



## Growth of the Decision Tree: Advances in Bottom-Up Climate Change Risk Management

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**Research Impact Statement:** Proposed advancements in the state of the art in climate change risk management, with emphasis on impact and likelihood aspects of multidimensional analysis.

**ABSTRACT:** There has recently been a return in climate change risk management practice to bottom-up, robustness-based planning paradigms introduced 40 years ago. The World Bank's decision tree framework (DTF) for "confronting climate uncertainty" is one incarnation of those paradigms. In order to better represent the state of the art in climate change risk assessment and evaluation techniques, this paper proposes: (1) an update to the DTF, replacing its "climate change stress test" with a multidimensional stress test; and (2) the addition of a Bayesian network framework that represents joint probabilistic behavior of uncertain parameters as sensitivity factors to aid in the weighting of scenarios of concern (the combination of conditions under which a water system fails to meet its performance targets). Using the updated DTF, water system planners and project managers would be better able to understand the relative magnitudes of the varied risks they face, and target investments in adaptation measures to best reduce their vulnerabilities to change. Next steps for the DTF include enhancements in: modeling of extreme event risks; coupling of human-hydrologic systems; integration of surface water and groundwater systems; the generation of tradeoffs between economic, social, and ecological factors; incorporation of water quality considerations; and interactive data visualization.

(KEYWORDS: sustainability; planning; uncertainty analysis; risk assessment; decision support systems; water resource economics; climate variability/change.)

### INTRODUCTION

Matalas and Fiering's (1977) chapter of the National Research Council's "Climate, Climatic Change, and Water Supply" was entitled, simply, "Water-Resource Systems Planning," and was remarkable in at least these four ways: (1) it acknowledged the nascent science indicating that anthropogenic climate change might have substantial impacts on water-resource systems; (2) it calmly

applied the tools of stochastic analysis to "reducing risk of error in anticipation of climate shifts"; (3) it addressed conflicts of interest and the need for water-resource system designs that satisfy economic, institutional, social, and political concerns; and (4) it introduced the three R's: Robustness, Regret, and Resilience, which had not previously been used in a water resource context.

The United States (U.S.) Water Resources Council's Principles and Standards for Planning Water and Related Land Resources (1973) "attempted to

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provide for uniformity and consistency in formulating alternative plans and in measuring, comparing, and judging their beneficial and adverse effects” (Eisel et al. 1982). Matalas and Fiering (1977) created an analytical construct that formalized the loose amalgamation of existing “best management practices” that had been developed by the engineering professionals of that era in response to the U.S. Water Resources Council’s (1973) guidance. Robustness they defined as “the insensitivity of system designs to errors, random or otherwise, in the estimates of those parameters affecting design choice.” Regret was “opportunity loss,” or the difference between the performance of the real system and the performance of the ideal system. The resilience of a system was described as its ability to adjust (or be operated in a different way) so as to keep economic losses below some critical threshold. Matalas and Fiering (1977) further drew distinctions between the resilience of a particular design and the resilience of a system, using the example that a system of small reservoirs may have higher resilience than a single, “equivalent,” large reservoir. Hashimoto et al. (1982) presented mathematical relationships for robustness, vulnerability, and resilience, and Loucks (1997) quantified sustainability (an algebraic combination of the three presented by Hashimoto et al. (1982)), but the foundational conceptualizations put forth by Matalas and Fiering (1977) remain essentially unchanged.

Matalas and Fiering (1977) argued that, “although it may not be possible at present quantitatively to define climatic change and its hydrological impacts even in probabilistic terms, the uncertainty can be dealt with explicitly in the development and management of water-resource systems.” Figure 1 is an example of their approach. It shows that, if some version of the water-resource system design is adequate over an area of the mean-variance ( $\mu$ ,  $\sigma$ ) plane of some hydro-climatic variable (e.g., streamflow) representative of some reasonable bounds of climate change uncertainty, then “precise specification of those parameter values becomes unimportant.” The design choice is made based upon the confidence of the planner in the likelihood (shown for the hydro-climatic parameters under consideration as pdfs on each axis of Figure 1, and elliptical bivariate confidence intervals on the response surface) of some combination of hydro-climatic characteristics, with ample safety margins, especially for designs that perform well over a relatively larger uncertainty space (e.g.,  $D_5$ ,  $D_6$ ). The design indicated in each enclosed subspace results in low regrets relative to other designs within the specified range of hydro-climatic characteristics.

In order to make Figure 1 and use it as a decision support tool, we need to: (1) be able to simulate the

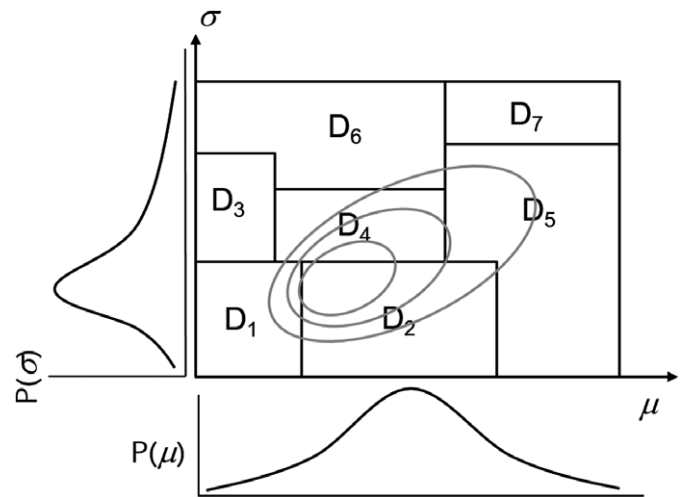


FIGURE 1. Optimal system design zones conditioned on  $\mu$  and  $\sigma$  of some hydro-climatic variable (e.g., streamflow). Modification of Matalas and Fiering (1977) figure 6.3a. Likelihood functions shown for the hydro-climatic parameters under consideration as pdfs on each axis, and elliptical bivariate confidence intervals on the response surface. The design indicated in each enclosed subspace results in low regrets relative to other designs within the specified range of hydro-climatic characteristics.

performance of our water-resource system across a wide range of hydro-climatic conditions; and (2) develop an estimate of the likelihoods associated with each enclosed subspace. Part 1 is the work of analysts. Part 2 is the work of decision makers, who must translate a combination of the most credible science (provided to them by analysts), their own sector-specific expertise, and their “beliefs” (influenced by relevant local experience), into weights on possible future local conditions (climate and other).

Much good work was accomplished between the late-1980s and the mid-2000s in part 1 of Matalas and Fiering’s (1977) paradigm (the simulation of water system performance across a wide range of hydro-climatic conditions). This was done, principally, by downscaling the global meteorological output of general circulation models (GCMs) for input to local or regional hydrologic models, and using the hydrologic models to develop input to project-specific (or system-specific) water-resource system models. Notable impact assessment examples include: the Sacramento-San Joaquin Basin (Gleick 1987; Lettenmaier and Gan 1990); the Delaware River Basin (McCabe and Ayers 1989); the Columbia River Basin (Hamlet and Lettenmaier 1999; Payne et al. 2004); the Colorado River Basin (Christensen et al. 2004); the city of Boston (Kirshen et al. 2008); and a U.S. regional assessment (Lettenmaier et al. 1999).

These studies all provided valuable insight into the water system response to altered climate. However, instead of generating response surfaces indicating

design preference across ranges of likelihood-weighted hydro-climatic conditions, most pre-2010 climate change risk assessments reported the water system performance that would result were climate change to occur as represented by a certain subset of simulations from whatever happened to be the current generation of Intergovernmental Panel on Climate Change climate change scenarios (or, in the case of most pre-2000 studies, climate change scenarios from available National Assessments run through the GCMs of participating climate modeling laboratories). Because the results were contingent on the quality of GCM output, and offered little information regarding the relative likelihood of each evaluated scenario, they tended to be of limited value for decision making (IEG 2012). In this way, these studies departed from the robustness-based planning paradigm presented in Figure 1. Decision scaling (Brown et al. 2012) and other scenario-neutral approaches to climate change risk management (e.g., Ben-Haim 2006; Lempert et al. 2006; Prudhomme et al. 2010) marked a return.

### *Robustness-Based, Bottom-Up Decision Analysis*

Bottom-up planning paradigms emphasize analysis tailored to the needs of the local project stakeholders (as opposed to top-down analysis developed for the generic case), and robustness-based planning paradigms value the ability to perform well across a wide range of unpredictable possible futures over the ability to perform optimally in some expected future state.

Decision scaling (also referred to as Climate Informed Decision Analysis) is an approach to integrating current best methods for climate risk assessment and robust decision analysis with simple procedures for risk management. First applied to the Upper Great Lakes (Brown et al. 2011), it makes use of a stress test for the identification of system vulnerabilities, and simple, direct techniques for the iterative reduction of system vulnerabilities through targeted design modifications. Its principal distinction relative to other robustness-based approaches, and its unique relevance to assessment of climate-change-related risks (among all other risks facing water-resource systems), is its bottom-up use of climate information: decision scaling uses weather generators (e.g., Steinschneider and Brown 2013) to condition climate scenarios primarily on statistics of internal variability and physically based local climate drivers. It refers to top-down climate science (e.g., GCM output) for likelihood information as a post-processing step in the vulnerability assessment only, superimposing a response surface similar to that shown in

Figure 1 with climate trend- and projection-derived bivariate probability density functions of shifts in key climate drivers (typically, annual average precipitation and temperature). The use of GCMs to drive climate change analysis is here referred to as top-down because GCMs are conditioned on large-scale oceanic-atmospheric interactions that, while they capture global or regional energy and water balances, tend not to effectively reproduce the local hydro-climatic patterns of concern (e.g., mean, autocorrelation, skew) to water-resource system planners (Brown and Wilby 2012).

Decision scaling, with its particular emphasis on climate-change-related risks, is part of a growing consensus that robustness-based approaches are needed to address uncertainty, generally, in infrastructure planning (Wilby and Dessai 2010). The approaches embracing robustness-based strategies are together an alternative to the most prominent kind of approaches to risk assessment, which assess system response under a limited set of plausible future climate, demographic, and land use conditions, with climate projections typically downscaled from time series of GCMs.

These robustness-based approaches tend also to be bottom-up in their development of decision-making pathways (e.g., Haasnoot et al. 2013). Stakeholders guide the process from beginning to end, and provide local-level (bottom-up) expertise in identification and characterization of historical system performance, desired future performance thresholds, and most promising pathways for adaptation.

### *Development of the Decision Tree Framework*

In the past 10–15 years, agencies involved in water-resource system planning have become aware of the need to account for climate change risks in their water-resource system designs. The need for an accepted process for climate change risk assessment at the World Bank, in particular, was elevated when, in 2013, the International Development Association (IDA, the World Bank's fund for the world's poorest countries), called for all IDA Country Partnership Frameworks to incorporate climate- and disaster-risk considerations into the analysis of the country's development challenges and priorities, and, when agreed upon with the country, to incorporate such considerations in the content of the World Bank-financed development programs.

The decision tree framework (DTF) (Ray and Brown 2015) outlined a pragmatic process for project planning under uncertainty in the water sector at the World Bank. The DTF was designed to respond to two problems. The first could be classified as a risk

*assessment* problem. Because risk is a function of both probability and impact (Dessai and Hulme 2004), the inability of climate projections to probabilistically represent uncertainty is a substantial impediment to the assessment of climate-related risks for proposed water-resource system projects. The uncertainty associated with future climate is largely irreducible in the temporal and spatial scales that are relevant to water resource projects (Stainforth et al. 2007). Climate projections provide limited and often biased explorations of the effects of internal climate variability, especially precipitation variability (Rocheta et al. 2014), and especially at the extremes (Trenberth et al. 2015), with amplified carryover effects for runoff estimates (Fekete et al. 2004). The DTF therefore adopted the robustness-based techniques of decision scaling for climate change risk assessment, using a climate change stress test to define scenarios of project-specific vulnerability (relative to performance thresholds), and consulting climate trends (e.g., from the local historical record, or paleodata) and projections (e.g., GCM output) for likelihood information as a post-processing step.

The second issue relates to risk *management*. Because it is unknown whether climate risks are large (Rockström et al. 2009; Arnell and Lloyd-Hughes 2014) or small (Frederick and Major 1997; Lins and Stakhiv 1998) relative to risks of other kinds (e.g., population growth, technology shift, natural disaster, market shift), over medium- to long-range periods, project planners are ill-equipped to incorporate climate uncertainty into a broader (all-uncertainty) assessment of a project's probability of success, and thus to make intelligent modifications to the project design that reduce its vulnerabilities to failure. The DTF therefore coupled the risk assessment strengths of decision scaling with advanced tools for decision making under uncertainty, such as robust decision making (Groves and Lempert 2007), robust stochastic optimization (Kasprzyk et al. 2013; Ray et al. 2014), and Dynamic Adaptive Policy Pathways (Haasnoot et al. 2013; Kwakkel et al. 2015).

### *Hierarchical Structure of the DTF*

In addition to addressing the fundamental science issues described above, the DTF was designed to make economic use of human and financial resources. The procedure consists of four successive phases: Phase 1, Project Screening; Phase 2, Initial Analysis; Phase 3, Climate Stress Test; and Phase 4, Climate Risk Management. Water-resource system projects are diverse, including water sector reform, water management, development of hydro-meteorological networks, and establishment of new

infrastructure, including water supply, sanitation, and hydroelectric facilities. The goal of the DTF was to develop a tool that would be applicable to all water-resource system projects, but that would allocate climate risk assessment effort in a way consistent with each project's potential sensitivity to that risk. The process was therefore designed to be hierarchical, with subsequent phases of analysis triggered only at need, by the findings of the previous phase. The hierarchical structure reduces the bureaucracy associated with a "new" type of risk assessment now required of each project manager, and gives planners the analytical guidance they need to concentrate on those risks most relevant to the performance of their designs.

This document proposes updates to the DTF based upon improved understanding of best practice in climate change risk management gained in the course of application of the DTF to pilot demonstration studies in hydropower development, multipurpose reservoir evaluation, and integrated urban planning (e.g., Bonzanigo et al. 2015; Ray et al. 2015a; Hydrosystems Research Group — UMass Amherst 2017), and proposes areas for future research which would most immediately address weaknesses in the DTF.

## MULTIDIMENSIONAL RISK ASSESSMENT

### *Multidimensional Stress Test*

In its original incarnation, Phase 3 of the DTF's approach to climate change risk assessment focused almost exclusively on reducing climate-change-related risks to project performance. However, it has become clear that, in order to be useful to project managers, investors, and decision makers, climate-change-related risks must be put in context of risks of other kinds. Previous studies have presented tools for multidimensional sensitivity analysis (Lempert et al. 2003, 2006) and applied those tools to water systems planning (e.g., Groves and Lempert 2007; Kasprzyk et al. 2013; Kwakkel et al. 2016), but none of those studies demonstrated a multidimensional stress test framework that is robustness-based and bottom-up in its approach to climate change risks.

Ray et al. (2018) therefore presented a generic methodology for evaluating climate change risks to water-resource systems (hydropower investments, specifically) that simultaneously evaluated risks of many types in a multidimensional stress test. The general methodology draws on the work of Lownsbery (2014), who presented a novel stress test approach to evaluation of variability and change in climate



(specifically, precipitation and temperature), as well as change in water demand (specifically, municipal, industrial, and agricultural) in the Apalachicola–Chattahoochee–Flint River Basin (Schlef et al. 2017).

The process presented by Ray et al. (2018) integrates simulated results from coupled climatic, glaciological, and hydrological models, informed by data from in situ and remote-sensing-based measurements that are bottom-up and site-specific. To those elements is added an infrastructure model to evaluate the resilience of water-resource system facilities that is responsive to changes in both climate and non-climate factors. A stress-testing approach applied to the model chain, coupled with a data mining algorithm, allows for identification of the relative significance of risks of different types to the project. Once the project vulnerabilities are identified, adaptation options can be quantitatively evaluated.

Ray et al. (2018) showed, in the case of a hydropower project in Nepal, that project lifetime (as a surrogate for risk of destruction by earthquake), discount rate, plant load factor (as a surrogate for risk of sediment damage to turbines), and temperature change are all relevant, but are less important predictors for economic performance than capital cost, electricity price, and precipitation amount. The study identified combinations of those conditions — future precipitation rates substantially lower than historical in combination with major capital cost overruns, for example — that would result in project failure (defined narrowly in this case not in reliability terms, as is typical in water-resource system planning, but as a negative net present value), but could not comment on the likelihood of the co-occurrence of a particular set of troublesome conditions. The need to better understand likelihoods of multidimensional future conditions, despite the existence of irreducible uncertainties that cannot easily be described by probability distributions, prompted research into Bayesian probabilistic inference.

### *Bayesian Probabilistic Inference*

In the context of water-resource systems planning, there are numerous sources of qualitative and quantitative information that can provide decision-relevant information. These include historical trends, projections of environmental, demographic, and financial factors, and expert opinion. However, basing probabilistic inference on structurally diverse and nonindependent sources of likelihood information such as these is fraught with danger. Omitting codependencies in social, economic, and environmental uncertainties (Vorosmarty et al. 2003; Hurd et al. 2004; Pahl-Wostl 2007; Schleich and Hillenbrand 2009; Olmstead 2014)

may lead to an underestimation of risks and the selection of ineffective or maladaptive planning strategies. To account for uncertainty codependencies in water-resource systems planning, Taner (2017) introduced the Bayesian Networks Decision Scaling (BNDS) framework.

Bayesian networks (BNs) (e.g., Pearl 1988; Newton 2010; Aguilera et al. 2011) allow representation of uncertainty through a graphical network of variables, each represented by a conditional probability distribution. The conditional probability distributions are propagated through a network structure to a posterior joint probability distribution of the system (Jensen and Nielsen 2007).

BNDS uses a stress test approach to identify system vulnerabilities relative to stakeholder-defined performance criteria, and a BN to develop a joint posterior probability distribution of the possible future (multidimensional) combinations of local conditions. It does this by making use of conditional and unconditional beliefs about each relevant exogenous factor (see Figure 2 for conceptual illustration). Resultant probabilistic information is evaluated together with the identified vulnerabilities to compare the robustness of the planning alternatives. By separating vulnerability identification from probabilistic inference, conflicts in beliefs are reduced in significance, and subject to a post-process sensitivity analysis on alternative beliefs regarding future conditions.

### *Updates to the DTF*

Updates to the DTF to reflect improvements in multidimensional stress testing and Bayesian probabilistic inference are presented in Figure 3. Phase 3 is now a “Multidimensional Stress Test,” and the output of Phase 3 is a “Multidimensional Risk Report.” In order to evaluate plausible risk at Phase 3 (accounting for codependencies in contributing uncertainties), Bayesian probabilistic inference is required.

## NEXT STEPS FOR CLIMATE CHANGE RISK MANAGEMENT

Practitioners of climate change risk management in water-resource systems have become adept at combining hydrological models with water system models in workflows that allow evaluation of the effect of climate change on “available water” (e.g., Miller et al. 2003; Arnold and Fohrer 2005; Yates et al. 2005; Arthington et al. 2010) or flood peaks (Zhou et al. 2012; Gain et al. 2013; Karamouz and Nazif 2013;

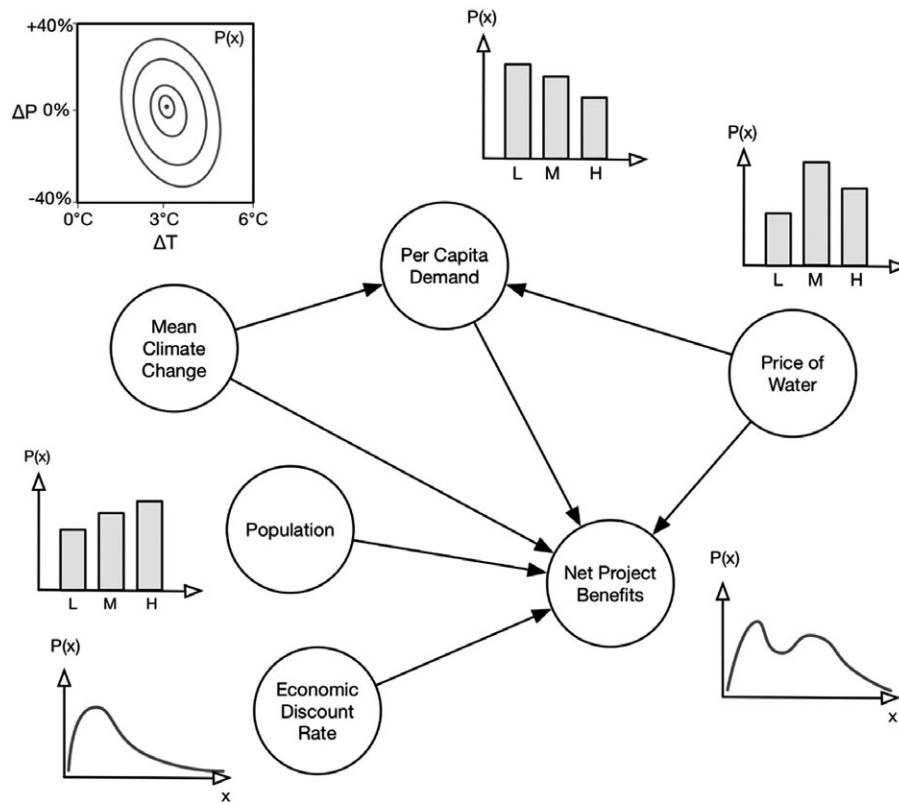


FIGURE 2. Conceptual illustration of multidimensional uncertainties in water-resource systems planning with probabilistic dependencies presented as contributing to a posterior distribution in a Bayesian network.

Yang et al. 2015), and the consequent effect on water-resource system performance.

The state of the art in climate change risk management is less mature in other aspects of water-resource systems. This section suggests six areas of weakness in assessments of this type: (1) modeling of extreme event risks; (2) coupling of human-hydrologic systems; (3) integration of surface water and groundwater systems; (4) the generation of tradeoffs between economic, social, and ecological factors; (5) incorporation of water quality considerations; and (6) interactive data visualization. It proposes, in only general terms, the type of research that would be most beneficial to strengthen the relevance to climate change risk management of each.

### Extreme Events

Large uncertainty stemming from inherent rarity, in combination with relatively short historical records, has made design for extreme events a consistent challenge to water-resource systems planners. Extreme events are difficult to simulate (e.g., by GCMs and other, more regional climate models), not only because the inherent rarity limits understanding

of the underlying driving forces but also because system variability, and not just the system mean state, must be correctly mathematically represented. This challenge of design for extreme events is further exacerbated by the possibility of nonstationarity due to climate change (Milly et al. 2002; Palmer and Ralsanen 2002; Trenberth 2011; Coumou and Rahmstorf 2012).

Phase 3 of the DTF would therefore benefit from greater clarity with reference to risks from extreme events, such as floods. Where extreme events are concerned, the response surface would no longer be a system metric such as reliability or vulnerability, but an expected value of damages or costs calculated from damage or cost functions and the extreme event distribution. While potential future changes in the damage or cost function due to changes in land use and human development should be accounted for in the stress test, here we focus on innovations relating to climate change impacts on extreme events.

A form of the stress test responsive to extreme event concerns could prescribe determination of the extreme event distribution from the streamflow time series output of a hydrologic model forced by stochastic realizations of precipitation and temperature with arbitrarily imposed trends. In studies taking this approach (e.g.,

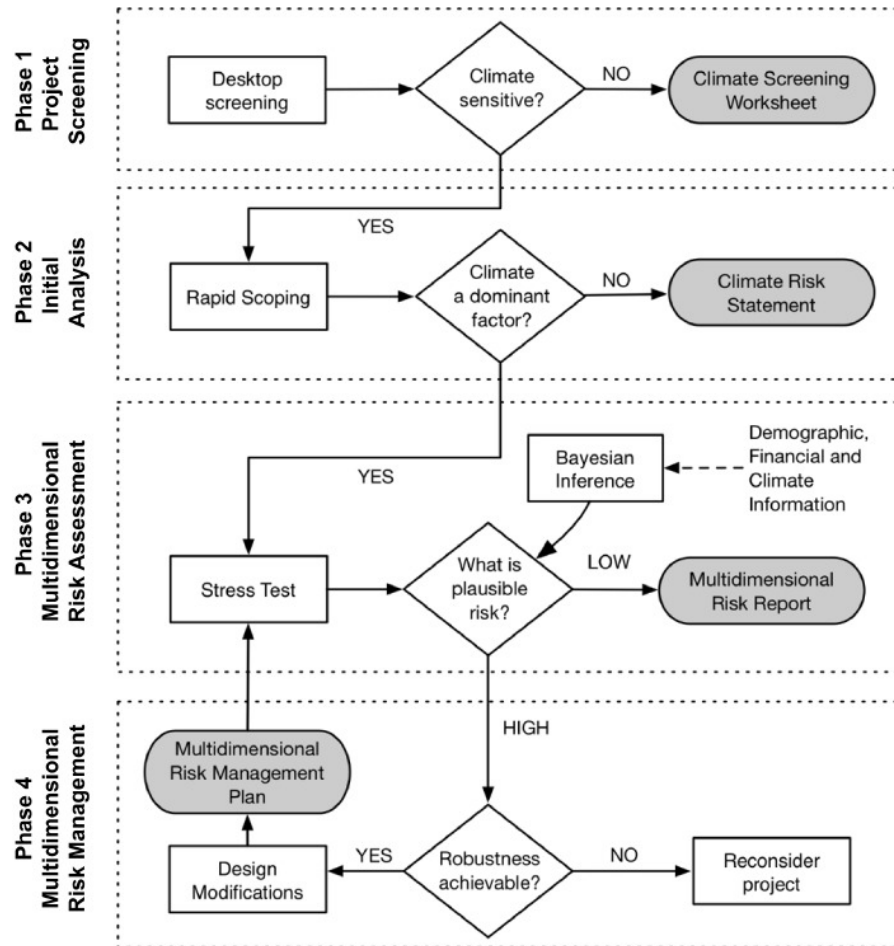


FIGURE 3. Decision tree framework — updated. Phase 3 is now a “multidimensional stress test,” and the output of Phase 3 is a “multidimensional risk report.” In order to evaluate plausible risk at Phase 3 (accounting for codependencies in contributing uncertainties), Bayesian probabilistic inference is required.

Steinschneider et al. 2015; Poff et al. 2016), the coefficient of variation of precipitation has been found to be an important (relative to climate shifts) driving force in the system response. One way to account for the relative importance of climate variability on system performance, then, would be to assign changes in climate variability (e.g., the coefficient of variation of precipitation) to at least one axis of the multidimensional response surface (see Figure 4).

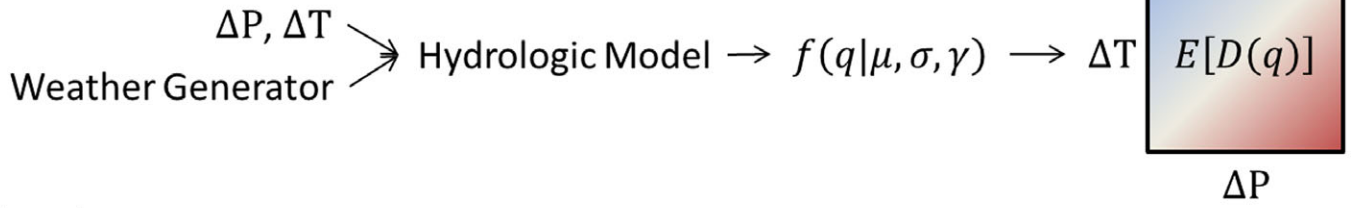
An alternative approach to a stress test for extreme events is to apply arbitrary trends directly to the parameters of the distribution, as was done by Spence and Brown (2016). While this approach is more direct, eliminating the need for a weather generator and hydrologic model, a link between the arbitrary trends and possible physical changes in the climate system may be more difficult to justify. Current research is on developing a climate informed stress test that maintains a justifiable link to physical changes in the climate system, yet directly modifies the distribution parameters (Schlef 2018). In such a stress test,

changes would be applied to stochastic realizations of large-scale ocean-atmospheric patterns, which, based on a demonstrated mechanistic link, would serve as covariates for the parameters of the extreme event distribution. While still in development, this advancement is a promising step toward design for extreme events in the face of climate change uncertainty.

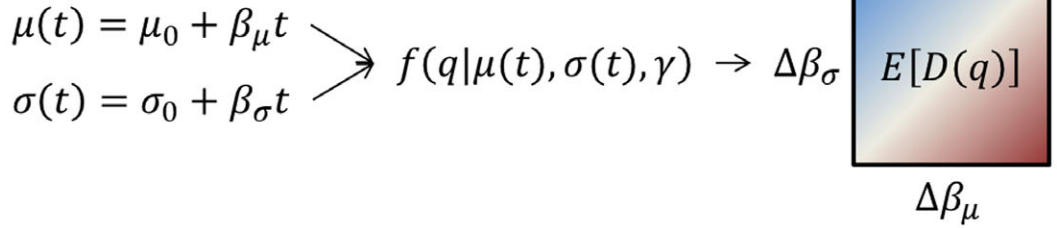
### *Coupled Human-Hydrologic Modeling*

Human activities on the surface hydrology system, including impoundment, withdrawals, and irrigation, are known to alter mesoscale hydro-meteorology and consequently affect water management decisions. These human alterations of surface hydrology are now widespread, and progressing at rapid pace (Wagener et al. 2010; Voeroesmarty et al. 2013; Zarfl et al. 2015; Wada et al. 2017). The interactive nature of human and hydrologic processes requires an evolution in hydrologic science, one that will result in new

## Basic



## Trend



## Climate Informed

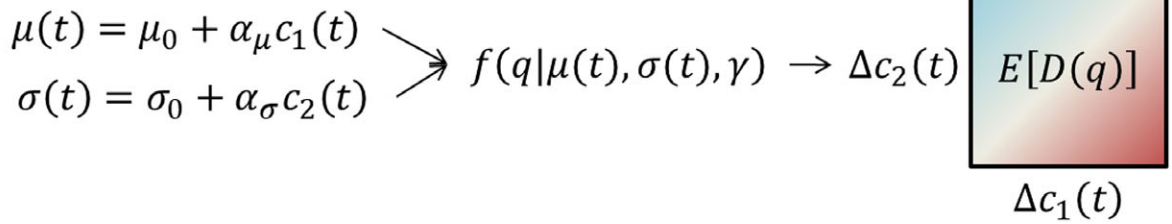


FIGURE 4. Progressive innovations of the stress test targeting design for extreme events.  $\Delta$  is change,  $P$  is precipitation,  $T$  is temperature,  $f(q|\mu, \sigma, \gamma)$  is the distribution of extreme event  $q$  with mean  $\mu$ , scale  $\sigma$ , and shape  $\gamma$ ,  $E[D(q)]$  is the expected value of the damages,  $t$  is time,  $\alpha$  and  $\beta$  are coefficients, and  $c_1$  and  $c_2$  are climate covariates.

methodologies designed to integrate watershed responses to all natural and anthropogenic hydrologic drivers.

Correspondingly, there has been great interest in coupling process-based hydrologic models to human water-resource systems models to better represent the reciprocal interactions and coevolution of the natural and human water systems. Coupled human-hydrologic models have proven useful to address a variety of water management challenges related to infrastructure operation, demand management, river restoration, climate change, and the regional water-energy-food nexus (Tomsic et al. 2007; Null et al. 2014; Nelson et al. 2016; Yang et al. 2016; Wada et al. 2017; Yang and Wi 2018). They have also been shown to be effective at facilitating stakeholder-driven modeling processes that help improve conceptualization of the water system, especially in transboundary river basins (Khan et al. 2017). Moreover, the development of coupled human-hydrologic models has played a crucial role in the application of the DTF to evaluate the resilience of

water system investments to climate, geophysical, and economic uncertainty (Ray et al. 2015b, 2018). In short, coupled human-hydrologic models explicitly incorporate human decisions within every time step that modifies the natural hydrology in the subsequent time step, in turn affecting human water use decisions via flexible system operating rules in an iterative loop. This is in contrast to the conventional approach to water system modeling in which the output of a hydrologic model unidirectionally comprises the input to a subsequent water infrastructure system model with no meaningful feedbacks.

Figure 5a illustrates an interbasin water transfer system, which is designed to supply a city through open canals, interconnecting reservoirs, and a pumping system. One way to build a coupled human-hydrologic model for this example water-resource system would be to combine two modeling components: (1) hydrologic models that simulate the hydrological cycle (i.e., evapotranspiration, runoff, infiltration, river channel flow) in a spatially distributed manner; and



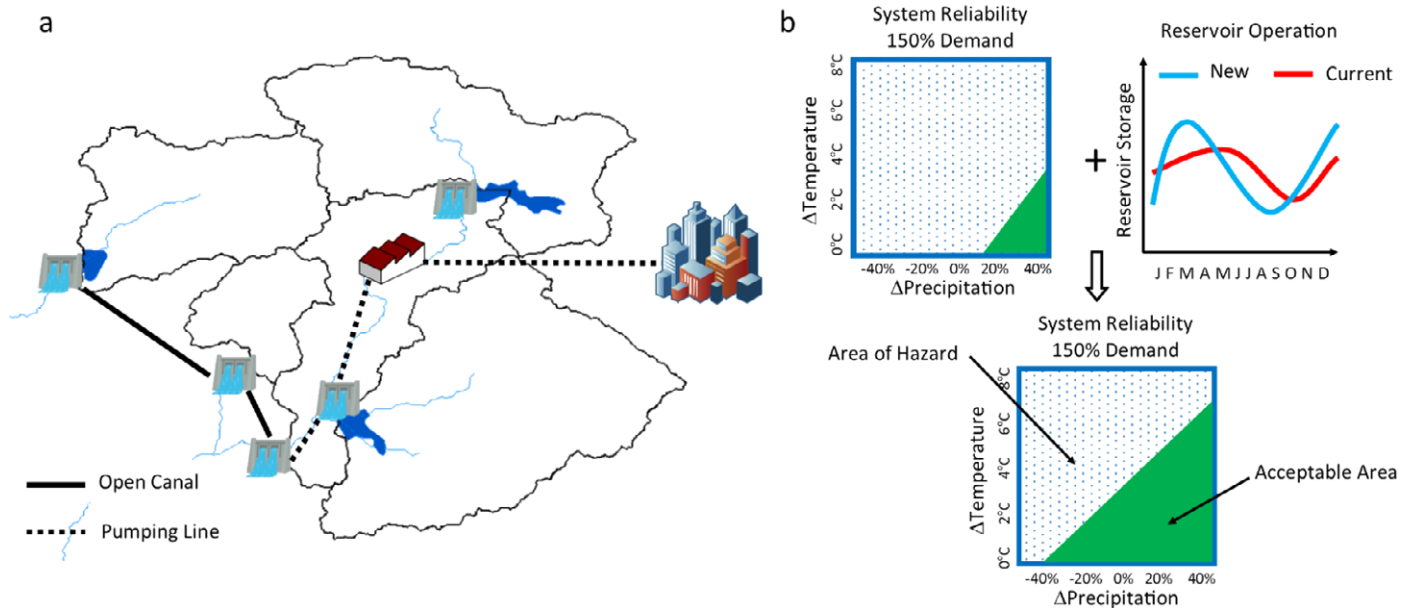


FIGURE 5. (a) Example interbasin water transfer system for urban water supply; (b) a test of the vulnerability of the system to precipitation and temperature change under demand increase with and without reservoir operation rule change.

(2) river operation models to simulate water regulations triggered by anthropogenic activities (e.g., reservoir operations, agricultural irrigation, diversions, etc.). The role of coupled human-hydrologic models framed this way can be of particular importance to improve the representation of hydrology and river operation interaction and advance the evaluation of the system-wide water management consequences under, for example, altered climatic and demand regimes.

Figure 5b provides a proof of concept regarding an adaptation plan (in this case, a new reservoir operation rule curve) that can be supported by a coupled human-hydrologic model. For the purposes of illustration, we assume that the water system might be under stress imposed by a demand increase of 50%, plus climate shifts of indeterminate magnitude. The green area (Figure 5b) represents acceptable system performance (e.g., >95% water supply reliability). Water supply reliability is defined as the fraction of the evaluated period during which the system successfully supplies the target delivery to the city. The coupled model aids in identification of an efficient mode of reservoir operation, leading to improved system resilience.

#### *Integrated Surface-Groundwater Modeling*

Given the critical role of groundwater in many river basins, climate change impacts on groundwater have recently received increased attention (Doell and Fiedler 2008; Treidel et al. 2012). Theoretical and observational

studies suggest strong feedbacks/interactions between surface and groundwater systems (Maxwell et al. 2007, 2011; Anyah et al. 2008; Maxwell and Kollet 2008; Jiang et al. 2009; Rihani et al. 2010; Therrien et al. 2012; Condon and Maxwell 2013; Taylor et al. 2013). Changes in mean climate conditions and variability directly influence groundwater dynamics through changes in recharge and evapotranspiration (Gorelick and Zheng 2015). However, indirect impacts of climate change (e.g., change in groundwater-sourced irrigation demand due to reduced surface water availability) are equally (or sometimes more) important in terms of impact on groundwater (Green et al. 2011).

In many river basins where baseflow forms a major component of streamflow, surface water allocation problems can often be traced to weak groundwater governance (Llamas and Martinez-Santos 2005). The ongoing litigation between Nebraska and Kansas over reduced flows in the Republican River due to intensive groundwater pumping is one example (Palazzo and Brozovic 2014). Continued consideration of two integrated aspects of the hydrologic cycle in isolation will result in missed opportunities to adapt in efficient ways.

Hydrologic modeling aspects of climate change risk management exercises could, but typically do not, use fully integrated models that solve groundwater and surface water flow equations simultaneously, enabling incorporation of interactions between surface water and groundwater (e.g., return flows, aquifer storage, and recovery) into current climate change adaptation models. Such integrated models have been available

for a decade (Jones et al. 2006; Kollet and Maxwell 2006; Ebel et al. 2009), and have been applied to a wide range of problems at different scales to explain observed surface and subsurface behavior as well as stream–groundwater interactions (Qu and Duffy 2007; Li et al. 2008; Shi et al. 2013; Camporese et al. 2014), but are only beginning to be embraced by the community of practitioners of water-resource system adaptation to climate change (Khan 2018).

### *Socio-economic and Ecological Tradeoffs*

Water-resource system planning processes are regularly faced with competing objectives and interests. Three classic categories of these objectives are: social, ecological, and economic. Tradeoffs between these objectives have been linked in some water-resource systems studies (e.g., Baron et al. 2002; Singh et al. 2015; Poff et al. 2016), but in general, advancements in social, ecological, and economic modeling remain in the bodies of literature specific to each respective discipline. Water-resource system planning processes rarely make use of best practices for incorporating social, ecological, or economic concerns.

While the field of water-resource systems analysis was founded on economics (Maass et al. 1962), in application the broader economic issues (beyond local project finances) tend to be relegated to postscript statements of need for “further study.” The U.S. Principles and Standards for Planning Water and Related Land Resources (U.S. Water Resources Council 1973), for example, “identified four distinct quality of life components on which to evaluate project effects: (1) National economic development, (2) environmental quality, (3) regional development, and (4) social well-being. The first two components were established as objectives which should be optimized in project planning and which, consequently, would be the primary accounts used to judge relative merit of projects. The remaining two components were acknowledged as important accounts for displaying additional information but would not be the principal factors in final decision-making” (Eisel et al. 1982). Therefore, though it is fundamental to the values of most institutions undertaking water-resource system planning and management, equitable distribution of water, both temporally (e.g., Jeuland and Whittington 2014; Rockström et al. 2014), and within populations (e.g., Wilk and Jonsson 2013; Cole et al. 2018) is rarely rigorously quantified and carefully considered in planning applications. Exceptions exist (such as the attention given to the upstream–downstream distribution of benefits and costs in recent studies of the Great Lakes, International Joint Commission 2012), but have not yet appreciably impacted standard practice.

Recent advancements in the field of freshwater ecology allow for quantification of how much water is critical (and when) to the ecological functioning of a river system (Karr 1991; Richter et al. 1996, 1997, 2003). Formalized methods for estimating ecological flow requirements can now be translated and implemented as performance objectives for large-scale water-resource system planning (e.g., the “Reservas de Agua” program in Mexico, and the Apalachicola–Chattahoochee–Flint River Basin, Ruhl 2005; Schlef 2018). Incorporating these lessons learned in ecological and social considerations into water-resource system models would lead to improved results.

Furthermore, while it has been the tradition of water-resource system planning paradigms to rely on an ability to define quantifiable thresholds for individual interests, this is not a tenable approach for all interests in every case, and continued effort is needed to consider how to incorporate nonquantifiable values of water (e.g., spiritual and cultural, Wolf 2008) into planning processes. Continued advancements in participatory planning processes (e.g., Kallis et al. 2006; Langsdale et al. 2013) will help water-resource systems planners navigate unfamiliar terrain in tradeoff analysis.

### *Surface Water Quality Modeling*

Declining water quality is now an issue of global concern, affecting even populations with relative abundance of surface water resources. The most prevalent problem is eutrophication, though acute chemical spills and chronic sewer-borne flows of personal care products and pharmaceuticals present mounting health hazards (UNEP 2016). Climate change is likely to exacerbate the problem by increasing the frequency and severity of local floods, mobilizing chemicals stored on the floodplain (Ryberg et al. 2014), and increasing the likelihood and severity of harmful algal blooms (HABs) (Dodds et al. 2009).

The impact of anthropogenic activities on water quality has been studied extensively (e.g., Jarvie et al. 2006; Bowes et al. 2014). Several studies have investigated the effect of climate change on riverine water quality (e.g., Tu 2009; Whitehead et al. 2009; Fan and Shibata 2015; Rostami et al. 2018), with particular attention given to temperature effects (e.g., Benitez-Gilabert et al. 2010). However, contaminant transport models have not typically been included in the coupled human-hydrologic modeling systems described above, and water quality concerns have therefore not been directly incorporated into bottom-up assessments of broader water system resilience.

Though much progress has been made in the fields of contaminant transport and water supply risk assessment (including climate change risk) independently,

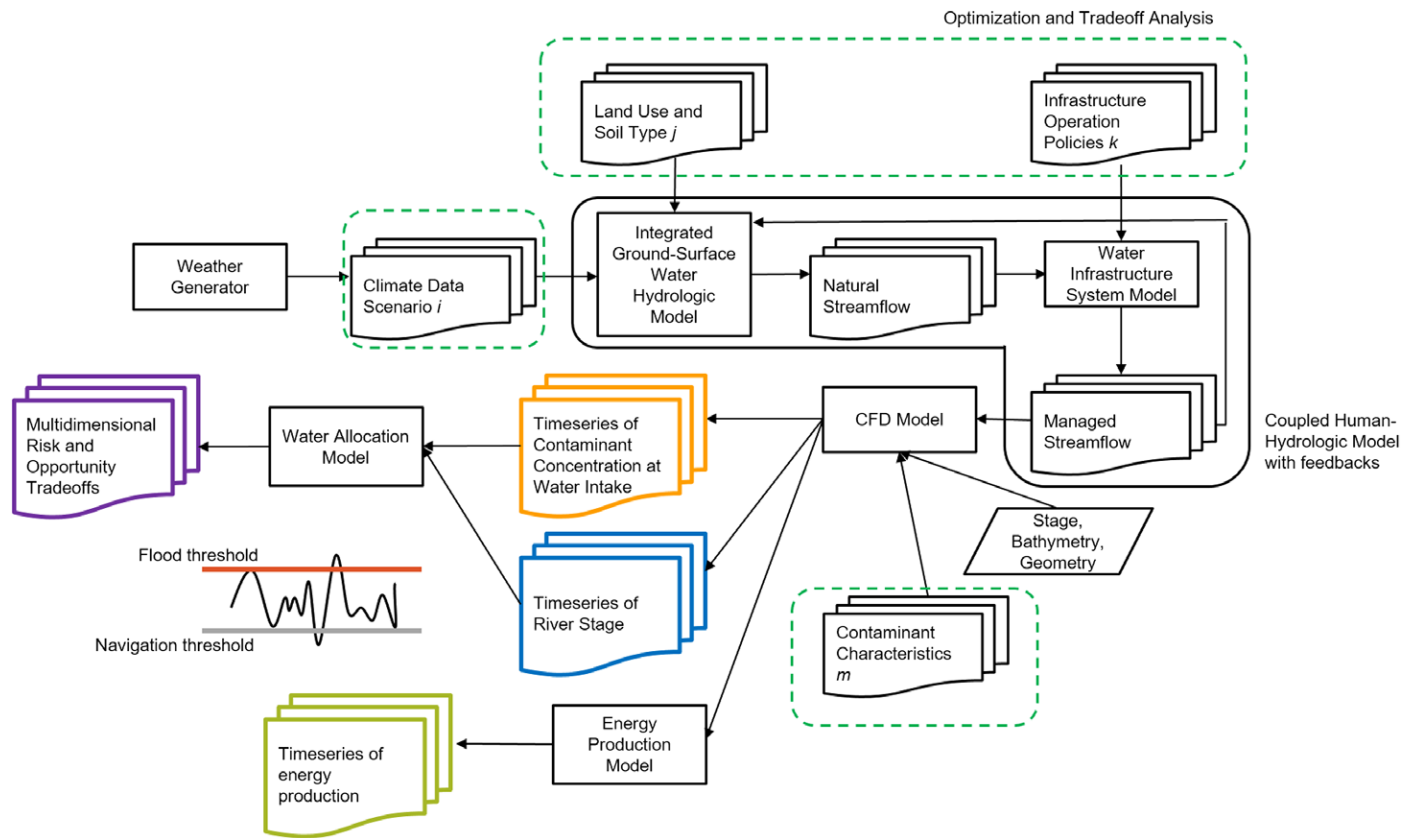


FIGURE 6. Model workflow for comprehensive water-resource system risk assessment in riparian cities, including water quality considerations.

surprisingly little work has been done to combine the tools of water-resource system risk assessment (e.g., weather generators, hydrologic models, demographic and land use models, economic tradeoff analysis, BNs) and computational fluid dynamics (CFD — advection, dispersion, and reaction of contaminants in a flowing water body). Many researchers have employed CFD models to simulate riverine pollutant transport (Wu 2004; Benkhaldoun et al. 2007; Li and Duffy 2011), but have done so without evaluation of CFD response to systematically varied hydro-climatological inputs. It is therefore anticipated that the modeling workflow presented in Figure 6 will be useful for a wide range of global riverine risk assessment applications with particular relevance to chemical spills and flood-borne river contamination. The integrated assessment approach shown in Figure 6 combines a coupled human-hydrologic model (including an integrated ground-surface water hydrologic model) with a CFD model, and enables simultaneous minimization of supply disruptions (including from water quality problems), flood damages and navigation interruptions, and maximization of energy production, under budget. Figure 6 is developed for a water-resource system with little off-line storage, as is true of many river-riparian

cities worldwide. If substantial off-line storage is available, then feedbacks are needed between the CFD model and the water infrastructure model.

The formulation presented in Figure 6 holds particular promise for informing the risks to riparian cities of HABs, an increasingly urgent problem in freshwater supplies globally (Sellner et al. 2003; Bullerjahn et al. 2016). Just as chemical contaminants can be classified and their transport characteristics perturbed, a sensitivity analysis can be performed on the factors contributing to HABs (e.g., nutrient loading, river velocity, and turbidity).

van Griensven and Meixner (2006) found that the major uncertainty in contaminant transport models relates to “the form of the model and how the processes are represented and how they are distributed across the landscape.” This indicates the importance of the two-dimensional CFD formulation, and a well-parameterized hydrologic model. Previous approaches to risk assessment or uncertainty analysis in problems of contaminant transport in surface water applications have been almost exclusively of the one-dimensional type (e.g., Hou et al. 2014; Gimeno et al. 2017), and so are not able to adequately evaluate risks of extended contaminant plume exposure. Risk assessment in

contaminant transport using two- or three-dimensional model formulations have predominated in applications relating to the subsurface (e.g., Gharamti et al. 2015), but do not have obvious carryover to riverine problems. Furthermore, previous approaches to climate change risk assessment in contaminant transport problems have tended to evaluate uncertainty in single inputs (e.g., meteorological uncertainty, Angevine et al. 2014), but as has been established above, a bottom-up approach to systematic exploration of a multidimensional risk space is needed.

Figure 7 is an illustration of risks to water supply in an urban area, for example, presented relative to some critical threshold of plume passage duration (e.g., two days) as a function of spill duration and river velocity. A more fundamental, disaggregated stress test would include: river velocity as a function of temperature, precipitation, water infrastructure (especially lock and dam) operation policy, and land use scenario; contamination event as a function of spill duration and contaminant characteristics (e.g., reactivity, volatility, and sorptive tendency); and supply disruption represented as a function of river velocity and contamination event, as well as antecedent storage condition (% of full storage). Resultant parallel coordinate plots (or other multidimensional visualizations) would be web-based and interactive, and accessible to decision makers evaluating system vulnerability.

### Interactive Data Visualization

The making of good water policy requires good communication on the part of analysts and vested

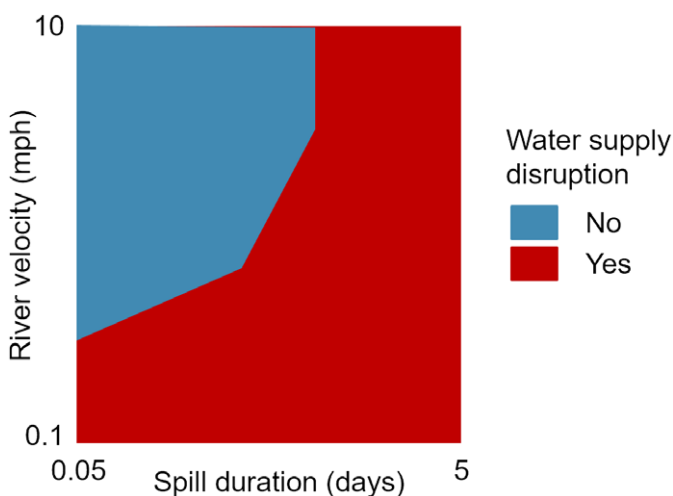


FIGURE 7. Illustrative water quality response surface. An illustration of risks to water supply in an urban area, for example, presented relative to some critical threshold of plume passage duration (e.g., two days) as a function of spill duration and river velocity.

stakeholders. Project managers and decision makers cannot be empowered to make best use of the available analytical results if they do not understand them, especially as climate change risk management exercises become increasingly multidimensional and multiobjective. Further progress is needed in interactive, online tools that gamify exploration of system risks and opportunities, and diffuse potential conflicts between stakeholders.

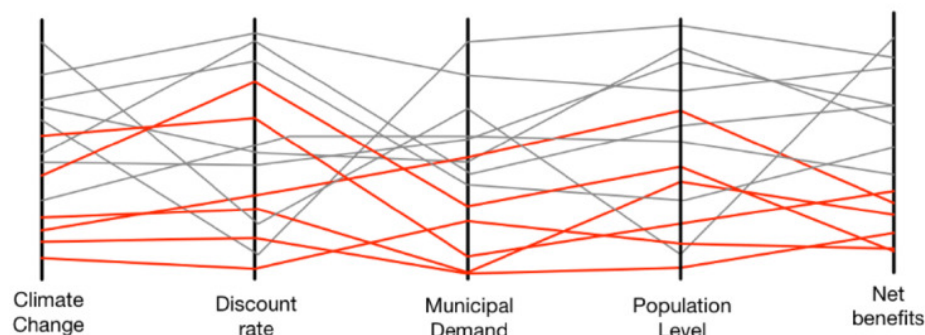
Recent improvements in the communication of results from multidimensional vulnerability analyses have focused on combining efficient data mining and optimization algorithms with interactive visualization tools. Some studies have developed web-based tools for stakeholder interaction (e.g., Walker and Chapra 2014; Whateley et al. 2015) that incorporate real-time simulation and gamified versions of many-dimensional visualizations. Hadka et al. (2015) presented a web-based visualization toolkit for exploring high-dimensional datasets to better understand system tradeoffs, vulnerabilities, and dependencies within the multiobjective robust decision-making framework, and Kwakkel (2017) developed an open-source “Exploratory Work Bench” demonstrating the use of machine learning algorithms and interactive data visualization for decision support in the Dynamic Adaptive Policy Pathways family of approaches.

Following on the work of Kasprzyk et al. (2013), interactive parallel coordinate plots have been used for visualization of multidimensional tradeoffs in stakeholder interaction games (e.g., Matrosov et al. 2015; Yang et al. 2016; Ray et al. 2018; Yang and Wi 2018). Sankey, or alluvial, diagrams (Schmidt 2008) are multivariate visualization techniques that are structurally similar to parallel coordinate plots, with the addition that results can be weighted (lines thickened) to show emphasis. For example, Figure 8 presents an illustration of two probabilistic assumptions about the future: a uniform weighting with the assumption that there is not sufficient information to distinguish the plausibility of one future state from another (Figure 8 Parallel coordinates plot), and a “belief-informed” weighting, where each future condition is weighted based on the corresponding normalized joint probability value (Figure 8 Alluvial plot). The plots are used to demonstrate the additional insight added when belief information is used to weight outcomes according to likelihood, and thereby to enable decisions better informed by the most credible scientific information and expert insight. Taner (2017) used interactive alluvial diagrams to visualize water-resource system risks (the product of vulnerabilities and their occurrence likelihoods) from the findings of multivariate vulnerability analysis.



**a) Parallel coordinates plot**

Depicting scenarios of vulnerable outcomes

**b) Alluvial plot**

Depicting scenarios of high risk outcomes

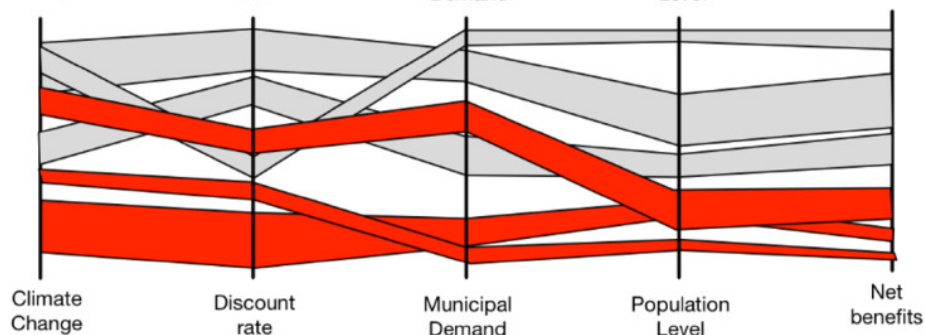


FIGURE 8. Alluvial plot for multidimensional risk visualization responsive to Bayesian probabilistic inference. The alluvial plot includes all information in the parallel coordinates plot, plus “belief-informed” weighting, in which each future condition is weighted based on the corresponding normalized joint probability value.

## SUMMARY

The state of the art in climate change risk management is a return to robustness-based, bottom-up analytical approaches presented by Matalas and Fiering (1977) 40 years ago. The DTF represents a return to Matalas and Fiering’s (1977) three R’s (robustness, resilience, and regret), and a blending of best practice in climate risk assessment and climate risk management. This paper proposes updates to Phase 3 of the DTF in response to what has been learned in application of the DTF to a number of pilot demonstration projects over the past few years: (1) the need to put climate change risks in context of risks of other kinds by using multidimensional risk assessments instead of just climate risk assessments; and (2) the need to use Bayesian weighting schemes to improve probabilistic inference when describing scenarios of interdependent future conditions.

This paper has further suggested six areas of weakness in assessments of this type: (1) modeling of extreme event risks; (2) coupling of human-hydrologic systems; (3) integration of surface water and groundwater systems; (4) the generation of tradeoffs between economic, social, and ecological factors; (5) incorporation of water quality considerations; and (6) interactive data visualization. It proposed, in only general terms, the type of research that would be

most beneficial to strengthen the relevance to climate change risk management of each.

We have not presented methods for risk assessment associated with stormwater flooding and multi-year storm events, but refer the reader to good examples of standard practice in texts such as Mays (2011), and demonstrations of the effect of climate nonstationarity on flood magnitude such as Read and Vogel (2016). Neither has this manuscript addressed risk assessment issues associated with the coastal zone. The reader is referred to literature related to the risks of compound river flood and storm surge events (e.g., Zheng et al. 2013; Ward et al. 2018), and methodologies for managing such risks at a large scale (e.g., Hall et al. 2005; Salman and Li 2018), especially with sea level rise (e.g., Wu et al. 2002; Ericson et al. 2006; Revi 2008; Jongman et al. 2012).

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