sampling from complex simulation models to achieve indicative outcomes.³²

Issues of sustainability and “green growth” have become important factors in water planning. The dimensions of uncertainty have shifted to more robustly integrating environmental risks into modeling and planning processes.

3.7 Toward Nested Critical Water Infrastructure Planning

Nearly all other US critical infrastructure sectors depend on power and water to produce goods and services; drawing upon natural water resources to enable the provision of lifeline services. When natural water resources become scarce due to drought, disasters, or mismanagement, electric power, water and wastewater systems may compete for water resources. In a worst-case scenario, the scarcity of natural water resources could result in electric power and water shortages that adversely affect the health and economic wellbeing of a region.

The linkages between diverse CIs, therefore, are not equal in significance or priority. They are nested because power and water can determine the capacity of other CIs to function under extremely disrupted circumstances.³³ However, this does not mean they are “uncorrelated.” Analytical models show that over the longer term a disturbed infrastructure with a reduced performance level draws all other CIs to the same reduced performance level. Further, even after full restoration of CIs, their near-term performance cannot return to full operations without external support, principally through funding but also through systems integration congruence.³⁴

Another example is relevant. Power systems are known as smart grids where digital information is transmitted in real-time from end-to-end of a power grid. These smart systems are increasingly necessary to deal with instabilities in power grids coming from variable energy sources, like wind, as well as variable end-uses, mostly electronic and computational platforms. Smart systems have intrinsic vulnerabilities, i.e., a smarter power grid is more reliant on an information-communications technology (ICT) backbone. Accordingly, security for such systems depends on a set of metrics and standards unfamiliar to institutional conventional electric power delivery

³⁰ Lisa Sholten, et.al., “Tackling uncertainty in multi-criteria decision analysis – An application to water supply infrastructure planning,” *European Journal of Operational Research*, Volume 242, Issue 1, 1 April 2015.

³¹ Eva H.Y. Beh, et.al., “Robust optimization of water infrastructure planning under deep uncertainty using metamodels,” *Environmental Modeling and Software*, Volume 93, July 2017.

³² Eva H.Y. Beh, et.al., *Ibid.*

³³ A caveat to this general point is that increasingly, other CI sectors are developing resilience plans and assets, which enable autonomous or near-autonomous operation during an electric power outage of sustained duration. Insofar as water infrastructure is provisions for continuous operation during a power outage, its risks to economy and society are reduced (assuming core water supplies are not diminished to a point where zero-sum tradeoffs between energy and other CI have to be made.

³⁴ Peter Klein and Fabian Klein, “Dynamics of interdependent critical infrastructures – A mathematical model with unexpected results,” *International Journal of Critical Infrastructure Protection*, 24 (2019) 69-77.

systems. The sustainability of a power system will depend on the secure and reliable operation of the new smart system;³⁵ hence, dependence on CI sectors interdependently impacted by disruptive events.

The outcome of events and event restoration noted above reveal a nested ambiguity to CI interdependent planning. The ambiguity is a function of institutional incongruity and the inherent uncertainty of unprecedented cross impact events. Until there is a richer pallet of cases in this important CI interdependency planning space, SMEs tasked with imagining reasonable possibilities as well as extreme events, which could lead to more or less catastrophic infrastructure consequences, are a low cost-high content pathway to increasing the robustness of water and power planning in particular.

A scenario approach is a significant value-add to contemporary planning within CI sectors because CI exposures and potential impacts are distinctive at local and regional levels. National level CI planning and management, by contrast, can be focused on sources of system failures, the hardening of system structures and processes, and the mitigation of CI impactful events, such as extreme hurricanes, or pandemic management.

Using scenario planning practices provides for enhancements to core water planning models and practices, which can be thought of as nested processes. That is, CI considerations treated as part of qualitative scenario development to inform core water planning tools do not burden core planning activities with costly new quantitative modeling requirements.

Over time, “nested CI planning” can be included in core water planning efforts, CI cross impacts can be programmed into quantitative models to further enhance water planning effectiveness. Finally, these steps serve decision-makers by providing event possibilities and related failures for their consideration.

4.0 Conclusions and Recommendations

Water planning in Texas, and within each of the cities of Texas following state plans and guidelines, provides a comprehensive contemporary look at factors influencing water requirements of for decades if not a century ahead. Austin’s remarkable 100-year water plan offers an enhanced model, which leverages sophisticated water modeling capabilities that informed its planning efforts. Other cities, e.g., Dallas and Houston, have distinctly relevant and thorough contemporary water plans as well.

This paper calls out opportunities for enhancing water planning, which enables the state, its cities, and water planning districts to incorporate more qualitative risks and opportunities that bear on both near-term and longer-term planning horizons. Scenario planning practices were discussed. Illustrations of how to integrate broad-based scenarios were included. They leverage existing narrow-cast scenarios used for assessing the robustness of quantitative water plans.

One additional consideration emerged from review of city and state water plans and covering relevant academic and trade literature on water planning. Over the last two decades, critical infrastructure planning has become a more important framework. It can be applied to existing planning systems and processes or it can be leveraged to create a new interstitial level of planning that integrates diverse CI plans. This enables individual plans to be more robust in dealing with essential services events. It also enhances state level plans for how to ensure effective coordination and mutual support across CIs running up to, during, and closing out severely disruptive events, such as droughts, flooding, or other natural or human induced attacks.

ISE recommends taking the following steps to evaluate and then determine if contemporary planning systems and processes across CIs are adequate or warrant enhancements. A sequence for doing so includes these steps:

- (1) Conduct a statewide review of existing critical infrastructure plans and identify the extent of integration for dealing with cross impacting interdependencies.
- (2) Based on findings in (1) develop a prototypical integrated CI planning process that leverages existing planning and minimizes added costs while maximizing added benefits in each of the main CI sectors.
- (3) Following the work in (2), conduct a pilot program that adds scenario planning to contemporary infrastructure planning and uses scenario planning techniques to create planning tools that help to integrate CI sector plans into an overall, comprehensive CI plan for the state and its cities.

Perhaps the most significant finding of this research is the scope of essential service interdependencies in the energy-water-food nexus that seems to stand alone when at the heart of each resides difficult allocation tradeoffs all decision-makers would prefer to avoid having to make.

³⁵ Baraa Mohandes, Reem Al Hammadi, Wasiu Sanusi, Toufic Mezher, Sameh El Khatib, “Advancing cyber-physical sustainability through integrated analysis of smart power systems: A case study on electric vehicles,” *International Journal of Critical Infrastructure Protection*, 23 (2018) 33-48.

ISE recommends that this constellation of planning domains and how they overlap become the new framework for essential service and critical infrastructure planning for the state. On the basis of success here, Texas could lead the nation in extending contemporary CI planning relevance for ensuring safe, reliable, and affordable essential services for the 21st Century.



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