Infrastructure capacity planning for reducing risks of future hydrologic extremes

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ABSTRACT

Floods and droughts and their associated economic, environmental, and social losses or damages are increasing in severity and frequency. Measures taken to reduce these losses or damages stemming from extreme events typically depend on how effective they are in reducing the consequences of having either too much or too little water and for longer periods of time. To identify trade-offs between the annual estimated loss or damage reduction, i.e., the benefits, however measured, and the average annual cost of various damage reduction measures, one can perform risk–cost analyses. Because of climate change, the likelihoods of future hydrologic extremes are both changing and uncertain. Also uncertain are any estimates of future damages that would occur given any specific extreme event. In addition, one cannot be certain of the future costs or benefits of damage reduction measures. This paper outlines a range of practical approaches for identifying these trade-offs, taking into account the uncertainties associated with future damages resulting from any specific flood or drought event, the changing uncertainties of future flood and drought events, and the uncertainty of future damage mitigation costs.

Key words: Damage reduction, Droughts, Floods, Infrastructure planning, Risk, Uncertainty

HIGHLIGHTS

- Explaining the impact of deep hydrologic uncertainty on water infrastructure planning.
- Discussing how the uncertainty of future hydrologic extremes influences extreme events plus safety factor approaches, scenario planning, and adaptive planning.
- Presenting a conceptual risk–cost model for infrastructure planning.
- Emphasizing the importance of determining the influence of assumptions regarding the future on current infrastructure capacity decisions.

INTRODUCTION

Rising global temperatures have resulted in more severe storms and droughts across much of Africa, Asia, Europe, and North America. Sea levels around the world are rising at rates greater than previously expected. The total human and environmental costs of these trends are often difficult to estimate, but insurance companies can and do measure their financial losses. These losses are both significant and increasing. The International Monetary Fund (IMF) estimated that worldwide climate change-induced damages cost insurance companies $80 billion in 2018, double the inflation-adjusted average for the previous 30 years. This annual damage cost exceeds $10 per year for each person living in the world today. In 2017, IMF estimates that additional uninsured losses reached $200 billion.

In some of the countries most exposed to climate change – Bangladesh, Egypt, India, Indonesia, Nigeria, the Philippines, and Vietnam – less than 1% of the population is insured against the consequences of extreme hydrologic events (Cantelmo *et al.*, 2019; Carney, 2019). These statistics, if nothing else, should motivate appropriate public agencies to develop and maintain methods to identify, evaluate, and manage these risks and to make plans to increase attention to these issues due to obvious increases in damage costs. Water infrastructure, in particular, is of critical importance to communities and economies. At a minimum, public agencies should be able to perform regular assessments of infrastructure capacity and resilience.

The role of infrastructure capacity planning in reducing the damage from floods, droughts, and water pollution is not a new subject. Approaches for defining the risks of exceeding specific values (such as flows, durations, or pollutant loads) of such events have been widely used and are typically based on historical data. The challenge today is that information derived from these historical data no longer appears representative of what might be observed in the future.

Although some sources treat the term 'risk' as interchangeable with probability, it is used here in its more widely accepted sense: to describe a combination of the probability and the consequence of some harmful event (USACE, 2019b). Because the consequences of a harmful event depend on many factors – including exposure, resilience, vulnerability, etc. – risk is a substantially more complex concept than mere probability. For this reason, planning approaches that account for probability alone fail to address many factors contributing to risks. Still, any discussion of risk begins with the consideration of probability.

The probabilities of extreme hydrologic events are changing, and the extent of those changes is uncertain. However, the direction of the changes is becoming increasingly apparent. Current calculations of the probability of exceeding any particular drought duration or any particular flood flow or stage based on historical data are likely to underestimate the probabilities of the same events in the future. Estimates of future damages resulting from any given hazardous event are also uncertain and changing over time. Similar adverse changes seem to apply to water pollution events that result from changes in population, in how land and water resources are used, managed, and developed, and in the growth of urbanization and industrialization. Again, these changes are uncertain as are their consequences. In short, future probabilities of damaging events will not resemble past or current estimates, nor will the damages associated with them (Changnon *et al.*, 2000; USGCRP, 2017; NOAA, 2018; Hill *et al.*, 2019).

Hence, it is not clear how to protect against a 100-year chance event in the future when the event associated with this likelihood is unknown. Events corresponding to the current 100-year return interval are becoming more likely. Hence return periods are likely decreasing, but in unknown ways. Therefore, the term 'return period' has little meaning when applied to future events (Salas *et al.*, 2018).

While it may be possible to identify events that society wishes to be protected from, the likelihood of any of them happening is uncertain. However, both the event's damage and its likelihood are factors usually considered in determining what is considered acceptable. For example, a family may be willing to spend the money needed to protect their home from a 100-year flood (that has a 26% chance of occurring at least once in the next 30 years), but not the amount of money needed to protect from a 200-year flood (that has only a 14% chance of occurring at least once in the next 30 years). But this calculus is upset if the future risk of a given flood event is unknown. Of all the options available for reducing risks, how much of each option should be implemented and paid for now, and on into the future, that will at least maintain acceptable levels of risk when the risks themselves are changing in unknown and possibly unpredictable ways? This paper addresses this question.

Rogers (1997) addressed the same question more than two decades ago, as has Hill *et al.* (2019) more recently at the Hoover Institution Rogers applied the standard capacity expansion model of operations research to a very narrow set of water infrastructure planning methods, all characterized by repeated choices of investment

decisions over time. Hill *et al.* (2019), on the other hand, took a very broad view of the capacity planning problem, focusing on resilience and robustness as the goals of planning, rather than cost minimization alone. The purpose of risk analysis is to better inform decision-making, especially for the many components of a water resources management system whose performance possesses various degrees of uncertainty. Yet risk analysis itself introduces its own elements of uncertainty, often in the form of unfamiliar and arcane statistical and probabilistic methods. These are far less transparent than simply selecting a design event for protection, based on its probability being exceeded and its cost. Note that there are two distinctly different risk/reliability evaluation processes involved in the planning of a particular infrastructure (USACE, 2019a) – formulating and assessing options – and the subsequent design. The approach outlined in this paper for planning infrastructure capacity investments for the reduced likelihood of damage from extreme hydrologic events is a conceptual one, simplified here for clarity. For any site-specific project, the functional relationships described here would be based on site-specific data. These relationships assume that the specific infrastructure under consideration is known, as well as its cost and effectiveness in reducing various measures of damage, whether economic, environmental, or social. In other words, we take a deterministic approach but the estimates we use for costs and probabilities could be based on stochastic analyses of alternative futures. Or they could be based on subjective judgments that may later warrant adjustment after computing the estimated consequences of those judgments. For a specific location and assumed type of infrastructure, detailed simulation studies may have to be made to identify the relations and data needed for carrying out the described approaches.

Several different methods for incorporating risk into infrastructure planning are presented here. These differ significantly with respect to data requirements, analytical complexity, and potential contribution to improved infrastructure decisions. However, all of these methods are capable of recognizing hydrologic uncertainty, either implicitly (extreme event plus safety factor) or explicitly (risk–cost analysis). The critical role of adaptive planning is emphasized throughout. There is no attempt to contribute to the state of the art; the purpose of the paper is to present practical approaches to water infrastructure planners under uncertainty.

Considerations in the choice of a method include not only implementation cost but also the degree to which the method makes appropriate use of available knowledge and the degree to which it supports decisions that are efficient in terms of the most likely future hydrology but robust with respect to hydrologic uncertainty.

This paper focuses on, and limits itself to, the risks of floods and droughts, and how they might be reduced. Damages resulting from these extreme hydrologic events can be expressed in economic, environmental, or social terms, as applicable at specific locations. The costs of infrastructure designed to reduce both probability and consequences of extreme events are typically expressed in monetary units while recognizing that the infrastructure itself can have ecologic, environmental, and social impacts, as well as economic costs.

APPROACHES TO PLANNING WATER INFRASTRUCTURE UNDER UNCERTAINTY

The following paragraphs describe some approaches that have been used or proposed for infrastructure capacity planning under uncertainty. These approaches are not mutually exclusive. Actual project planning may encounter different types of uncertainty, ranging from statistical uncertainty that can be expressed in terms of available historical data to deep uncertainty, where little or nothing is known about the range of possible outcomes (Fletcher *et al.*, 2017, 2019). The planner may use different approaches to characterize different types of uncertainty. Also, this list of planning approaches is not exhaustive; other approaches are possible.

Extreme event plus safety factor

Knowing that probabilities of events may be uncertain and changing, is there value in defining engineering standards in terms of probabilities rather than just selecting some extreme event to protect from, and then adding a

safety factor (e.g., 'freeboard') to deal with uncertainties and 'unknown unknowns'? Ultimately, the purpose of risk analysis is to find solutions that are risk–cost-effective. That is, the level of risk and the cost of preventing damages associated with the level of risk are deemed socially acceptable or 'tolerable'. For example, the Standard Project Hurricane used by the USACE is based on the concept of a maximum damaging Category 3 hurricane. The probable maximum precipitation, also used in some contexts, is based on a concatenation of a series of low probability events that cause soil saturation and intense rainfall. Measures may be taken to protect against any damage resulting from these events. The cost of protection from more extreme events might be considered too costly given the low probabilities of such events happening. But the practice of limiting protection to events not exceeding some arbitrary level may not be socially beneficial or acceptable.

There are weaknesses in this safety factor approach. While the definitions of the protected event and the amount of freeboard may be based on historical data, changing probabilities due to changes in land use and climate, e.g., and uncertain future consequences can render historical data irrelevant to future extremes. Therefore, many of the facets of a safety factor are essentially arbitrary choices. There is usually no determination of the efficiency of this approach under likely conditions. The cost of constructing infrastructure to this standard may greatly exceed the damage avoided, or not. In most cases, residual probabilities (for events more severe than the protected event) are not considered, even though they may be substantial. Changes in the consequences of various events, which are themselves changing, are not considered at all. Nothing can be said about the robustness of any resulting plan with respect to a range of extremes.

The extreme event plus safety factor approach has some advantages: it uses data that are often readily available, and it avoids any kind of complex analysis. But while it may have been acceptable when probabilities and possible damages were known with some degree of certainty and were not believed to be changing over time, it is seriously deficient in a world where probabilities of extreme events are increasingly uncertain, as are their consequences. Evidence of the limitations of this approach in practice is provided by the fact that after many years of designing projects based on fixed criteria such as Standard Project Flood, the US Army Corps of Engineers no longer employs this design target, opting instead for risk–cost modeling (USACE, 2019b).

Scenario planning

Because of its usefulness in cases of extreme uncertainty and change, scenario planning has found a wide range of applications. At its most basic, the method consists of the definition, analysis, and comparison of a number of scenarios. A scenario is defined by Peterson et al. (2003), as 'a structured account of a possible future'. A scenario can be entirely or partially quantitative. There is a large literature on the methods and criteria for developing scenarios (Amer et al., 2012).

Generally, scenarios need to be comprehensive: they must include all demographic, economic, social, ecological, and other factors that determine the damage associated with a given hydrologic extreme. They must also be internally consistent. So long as scenarios are plausible, there is no need to assign a likelihood. Scenarios are about the possible, not the probable.

In most public sector applications, scenario planning considers the consequences of some policy or action, based on scenarios which define a range of possible external factors (demography, economic conditions, etc.). When considering future hydrologic extremes, however, some external factors can be held constant over all scenarios or may be varied for groups of scenarios. Each scenario incorporates the infrastructure plan that is to be evaluated. Then the main issue is the assumption, in each scenario, of some extreme hydrologic event along with the damage that would result from that event, given all the other elements of the scenario. The entire process can then be repeated with a different infrastructure plan scenario.

In its basic form, scenario planning of water infrastructure does not address efficiency. While a comparison of damage estimates for different scenarios may show a range of outcomes, since their probabilities are neither known nor assumed, there is no way to compare an estimated outcome to, e.g., infrastructure cost. The principal benefits of a scenario approach are to reveal unexpected outcomes (which may lead to the development of better plans), and to identify plans which are robust with respect to one or more, including hydrologic, uncertainties.

Adaptive planning

Hydrologic, economic, environmental, technological, and social uncertainties create a challenge to effective infrastructure capacity planning, especially where large-scale, long-lived facilities are under consideration. As the time scale increases, so does the importance of considering uncertainties with respect to the future demand for infrastructure services, future technological progress, long-term environmental impacts, etc. Commitments are often made to large, long-lived projects in the interest of minimizing life cycle cost as well political expediency. But these decisions raise the possibility of facilities that are inappropriately sized, have unexpected environmental impacts, and/or become technologically obsolete. Also, these facilities may be vulnerable to hydrologic events not anticipated at the time of planning.

Adaptive planning is one approach for reducing the long-term risks associated with these considerations, as well as those resulting from hydrologic uncertainty. Adaptive planning assumes that plans will be updated through an ongoing process of adaptable decision-making. Rather than following a predetermined path, decisions are adjusted as forecasted conditions and outcomes of prior management actions are better understood (National Research Council, 2004). The purpose of adaptive planning is to achieve more effective planning over time in the face of an uncertain future (Haasnoot et al., 2013; Beh et al., 2015; Hui et al., 2018; Erfani & Harou, 2021).

The general principle of adaptive planning is to avoid plans or proposed actions that close future options. These options can be addressed later, as some of the uncertainties present in the initial plan are partially resolved and new ones emerge. In this way, risks due to a number of uncertainties, including hydrologic uncertainty, are considered. However, there are costs associated with this approach. It requires careful monitoring of the performance of the planned infrastructure throughout its life, as well as analysis and design costs whenever interim decisions must be made. It is possible that the life cycle cost for the adaptively managed facility might turn out to be less than for a one-time design, but it may also be greater.

Risk–cost modeling

Another approach to planning under uncertainty involves actively managing and modeling risk along with the cost of reducing risk. Hydrologic risk is managed by developing resilience in affected communities (thereby reducing exposure and vulnerability) and by planning policies and actions that mitigate adverse impacts, should a harmful event occur (National Research Council, 2012). Risk–cost modeling supports the development of effective mitigation while informing decision-makers of the possible exposure to risk.

Planning under deep uncertainty

In most cases of planning under uncertainty, something is known about our future. Both hydrologic variables and vulnerability to damage may have plausible upper and/or lower bounds. Future trends may be seen as uncertain deviations from past experience. A statistical representation of uncertain future conditions may be possible. Various planning approaches can be used, depending on the information available. Said differently, planning under uncertainty may involve the application of the mathematics of probability and statistics because some information/data are generally available.

In contrast, the most challenging planning problem arises where the future is characterized not just by limited information, but by true uncertainty. This means that no useful data exist, that is one 'doesn't have a clue'. True

uncertainty is now often replaced by the term deep uncertainty. Deep uncertainty is defined by Lempert *et al.* (2003) as:

> '… the condition in which analysts do not know or the parties to a decision cannot agree upon (1) the appropriate models to describe interactions among a system's variables, (2) the probability distributions to represent uncertainty about key parameters in the models, and/or (3) how to value the desirability of alternative outcomes.'

The usual approach to planning problems of this kind is to focus on robustness, where outcomes are least sensitive to various realizations of the underlying variables. Recent work at the RAND Corporation (2021) has produced a guide to decision-making under deep uncertainty, combining the methods of scenario analysis and adaptive planning to achieve a robust, broadly acceptable plan.

INFRASTRUCTURE OPTIONS AND RISK REDUCTION

Various options exist for preventing or mitigating the adverse impacts associated with droughts or floods. These adverse effects lead to damages, which can be measured in monetary as well as non-monetary terms. The following subsections illustrate how risks and related damages can be conceptualized. This allows various options for risk reduction to be modeled under conditions of various assumed probabilities of hydrologic extremes.

Droughts

There are several mitigation measures that can be used to reduce the impacts caused by drought. These include any measure that reduces the demand for water, including, e.g.:

- Soil and water conservation and irrigation practices that result in less water use.
- Various urban water conservation measures, including pricing.
- Technological fixes, such as low-flow toilets, showerheads, and washing machines.
- Interconnecting smaller municipal water supply systems and augmenting with groundwater.
- Reducing demands through leak detection and repairs.

They also include measures that increase the supply of water, such as

- Desalination of seawater, water recycling, and rainwater harvesting.
- Conjunctive use of surface and groundwater reservoirs.
- Interconnections among rivers and reservoirs within and outside river basins.

Prolonged droughts can lead to adverse health, social, economic, and political impacts. Any measures taken in advance of drought events that address these potential impacts can reduce if not prevent their adverse impacts. Such measures include:

- Storage and distribution of food and medical supplies.
- Unemployment and crop failure insurance.

Provision of alternative sources of energy to mitigate any reductions due to lack of water, say for hydropower or cooling. None of these options can change the duration and severity of any drought. What they can do is reduce the damage resulting from it. Of interest here is the trade-off between the costs of drought damage reduction measures and the extent of such damage reductions. It is important to note that not all measures are equally reliable in their ability to eliminate or reduce drought-related damage. Even if one could effectively calculate

these factors, there are always considerable uncertainties associated with each management measure, which often depends on the fallibility of human factors and interpretation of information.

Given a scenario that includes assumed estimates of the probabilities or return periods of various drought durations and severities and the damages resulting from them, the estimated annual damages associated with measures taken to reduce drought damage can be compared to annual implementation costs.

To outline how such risk–cost trade-offs can be estimated, the relationship between drought damages and drought likelihood needs to be defined. Again, since this estimation is itself uncertain, this damage function can be considered as a scenario. Risk can be expressed as the probability of some level of drought damage being exceeded.

Measures taken to mitigate drought impacts can be implemented in stages as the severity of drought increases. Drought management triggers can be assigned to drought durations and severities, i.e., the number of days of water shortage and the extent of that shortage (such as specified aquifer or reservoir storage levels or river flows). The probability distribution of annual drought damages can be based on historical annual drought data, but if so, this will not reflect future changes in this distribution due to climate change. These changes of course are unknown and hence will have to be based on assumed drought event scenarios. From these scenarios, the probability of drought duration exceedance functions can be estimated by subtracting the cumulative probability distribution of damage (the probability that the actual damage will not exceed some specified damage) from 1.

Assume the function $PE_D(D)$ defines the probability of a specific annual drought damage D being exceeded. The expected annual drought damage, $E_D[D]$, is the area under this exceedance function, i.e., the integral of $PE_D(D)$ over all values of damages D.

$$E_D[D] = \int PE_D(D)dD \tag{1}$$

A changing climate is causing a change in this expected annual damage over time. In regions where droughts are lasting longer and hence drought damages are increasing, it is reasonable to take that into account when planning current drought damage mitigation measures. Letting the index t represent a future time period, we can develop scenarios of shifting probabilities of annual drought damages, $PE_{Dt}(D)$, and use them to compute the corresponding estimated annual drought damages, $E_{Dt}[D]$ in each period t. This will be useful for the next step of computing the estimated present net benefits of future drought mitigation measures.

Drought damages can be reduced in various ways, as discussed earlier in this section. Those damage reduction measures will have costs. For the purposes of this paper, assume these damage reduction measures are discrete independent of each other. Let $C_{it}(\delta_{it})$ be the estimated annual cost function applicable in period t for reducing drought damage D by δ_{it} using measure i. To be determined are the damage reduction values δ_{it} that maximize the present value of the damage reduction net benefits – the reduced estimated annual damages less the costs of damage reduction. Letting r be the periodic interest rate, this goal is equivalent to:

$$\text{Maximizing} \sum_t \left\{ \sum_i (\delta_{it} - C_{it}(\delta_{it})) \right\} (1/(1+r)^{t-1}) \text{ where } \sum_i \delta_{it} \le E_{Dt}[D] \tag{2}$$

This approach can apply to each type of damage, whether economic, environmental, or social, as long as such damages can be quantified and along with the values of $C_{it}(\delta_{it})$, expressed in comparable damage units. If not, it becomes a multi-objective trade-off between damage reduction and cost. More detail is available in the handbooks edited by Jain & Singh (2019), Singh (2017), Singh et al. (2007), and Mays (1996).
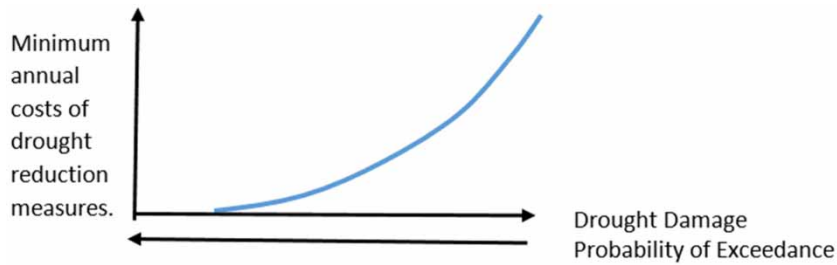
Fig. 1 | Function showing minimum total costs, $C_i(\delta_i)$, of protecting from droughts causing specified damages or having a specified probability of being exceeded. Actual cost functions, $C_i(\delta_i)$, may include fixed costs together with economies of scale.
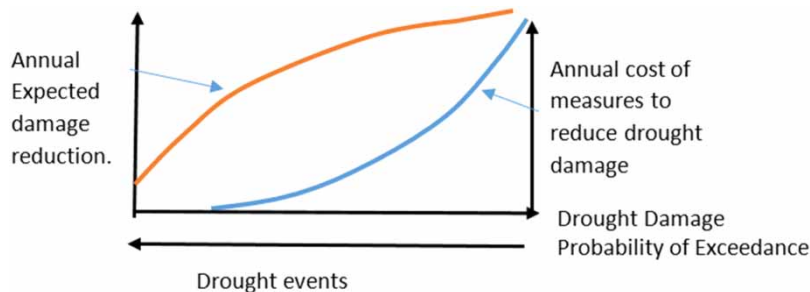
Fig. 2 | Functions showing trade-offs between minimum costs of reducing estimated annual drought damages, $\sum_i C_i(\delta_i)$, and resulting annual drought damage reduction benefits, $\sum_i \delta_i$. Actual cost functions may include fixed costs together with economies of scale that are not shown in this example.

The derivation and use of estimated annual damage reduction values as outlined above are just one approach for informing those responsible for deciding which measures to take to hedge against future droughts and their damages. Another approach is to decide what level of drought risk, $PE_D(D)$, or damage, D, to protect from, and identify the least-cost set of measures, δ_I, that will accomplish that. This trade-off is illustrated in Figure 1. That selection process could be based on other criteria besides cost, as deemed appropriate.

Obviously different drought reduction measures will result in different estimated annual damage reductions and will cost different amounts of money. Considering different sets of drought reduction measures and their annual estimated damage reductions and costs, trade-offs between those damage reductions and costs can be defined as illustrated in Figure 2. If damages are expressed in monetary terms, say dollars, the particular set of measures that maximize the estimated damage reduction less cost can be identified.

The above discussion has assumed known risks, perhaps based on historical data (Vogel & Castellarin, 2016). Of course, these return periods are changing due to many factors, including climate change. Furthermore, these changes are uncertain and this uncertainty is itself unknown (Hall *et al.*, 2014; Read & Vogel, 2015, 2016a, 2016b; Salas *et al.*, 2018). So the question of what and the extent of measures to take to accomplish future drought damage reduction targets or to protect from droughts having specified return periods is still unaddressed. These issues will be examined after a discussion of flood risk reduction measures that follow.

Floods

Unlike droughts, floods can occur relatively quickly giving less opportunities for adaptive measures as the severity of a flood increases. Strategies to reduce threats to life and property from flooding include those that:

- reduce the susceptibility to flood damage and disruption;
- reduce the adverse impacts of floods on individuals and the community; and
- alter the flood stages and/or durations themselves.

Susceptibility to flood damage and disruption can be reduced through appropriate floodplain zoning and other regulations pertaining to land-use development and drainage, disaster preparedness, assistance including flood insurance, and recovery planning and programs, flood proofing, and the development and use of flood forecasting and warning capabilities.

The adverse impact of flooding on individuals and the community can be reduced through information and education programs, flood insurance, tax adjustments, emergency and rescue services, and flood damage recovery efforts.

Flood stages and durations can be reduced through the operation of reservoirs, installation of dikes, levees, and floodwalls, channel dredging and modification, high-flow diversions, floodplain modifications, and detention storage.

Along coastal shorelines, structural measures include barrier protection, interior flood gates, road/rail elevation, levees, floodwalls, bulkheads, seawalls, revetments, beach restoration, breakwaters, and storm system drainage improvements.

Coastal zone flood management options include building retrofit (elevation and flood proofing), managed coastal retreat, emergency evacuation plans, early warning systems, public education/risk communication, flood insurance, wetland restoration, and implementing living shorelines, green storm-water management, reefs, and submerged aquatic vegetation.

Each or a combination of these flood damage reduction measures can change the relationships defining damages and the probability of exceedances associated with flood events. Following the conceptual approach taken to estimate estimated annual drought damages and how they might be reduced, consider a potential flood damage site. Let S be the stage or height of a flood at that site that causes D damages. Define the relationship between stage S and damage D as the function $D = f(S)$. Having records of the maximum flood stage in each year for a number of years allows one to define the probability of exceedance function associated with flood stages at particular locations. Let that function be designated as $PE_S(S)$. The estimated annual flood stage is the area under that probability of exceedance function:

$$E_S[S] = \int PE_S(S)\mathrm{d}S \tag{3}$$

Knowing the damages and probability of exceedance associated with any specific flood stage S allows the calculation of the probability of exceedance of the corresponding specific damages:

$$PE_F(D) = PE_S(f(S)) \text{ where } D = f(S) \tag{4}$$

and the estimated annual flood damage, $E_F[D]$

$$E_F[D] = \int PE_F(D)\mathrm{d}D \tag{5}$$

Any measures taken now to reduce flood damage should take into consideration the changes over time that will alter both the flood damage function, $f(S)$ (such as urban development on the floodplain) and the probability of

exceedance, $PE_S(f(S))$ (such as resulting from changes in precipitation due to climate change) associated with any flood stage S. Letting the index t represents a future time period, one can create scenarios of future exceedance probabilities and damage functions to calculate future estimated annual damage functions, $E_{Ft}[D]$.

Flood damages can be reduced in various ways, either by altering the stage damage function (such as by flood proofing structures on the floodplain) or by altering the probability of exceedance distribution (such as by levees or reservoir flood storage capacity or operation during a flood period). Those damage reduction measures will have costs. Various combinations of them will have different total costs. Let $C_t(\delta_t)$ be the estimated minimum annual cost function applicable in period t for reducing the remaining estimated annual flood damage $E_{Ft}[D]$ by δ_t. To be determined are the damage reduction values δ_t that maximize the present value of the damage reduction net benefits – the reduced estimated annual damages less the costs of damage reduction. Letting r be the periodic interest rate, this goal is equivalent to:

$$\text{Maximizing} \sum_t (\delta_t - C_t(\delta_t))\}(1/(1+r)^{t-1}) \text{ where } \delta_t \le E_{Ft}[D] \tag{6}$$

This approach can apply to each type of damage, whether economic, environmental, or social as long as such damages can be quantified using the same units as $C_t(\delta_t)$. If not, it becomes a multi-objective trade-off between damage reduction and cost. More detail is available in the handbooks edited by Jain & Singh (2019), Singh (2017), Singh et al. (2007), and Mays (1996).

IMPACT OF CHANGING EXTREMES

While there are exceptions (Hirsch & Ryberg, 2012), recent observations generally show that more extremes are occurring more frequently (Doocy et al., 2013; Kunkel et al., 2013; Peterson et al., 2013; Hall et al., 2014; Blöschl et al., 2015; IPCC, 2018). Hydrologically related probability distributions are changing, i.e., are non-stationary, and that change is hard to predict (Blöschl et al., 2015; Hu et al., 2018). From Figure 3, the translation of the event values, such as drought duration or flood stage, on the vertical axis of the upper right quadrant to the horizontal axis of the lower left quadrant is accomplished by the blue line in the upper left quadrant. Raising that linear function, such as shown in green, shortens the scale on the horizontal axis. This green function, whether linear or not, can represent the impact of extreme events due to climate change. The same events now have a higher probability of occurring and hence the estimated damages will increase.

As shown in Figure 3, increases in the magnitude of hydrologic events such as the magnitude and duration of drought restrictions or flood stages will result in increases in estimated annual damages. This will impact the trade-offs between annual estimated damage reductions and annual costs of measures taken to achieve such reductions. It will also impact the trade-offs between target return periods and the annual costs of measures taken to avoid events less than or equal to those target values. Hence, the fundamental question (addressed in the next section) is one of determining what measures should be taken today given the estimated need to increase the capacity of such measures in the future to accomplish the same, or even different, goals. Failure to consider the increasing future risks can result in infrastructure investments that will fail to function or serve society for as long as originally expected (World Energy Council, 2015; Davenport, 2018).

INFRASTRUCTURE CAPACITY PLANNING OVER TIME

Capacity planning addresses how much infrastructure capacity to build and when in order to meet the desired risk or estimated damage reduction goals over time. Whether the goal is to maximize the difference between the estimated annual damage reduction and annual infrastructure cost or to achieve protection up to a specified
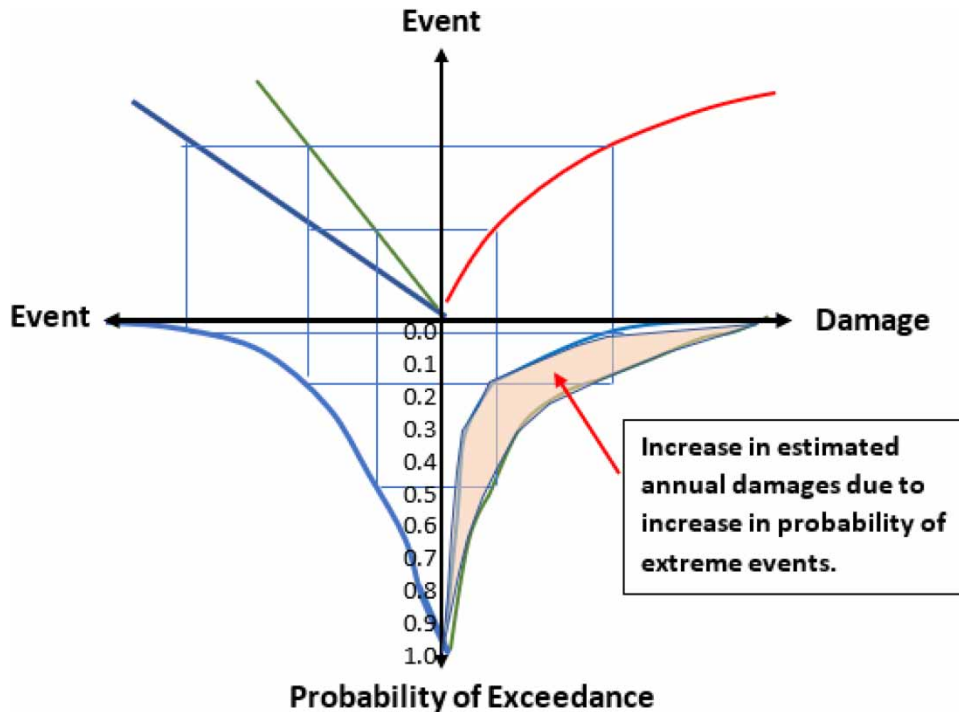
Fig. 3 | Estimating the impact of decreasing return periods associated with various hydrologic events. The magnitude of the event, however measured, increases in the direction of the arrows on the respective event axes. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wp.2021.242.

return period at minimum cost, the question of what types of infrastructure and their design capacities should be built is not a trivial one. Even assuming no change in risks or potential damages over time, the fact that infrastructure costs typically include fixed as well as variable costs, and exhibit economies of scale, makes it economical to build more capacity than is needed at the time construction takes place. Add to this, the need to meet an uncertain but likely increasing future demand, the issue is how much to build and when. Here our demand is the capacity required to protect from an increasingly severe hydrological event or the capacity required to meet increasing estimated damage reduction targets.

Based on observed trends and analyses as outlined above, assume one can estimate the demand for infrastructure capacity that is needed to meet specified risk or estimated damage reduction goals over the next several decades. Also assume that the costs of new infrastructure capacity can be estimated for this period, as well as the interest rate that defines present values of costs. All these values are uncertain, and the impact of this uncertainty needs to be addressed, but first assume such data can be estimated.

Let K_t be the existing capacity of infrastructure at the beginning of time period t. Except for K_1 for the current period, $t = 1$, these values need to be defined for future periods t such that they meet or exceed the assumed known capacity demand targets, KD_t. Clearly, there are many values of K_t that will meet this constraint for each period t. Which values are best depends on the criteria chosen for evaluating alternatives. If a least-cost capacity expansion schedule is of interest, then cost estimates are needed for capacity additions, KA_t, in each period t. Assume such costs can be estimated and then discounted to the present time. Let the function $C(KA_t, K_t)$ be the present value of the cost of adding KA_t capacity to an existing capacity K_t during construction

period t. Using these data, an optimization model can be developed and solved to identify the values of each KA_t variable that results in a least-cost capacity expansion schedule identifying how much capacity to add and when over a predefined time horizon.

$$\text{Minimize Total Costs} = \sum_t C(KA_t, K_t) \text{ subject to } K_t + KA_t = K_{t+1} \geq KD_t \text{ for each period } t \tag{7}$$

Whatever the values of those future capacity additions, they are based on numerous assumptions concerning time horizons, future demands, KD_t, costs, $C(KA_t, K_t)$, and interest rates, all of which are uncertain. Thus, different estimates of these parameter values should be used to test if any such assumed conditions alter the value of the variable of most interest, namely what to do now, KA_1. If not, one can be more confident of that possible decision that best satisfies the objective, in this case, to minimize the present value of the total cost. Rogers (1997) provides a more detailed discussion of this approach, although his analysis is restricted to the case where repeated investment decisions are possible over time. Also, see Hall *et al.* (2020) for an interesting case study in risk-based planning applied to the water industry in England.

When the future is not only unknown but non-stationary, i.e., there is no probabilistic basis for stating what the future may be, and as a result, any capacity expansion schedule needs to be adaptive (Kwakkel *et al.*, 2016; Pahl-Wostl, 2016; Söderholm *et al.*, 2018). Of interest is the current decision for the current time period. The capacity to add now, if any, surely needs to be based on the best guess of future demands and costs and discount rates. Any later decisions should be informed using updated estimates of all these uncertain parameter values.

SUMMARY

A changing climate is bringing with it increasing hydrologic extremes. These extremes can result in damages, the extent to which depends on measures taken in advance to reduce the damages that would otherwise occur from those extreme events. Infrastructure capacity planning cannot escape consideration of the uncertainty regarding future hydrologic extremes as well as the myriad other factors involved in infrastructure design. All of these potentially affect future flood and drought damages. This paper has outlined a number of approaches to incorporating uncertainty into risk reduction in infrastructure planning.

To estimate estimated annual damages that could result from an extreme hydrologic event one needs to know the probability of such an event being equaled or exceeded. Because of climate change, these probabilities are changing and therefore unknown. Not only is there uncertainty in the likelihood of future hydrologic extremes, but there is also uncertainty in the future damages that would occur given specific extreme events. Similarly, the future costs of damage reduction measures are uncertain.

In considering the various approaches to infrastructure planning over time and under uncertainty, emphasis has been placed on the investment in the first period. Errors due to uncertainty regarding infrastructure requirements may be less costly in later years. One reason is the opportunity for adaptive planning, an advantage that increases in value as the time between investment decisions becomes smaller. This point is illustrated by Rogers (1997). That analysis assumed a repeated choice of investment decisions over time and the result was that the first-year investment was almost invariant with respect to uncertainty regarding future conditions. As noted by Rogers, this result does not necessarily hold for the kind of large, indivisible, irreversible investments typical of water infrastructure.

All these uncertainties do not change the fact that we continue to make decisions to protect communities from future hazards. The approach to risk–cost analysis outlined in this paper is designed to assist such decision-making. Because of all these uncertainties, the approach involves using multiple scenarios, each of which includes estimates of these uncertain risks, damages, and costs. The estimated values derived from all these scenarios (or the scenario that meets a specified degree of reliability of estimated annual damage) can be used in an

adaptive capacity expansion approach, where over time the analysis results can adapt to changes in future estimates of all these uncertainties.

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