



International Journal of Multidisciplinary Research and Growth Evaluation.

Uncertainties in Global Water Infrastructure: Exploring Sensitivities and Interdependencies

Tanay Kulkarni

Infrastructure Management Consultant, USA

* Corresponding Author: **Tanay Kulkarni**

Article Info

ISSN (online): 2582-7138

Volume: 04

Issue: 04

July-August 2023

Received: 28-06-2023

Accepted: 25-07-2023

Page No: 1131-1138

Abstract

Global water infrastructure stands at the crossroads of pressing challenges—including environmental degradation, socio-economic pressures, and climate change—that significantly complicate planning and decision-making. The United Nations Sustainable Development Goals, mounting concerns about climate extremes, and shifts in global demographics underline the imperative for robust and adaptive water infrastructure systems. This review paper explores global water infrastructure projects' uncertainties, vulnerabilities, and interactions. It investigates a suite of aspects ranging from risk allocation under public-private partnership frameworks to advanced engineering technologies for online water quality monitoring, as well as scenario-neutral and scenario-informed approaches to vulnerability analysis. Furthermore, we discuss how shifts in hydrological regimes, socio-economic demands, and institutional complexities interweave to challenge conventional water management paradigms. The review concludes by advocating for integrated and adaptive water management solutions, emphasizing the synergy of engineering, economics, and governance to achieve sustainable outcomes in water infrastructure planning.

DOI: <https://doi.org/10.54660/IJMRGE.2023.4.4.1131-1138>

Keywords: Sustainable urban water management; Infrastructure; Multi-criteria decision making; Risk assessment and management; Sensitivity analysis; Uncertainties

1. Introduction

Water infrastructure systems—encompassing water supply, sanitation, stormwater management, and wastewater treatment—are fundamental to human well-being, economic activities, and ecological stewardship (Hellström, Jeppsson, & Kärrman, 2000). These systems have historically been planned by referencing known hydrologic conditions and established socio-economic norms, often presuming stationarity in climate and steady growth in demands (Brown, Keath, & Wong, 2009). However, the contemporary era is marked by significant disruption: intensifying climate change impacts (Christensen *et al*, 2007), accelerating urbanization (Zhou, 2014), aging assets (Truffer *et al*, 2010), and evolving socio-political contexts (Marques & Berg, 2010). These drivers add layers of uncertainty to the entire water infrastructure life cycle—from initial feasibility to design, construction, and eventual operation and maintenance (Hajkowicz & Collins, 2007).

At the same time, water projects are increasingly expected to serve multiple, and sometimes competing, objectives: from ensuring public health and hygiene (Sadiq & Rodriguez, 2004) to enabling socio-economic opportunities (Aschauer, 1990) and protecting or even enhancing environmental conditions (Wong & Brown, 2009). The heightened variability in climatic parameters, from shifting precipitation patterns to extreme drought or flood conditions (Naumann *et al*, 2014), calls for scenario-based and vulnerability-informed planning frameworks that can robustly guide policy and investment decisions (Quinn *et al*, 2020). The complexities are further magnified by stakeholder multiplicity (Lienert, Schnetzer, & Ingold, 2013), where each actor—be it municipal authorities, private investors, agricultural interests, or environmental advocates—operates with unique values, risk tolerances, and resource constraints (Brown, Keath, & Wong, 2009).

This situation underscores the necessity of an integrated approach that systematically accounts for uncertainties in climate projections, water demand forecasts, socio-institutional factors, and technological innovations (Hutton, Haller, & Bartram, 2007). In parallel, public-private partnerships (PPPs) have become a salient vehicle for executing large water infrastructure projects, shifting risk allocation and sharing responsibilities among state and private sectors (Marques & Berg, 2010). The success of these partnerships' hinges on well-articulated contracts that align incentives and responsibilities, ensuring that risks rest with the party best able to manage them (Crampes & Estache, 1998).

Consequently, this paper seeks to:

1. Explore the major uncertainties in global water infrastructure, focusing on climatic, socio-economic, and institutional drivers.
2. Demonstrate how advanced modeling methods—particularly scenario-neutral analyses—facilitate robust decision-making under deep uncertainty (Lempert & Collins, 2007; Prudhomme *et al.*, 2010).
3. Examine the interplay of these uncertainties, highlighting how alternative experimental design choices in vulnerability assessment can alter conclusions about critical factors, stakeholder sensitivities, and policy robustness (Quinn *et al.*, 2020).
4. Present a correlation matrix for uncertainties, gleaned from references that highlight interactions among hydrologic, institutional, and socio-technical variables.
5. Synthesize best practices for applying multi-criteria analyses (MCA) and resilience frameworks (Hajkowicz & Collins, 2007) in water infrastructure planning.

In the next section, we undertake a comprehensive literature review of water infrastructure uncertainties, citing over 40 relevant works that anchor our conceptual and methodological approaches. Subsequent sections detail the methodological frameworks, culminating with policy implications for designing robust and adaptive water infrastructure systems.

2. Literature review of water infrastructure uncertainties

2.1 Historical evolution of water infrastructure management

Historically, water and wastewater systems have incrementally evolved to address pressing public health and environmental concerns (Brown, Keath, & Wong, 2009). The 19th and early 20th centuries witnessed a “Water Supply City” paradigm, focusing on centralized hydraulic engineering solutions for drinking water provision (Hellström *et al.*, 2000). Subsequent eras, from the “Sewered City” onward, integrated wastewater disposal and drainage to mitigate flood risk (Brown, Keath, & Wong, 2009). In many high-income regions, these infrastructures have matured but now face obsolescence, requiring expensive overhauls or expansions (Lienert *et al.*, 2013). Meanwhile, water resource management philosophies have shifted from supply-side expansions—build more dams, channels, and pipes—to integrated, demand-oriented frameworks. The rise of Integrated Urban Water Management (IUWM) and Water Sensitive Urban Design (WSUD) underscores the multi-faceted approach—recognizing the water cycle as an interconnected system of supply, sewage, and stormwater

management that must simultaneously meet social, environmental, and economic objectives (Wong, 2006; Zhou, 2014).

2.2 Emergence of complexity and deep uncertainty

Modern water systems face deep uncertainties due to climate change, rapid urbanization, changing governance structures, and shifting socio-economic conditions. The shift away from stationary hydrologic assumptions is particularly significant: as climate warming intensifies, precipitation extremes—droughts and floods—are predicted to become more frequent and severe (Christensen *et al.*, 2007; IPCC, 2013). This has led to new modeling frameworks, such as scenario-neutral and robust decision-making analyses, to stress-test infrastructure design assumptions (Brown & Wilby, 2012). Simultaneously, socio-economic evolutions—population growth, rising standards of living, altered consumption patterns—change the demand side in ways that are difficult to forecast precisely (Groves *et al.*, 2015). The combined effect can amplify the potential for surprise events, or “black swans,” that reveal system vulnerabilities (Quinn *et al.*, 2020).

2.3 Risk allocation and public-private partnerships

Infrastructure projects, especially in developing and emerging economies, increasingly rely on partnerships with private enterprises. PPPs are lauded for infusing capital, technical expertise, and managerial efficiency, but risk assignment is crucial (Marques & Berg, 2010). A contract that places all risk on the private sector can prompt cost escalation and renegotiation soon after project launch (Guasch, 2004). On the other hand, a purely public arrangement may lead to moral hazard, poor incentives for efficiency, or insufficient funds for maintenance (Nisar, 2007).

Hence, contract design must be carefully studied for key risk classes: political, demand, financial, operational, and environmental (Crampes & Estache, 1998). For water utilities, the difficulty arises in the mismatch between short political cycles and the long horizon of water infrastructure assets (Marques, 2010). The literature suggests that robust PPP contracts include meticulously defined responsibilities, contingency plans, performance-based metrics, and explicit renegotiation clauses under extraordinary circumstances (Haarmeyer & Mody, 1998; Marques & Berg, 2009).

2.4 On-Line monitoring and early warning systems

Concurrent with the shift in financing and management, new technologies in water quality monitoring have emerged. On-line sensors for turbidity, chlorine residual, pH, and advanced biomonitoring provide near-real-time data to detect contamination events, whether accidental or intentional (Storey *et al.*, 2010). A major impetus for these technologies is the desire to replace lagged laboratory analysis with immediate feedback loops that can inform operators promptly, thus limiting adverse health impacts (Frey & Sullivan, 2004; van der Gaag & Volz, 2008).

Nevertheless, these advanced systems face operational and interpretational hurdles. Maintaining sensor calibrations, dealing with fouling, and processing large data streams in real time remain persistent obstacles (USEPA, 2005). Integrating early warning systems within a broader risk management framework demands clear institutional roles, where communication protocols trigger appropriate operational responses and public advisories (Storey *et al.*, 2010).

2.5 Multiple criteria analysis and decision support

In the face of multiple, conflicting objectives—cost-efficiency, reliability, water quality, ecological integrity—multi-criteria analysis (MCA) frameworks have gained traction in water management (Hajkowicz & Collins, 2007). MCA methods—ranging from simple weighted summation (Keeney & Raiffa, 1993) to outranking approaches such as ELECTRE/PROMETHEE (Figueira *et al*, 2005a, 2005b)—help decision-makers rank or score alternative project designs. For instance, selecting a reservoir expansion vs. a water reuse plant vs. demand management can be evaluated along axes of cost, environmental impact, social acceptance, and health outcomes.

Hajkowicz and Collins (2007) highlight the surging popularity of MCA in water resources planning, citing over 100 case studies worldwide. Pairwise comparison approaches (AHP, ANP) can facilitate group decision-making when data are uncertain or intangible criteria weigh heavily (Saaty, 1987). Meanwhile, advanced fuzzy set analyses handle lexical uncertainties in stakeholder judgments (Zadeh, 1965; Islam *et al*, 2017). The synergy of MCA with scenario analyses—both scenario-neutral and scenario-informed—enhances the robustness of final recommendations (Dittrich *et al*, 2016).

2.6 Scenario-Neutral Approaches vs. Scenario-Informed

With no consensus on how precisely to characterize future climate conditions, many water managers adopt scenario-neutral approaches (Brown *et al*, 2012). They sample an expansive range of temperature and precipitation changes and treat them as equally plausible, identifying the “vulnerability domain” in which performance metrics fail to meet thresholds (Prudhomme *et al*, 2010). This approach avoids over-reliance on climate model ensembles that might poorly capture local variability or be correlated in ways that hamper independent sampling (Steinschneider *et al*, 2015).

However, as Quinn *et al* (2020) emphasize, the choice of range and the assumption of uniform independence across hydrologic factors can significantly sway conclusions about user vulnerabilities and policy robustness. Scenario-informed approaches, by contrast, incorporate available climate model projections or paleohydrologic reconstructions to limit the scenario space. But these too can omit extremes not present in the projections or fail to reflect actual future forcing scenarios (Stainforth *et al*, 2007). Reconciling these approaches demands a multi-pronged analysis that tests the sensitivity of policy decisions to the assumptions embedded in each scenario design (Herman *et al*, 2020).

2.7 Institutions, stakeholders, and participation

Beyond the technical complexities, water infrastructure planning is intrinsically socio-political (Hering & Ingold, 2012). Investigations in stakeholder analysis consistently find that the success of large-scale projects depends on structured involvement of relevant actors, from private sector operators to local communities, from regulators to NGOs (Lienert *et al*, 2013). Tools such as social network analysis reveal the fragmentation between different administrative levels—federal, state, municipal—and between water supply, wastewater, and stormwater sectors (Brown, Keath, & Wong, 2009). This fragmentation can hamper integrated and adaptive strategies (Ingold *et al*, 2010).

Stakeholder analysis combined with social network analysis offers fine-grained insights into the power dynamics,

collaboration, and trust relationships among entities, which influence how effectively new measures are implemented (Lienert *et al*, 2013). This is especially pertinent for complex transboundary or cross-jurisdictional water systems, for example, the Colorado River, where hundreds of diverging uses must be balanced under prior appropriation law (Quinn *et al*, 2020).

2.8 The role of sensitivity and uncertainty analyses

In scenario-based planning, it is not enough to define a scenario space. Analysts must also parse out which factors most strongly affect performance. Sensitivity analyses—decomposing the variance in model outputs relative to uncertain inputs—help identify high-priority uncertainties for monitoring or research (Kwakkel, 2017). Herman *et al* (2015) demonstrate how factor-mapping and factor-ranking analyses can highlight the threshold conditions at which system performance flips from success to failure. This approach is especially valuable for designing adaptive management triggers: “If precipitation declines beyond X, or if population growth surpasses Y, then implement the next stage of infrastructure expansion” (Groves *et al*, 2015).

Nevertheless, the results of factor-ranking sensitivity analyses can vary if the scenario space is restricted or expanded in ways that systematically skew the distribution of inputs. As Quinn *et al* (2020) highlight, factor importance for water user vulnerabilities in the Upper Colorado River changed drastically when scenario expansions were introduced or when certain climate extremes were considered improbable. This points to an urgent need for meta-sensitivity analysis over alternative scenario designs (Saltelli *et al*, 2020).

3. Key uncertainties, vulnerabilities, and sensitivity approaches

In this section, we synthesize the complexities discussed in the preceding literature and elaborate on how they manifest in real-world contexts. We structure this discussion around three major dimensions of uncertainties: (1) climatic and hydrologic uncertainties, (2) socio-economic and institutional uncertainties, and (3) technological and operational uncertainties. We further demonstrate how these uncertainties interconnect with project vulnerabilities and how sensitivity analyses can clarify or obfuscate which factors truly matter for robust infrastructure management. Along the way, we present a correlation matrix that conceptualizes the multiple interdependencies.

3.1 Climatic and hydrologic uncertainties

3.1.1 Changing precipitation and temperature patterns

One foundational uncertainty lies in how precipitation regimes shift with global warming (IPCC, 2013). Regions dependent on snowmelt—such as the western United States, central Asia, and the European Alps—may see earlier runoff peaks (Barnett *et al*, 2005). This shift threatens well-established storage and distribution schedules (Herman & Giuliani, 2018). Meanwhile, temperature increases can exacerbate evapotranspiration, thus raising irrigation demands. For instance, in the Upper Colorado River Basin, Quinn *et al* (2020) found that rising temperatures were a primary driver of water scarcity for mid-priority water right holders.

A critical question is whether future precipitation–temperature combos remain within historical envelopes or if

“nonstationary” phenomena produce unprecedented extremes. Paleo-based evidence for the southwestern United States suggests the possibility of megadroughts more severe than any in modern records (Woodhouse *et al*, 2006). If so, reservoir rule curves or irrigation expansions might fail catastrophically (Ault *et al*, 2014). In scenario-neutral analyses, the entire feasible domain of T–P changes may be sampled, yet a uniform weighting across that domain may overemphasize improbable extremes (Brown & Wilby, 2012). On the other hand, ignoring these extremes might produce under-robust solutions.

3.1.2 Flood risk and storm intensity

Though dryness and scarcity often top water managers’ concerns, extreme rainfall and floods can also disrupt infrastructure. Urban drainage systems designed for storms of a certain return period may be overwhelmed by intensifying convective events (Zhou, 2014). The coupling to aging combined sewer overflow (CSO) systems means elevated risk of contamination in receiving water bodies. Designing for these extremes requires new precipitation frequency estimates with wide uncertainty bounds. Scenario-neutral frameworks typically vary the intensity and frequency of storms across a wide range, but local hydroclimatological processes can exhibit strong correlation structures—synchronous temperature and precipitation shifts, among others (Herman *et al*, 2015).

3.1.3 Groundwater Depletion

An often-overlooked aspect is the reliance on groundwater for bridging supply shortfalls. Chronic overpumping in aquifer systems worldwide (e.g., North China Plain, Indo-Gangetic Basin, southwestern United States) points to unsustainable usage patterns (Barthel & Banzhaf, 2016). The vulnerability arises when groundwater is presumed as a fallback under climate-induced surface shortfalls, yet the resource itself is diminishing. Sensitivity analyses that only consider climate variability, ignoring aquifer drawdown, can drastically underestimate supply risk (Babiker *et al*, 2005). Under deeper integration, uncertain aquifer recharge rates, driven by land use changes (Wong & Brown, 2009) and climate shifts, complicate future water budgeting.

3.2 Socio-Economic and institutional uncertainties

3.2.1 Population growth and urbanization

Global population is expected to surpass 9 billion in the coming decades, with the majority of growth in urban areas (United Nations, 2019). Rapid urbanization implies heightened water demands for domestic, commercial, and industrial purposes, as well as increased impervious surfaces that intensify stormwater runoff (Zhou, 2014). The location, timing, and scale of these changes remain uncertain, complicating capacity expansions for water distribution, sanitation networks, and storm drains (Brown, Keath, & Wong, 2009).

In many middle-income countries, the speed of new construction is outpacing institutional capacity to regulate or integrate best practices (Brown *et al*, 2012). Scenario analyses that treat population growth as a single uncertain variable might miss the spatial dimension: exurban expansions can add complexity if water must be transported across watersheds or if new wastewater disposal sites cannot be sited easily (Lienert *et al*, 2013). Some scenario-based approaches incorporate multiple socio-economic “storylines”

(Ray *et al*, 2018), but the complexity of real estate, Demographics, and infrastructure financing fosters large irreducible uncertainty.

3.2.2 Economic growth and water pricing

Parallel to population growth are uncertain demands shaped by shifting economic activities—agribusiness expansions, shifts from water-intensive manufacturing to services, or changes in global supply chains (Aschauer, 1990). Where water pricing is regulated, as it is in many PPP or municipal contexts, the tariff structure heavily influences consumption patterns and cost recovery (Hutton, Haller, & Bartram, 2007). Price elasticity of demand is itself uncertain, further muddying the reliability of revenue forecasts for PPP investors (Marques & Berg, 2010). Moreover, subsidy policies for agriculture or low-income households can produce demand patterns that deviate from purely market-driven logic.

Hence, a robust water infrastructure plan must handle broad ranges in potential demand. Freedman (2018) found that localities adopt “adaptive tariffs” triggered by certain levels of system stress, requiring scenario-based modeling that includes uncertain triggers. The synergy with climate extremes is non-trivial: if a region’s economy depends on stable hydropower or eco-tourism, a multi-year drought might degrade fiscal capacity to expand infrastructure (Naumann *et al*, 2014).

3.2.3 Governance and Policy

Institutional fragmentation can hamper integrated water management. Federal–state–local tensions, overlapping agency roles, or conflicting legal frameworks shape how water is allocated or regulated (Brown, Keath, & Wong, 2009). A prime example is the Colorado River Compact, which imposes constraints on upstream consumptive uses to ensure downstream deliveries, but the enforcement mechanism under extraordinary drought remains uncertain (Quinn *et al*, 2020). Similarly, in transnational basins like the Nile or Mekong, multi-lateral treaties may or may not hold if hydropolitical relations sour.

Uncertainty in governance can manifest as abrupt policy shifts or renegotiations. In PPP contexts, the risk of expropriation or abrupt changes in water tariffs fosters uncertainty for private investors (Marques & Berg, 2010). In scenario-driven approaches, these governance uncertainties are typically approximated by discrete “shock” scenarios (Herman *et al*, 2015). Factor-importance analyses struggle to incorporate these low-probability, high-impact institutional shifts (Hoffmann *et al*, 2011).

3.3 Technological and operational uncertainties

3.3.1 Advanced monitoring and early warning

The advent of on-line sensors for water quality is hailed as a major operational improvement, permitting real-time detection of accidental or intentional contamination (Storey *et al*, 2010). However, the technology has limitations: sensor drift, false positives, maintenance overhead, and big-data complexity hamper widespread deployment. Even if utility managers plan for a certain operational advantage from these systems, the realized benefit might be uncertain (Hohman, 2007). The interplay of limited budgets, untested commercial products, and potential for nuisance alarms is an institutional friction, further complicating scenario-based reliability planning (van der Gaag & Volz, 2008).

3.3.2 Infrastructure aging and maintenance

Water systems in developed nations are often old, with some pipes exceeding a century of service. Proactive rehabilitation or replacement is hindered by uncertain asset condition and limited finances. Meanwhile, developing countries often face the opposite problem: leapfrogging from minimal water infrastructure to advanced solutions that require robust institutional and financial architecture. The classical approach of building large, centralized plants is sometimes overshadowed by small-scale, decentralized or modular systems advocated under water-sensitive paradigms (Wong & Brown, 2009). The success of such new approaches depends on local acceptance, reliability of supply chains, and operator training.

Adopting mechanistic or statistical models of asset failure can improve maintenance scheduling, but large data gaps remain. Info-gap decision theory (Ben-Haim, 2006) is occasionally used to handle severe knowledge deficits about system deterioration, but its adoption is not universal. Meanwhile, multi-objective robust optimization frameworks unify decisions about expansions, upgrades, and day-to-day operations under uncertain deterioration (Herman *et al*, 2014).

3.4 Sensitivity analysis of factor importance

Once a scenario space is defined, factor-ranking sensitivity analysis decomposes which uncertainties most explain the variance in performance (Saltelli *et al*, 2008; Herman *et al*, 2015). For a water supply reliability model, this might rank the portion of variance explained by precipitation, temperature, reservoir capacity, operational rules, or demand growth. If precipitation emerges as primary, the recommended monitoring might focus on precipitation trends (Groves *et al*, 2015). If institutional stability or PPP contract terms overshadow climatic factors, the approach to risk management changes fundamentally (Marques & Berg, 2010).

However, as Herman *et al* (2015) and Quinn *et al* (2020) caution, the scenario design—how factors are sampled, their ranges, correlation constraints—shapes these sensitivity results. Under a broad uniform design, certain extremes might overshadow other plausible conditions. Under a more constrained scenario set (e.g., climate model-based), factor importance might differ. The final best practice is to test factor-importance across multiple scenario sets to ensure consistency (Herman *et al*, 2020).

3.5 Implications for monitoring program design and adaptive management

From a policy standpoint, once factor-importance is established, water agencies can direct monitoring resources to track the most critical uncertainties (Kwakkel *et al*, 2016). If local precipitation is not as relevant as external water import availability, emphasis might shift to measuring flows from import basins or analyzing interstate compacts (Groves *et al*, 2015). Alternatively, if workforce availability emerges as a critical factor for expansions, policies might incorporate robust labor development or contract structures that handle labor shortfalls (Marques & Berg, 2010).

Similarly, adaptive management uses factor-based triggers. If scenario analyses show that a certain threshold in temperature rise plus a certain precipitation deficit cause reliability failure, managers define triggers for new expansions at that threshold (Haasnoot *et al*, 2013). This synergy between

advanced monitoring and scenario-based triggers is powerful, but only if scenario designs do not systematically omit relevant extremes.

3.6 Contrasting scenario-neutral vs. scenario-informed approaches

We re-emphasize the tension between scenario-neutral sampling, which uses wide uniform bounds, and scenario-informed sampling, which uses climate projections or paleodata (Brown & Wilby, 2012; Quinn *et al*, 2020). The scenario-neutral approach can artificially inflate the presence of extreme dryness or wetness, whereas scenario-informed might exclude out-of-sample extremes. Both might incorrectly identify the primary risk drivers or robust solutions. The recommended approach is a multi-design exploration (Herman *et al*, 2020).

In the Colorado River Basin, scenario-neutral analyses of temperature and precipitation identified temperature as the main driver for mid-priority water user shortages (Quinn *et al*, 2020). But restricting the scenario space to historical or paleo ranges might highlight precipitation as more important. Divergent conclusions hamper consistent management triggers, thereby undermining “neutrality.” Summarizing multiple scenario sets can yield robust strategies that function well across them or highlight unsolved trade-offs.

3.7 Real-World illustrations: The Colorado River basin

As a deeper illustration, Quinn *et al* (2020) studied hundreds of water users in the Upper Colorado River Basin. Their analysis found that differences in scenario range expansions or correlations significantly affect which factors appear most critical for user vulnerabilities. For instance, a scenario set strongly focusing on temperature extremes singled out temperature as the culprit for water stress among junior rights. Another scenario set that recognized the correlated precipitation–temperature extremes from climate models found precipitation deficits overshadowed temperature alone. Ranking user robustness shifted accordingly, with some mid-priority users faring better under one scenario set but worse under another.

These divergences matter for policy: a manager that invests in advanced temperature-based monitoring might miss the early signals of persistent precipitation shortfalls if the system truly depends on correlated dryness (Brown & Wilby, 2012). The ultimate conclusion is that water resource planners must examine multiple scenario framings to avoid illusions of robustness or illusions of factor importance.

3.8 Synthesis: Toward a holistic understanding

The preceding sections highlight that water infrastructure vulnerability cannot be reduced to single-dimension analyses. We have seen how climate, socio-economics, and institutions each exhibit internal complexities and cross-factor correlations. Traditional single-scenario or single-criterion analyses fail to capture these multi-dimensional vulnerabilities and potential interactions. The integrated approach championed by leading frameworks (Brown, Keath, & Wong, 2009; Herman *et al*, 2014) is essential for both new and existing water infrastructure.

Key takeaways include:

- **Uncertainty layering:** The interplay of climate extremes with socio-economic shifts can create non-linear or threshold-based vulnerabilities.

- **Risk allocation:** PPP contracts must explicitly handle potential climate or policy shocks.
- **Monitoring:** Next-generation sensor systems can reduce latency in responding to contamination or shortage events, but sustaining them requires robust institutional arrangements.
- **Multi-design scenario analyses:** Planners are encouraged to test factor-importance under multiple scenario expansions, reducing the likelihood of misguided policy triggers or misallocated resources.

4. Conclusions and recommendations

This review interrogates the deep complexities of planning, constructing, and operating water infrastructure under multi-dimensional uncertainties. It is found that:

1. **Infrastructure is multi-dimensional:** Beyond physical pipes and plants, water systems integrate social, economic, political, and technological elements that shape resilience (Aschauer, 1990; Brown, Keath, & Wong, 2009).
2. **Deep uncertainty abounds:** No single approach comprehensively addresses the unpredictability of climate, socio-economics, or institutional change. Stationarity assumptions are obsolete, mandating scenario-based approaches (Brown *et al*, 2012; Lempert & Collins, 2007).
3. **Scenario design drives vulnerability and robustness conclusions:** So-called scenario-neutral approaches are not inherently neutral. Their uniform sampling can mismatch real-world correlation structures, leading to different factor-importance and user vulnerability outcomes than scenario-informed or hybrid approaches (Quinn *et al*, 2020; Herman *et al*, 2020).
4. **PPP contract design is critical:** Partnerships expedite capital inflows but require carefully designed risk-sharing and oversight. The mismatch between short political cycles and the long horizon of infrastructure assets can cause frequent renegotiations if not properly accounted for (Crampes & Estache, 1998; Marques & Berg, 2010).
5. **Technological innovations:** On-line water quality monitoring and advanced early warning systems promise improved safety but face reliability and interpretational hurdles (Storey *et al*, 2010). Integrating them effectively demands stable institutional frameworks and robust data systems.
6. **MCA and participatory governance:** Multi-criteria methods help navigate complex trade-offs and incorporate stakeholder values. Social network analysis reveals fragmentation across governance levels, highlighting the need for integrated institutional arrangements to support water-sensitive transitions (Lienert *et al*, 2013; Brown, Keath, & Wong, 2009).
7. **Adaptive management:** Identifying triggers for action requires clarity on which uncertainties to monitor. Factor-importance analyses must be consistent across multiple scenario designs or risk overlooking critical thresholds (Groves *et al*, 2015; Quinn *et al*, 2020).

In conclusion, forging a path toward sustainable and robust water infrastructure demands a synergy of scenario-based modeling, multi-criteria decision support, carefully structured PPPs, advanced monitoring technologies, and inclusive stakeholder processes. The “neutrality” of scenario

analyses is, in practice, conditional upon the scenario design. Planners should adopt multi-design frameworks to ensure that their insights into factor-importance and policy robustness remain valid amid the unknown contours of future climate, socio-economics, and governance. By implementing these recommended best practices, water infrastructure systems can better address the intensifying challenges of the 21st century—securing reliable services, protecting public health, and safeguarding ecosystems for generations to come.

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