

Keeping infrastructure reliable under climate uncertainty

Characterizing infrastructure vulnerability to climate change is essential given the long asset lives, criticality of services delivered and high costs of upgrading and maintaining these systems. Reconciling uncertainty from past infrastructure design decisions with future uncertainty of climate change will help prioritize limited resources to high risk assets.

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Every day, engineers, planners and stakeholders make choices for infrastructure that directly involve environmental variables. They size pumps and stormwater drainage infrastructure based on the intensity of precipitation and corresponding water flows, or risk allowing roads and neighbourhoods to flood^{1,2}. They choose power line materials based on peak expected summertime temperatures to ensure that heat generated by the lines can sufficiently dissipate away³. Bridge engineers design foundations to maintain integrity under severe water flows. Many thermoelectric power facilities are sensitive to influent water temperatures^{4,5}; a slight temperature increase could result in efficiency losses that make operation uneconomical. Separating design and management of infrastructure from the environment in policy and decision-making is impossible⁶.

As the impacts of climate change increasingly start to affect infrastructure performance, stakeholders have to reconcile how to continue to keep their systems reliable over multi-decadal service lives with growing climatic uncertainty. Given the limited resources available to upgrade infrastructure, strategic investment in climate adaptation is needed. This will require acknowledging the limitations of current infrastructure design processes, which codify the use of past conditions by assuming these are useful predictors of the future, and recognizing that simply armouring infrastructure everywhere in anticipation of more extremes may ineffectively deploy scarce resources away from the highest risk assets.

Design from historical conditions

The crux of the challenge of adapting infrastructure to climate change lies in the implicit acceptance of climate certainty in the infrastructure design process. Design of new infrastructure, including the climate extremes they can withstand (heat,

precipitation, water flows, cold, wind and fire, and so on), is largely based on historical conditions. Yet in the mid-twentieth century, when much of our infrastructure was built, low-fidelity data on temperature, precipitation, streamflow and other factors informing designs were generated from newly deployed environmental sensor networks. Large uncertainty often existed with these data resulting from the sensor itself, the spatio-temporal density of the sensor network, human or mechanical error⁷ and how the data were summarized and presented. These conditions most likely resulted in both over- and under-design outcomes, leading to situations where infrastructure was more robust than it needed to be and situations where it was not robust enough, respectively. Additional data and improved sensing technologies have now provided a clearer picture of current environmental conditions, but there remains uncertainty as to what conditions existing infrastructure were designed for.

Infrastructure design continues to allow past conditions to be predictors of the future, despite growing evidence to the contrary^{1,2,8}. Although engineers have always had to grapple with the question of how robust infrastructure should be, and they have the technical expertise to design for increasingly frequent and stronger extreme events, it is not desirable for one individual or firm to arbitrate the economic and social costs of failure. As such, towns, cities, regions, states and countries have codified the level of risk that their infrastructure should be able to withstand. For instance, stormwater management systems under roads are often designed to be able to handle up to a 10-year event (an event that has, on average, a 10% chance of occurring every year based on historical records). Larger assets are often designed for a 100-year event (1% chance of occurring each year)¹. This 'return period' codification sets the minimum level of legal risk that the engineer must design infrastructure for. But infrastructure lasts for

several decades or longer, and even under a stationary climate, the risk of 'failure' is non-trivial. The probability of a 100-year event happening at least once over a 50-year asset life is nearly 40%. If uncertainty has resulted in under- or over-design of twentieth century infrastructure, then how well prepared are assets for the future? Climate change and the resulting gradual change in environmental conditions, as well as extreme events, are entirely characterized through uncertainty. As such, decisions about how to prepare infrastructure for climate change appear to be caught between past and future uncertainty, and infrastructure design and management standards do not recognize or address this complexity.

Design for uncertain climate change

As many climatic variables are projected to occur with more intense and frequent extreme events, possibly with unpredictable patterns and negative feedback loops with other environmental processes, it is often assumed that all infrastructure systems are going to be at greater risk for failure. As such, a default position of concern about infrastructure reliability is quite reasonable. But the challenge of understanding how vulnerable infrastructures are in a changing climate remains a complex process driven by historical and current choices. Characterizing infrastructure vulnerability is important given the high costs of upgrading and maintaining the systems: under increasing climate threats, decisions must be made about which assets to prioritize.

Two key dimensions define four domains for infrastructure decision-making under climate change: (1) whether the conditions that we originally designed a particular asset to be able to withstand have become better or worse, and (2) whether climate change and associated extreme events in this location are projected to weaken or become more severe over the asset's lifetime (Fig. 1). If climate change is likely going to result in worsening conditions for the asset,

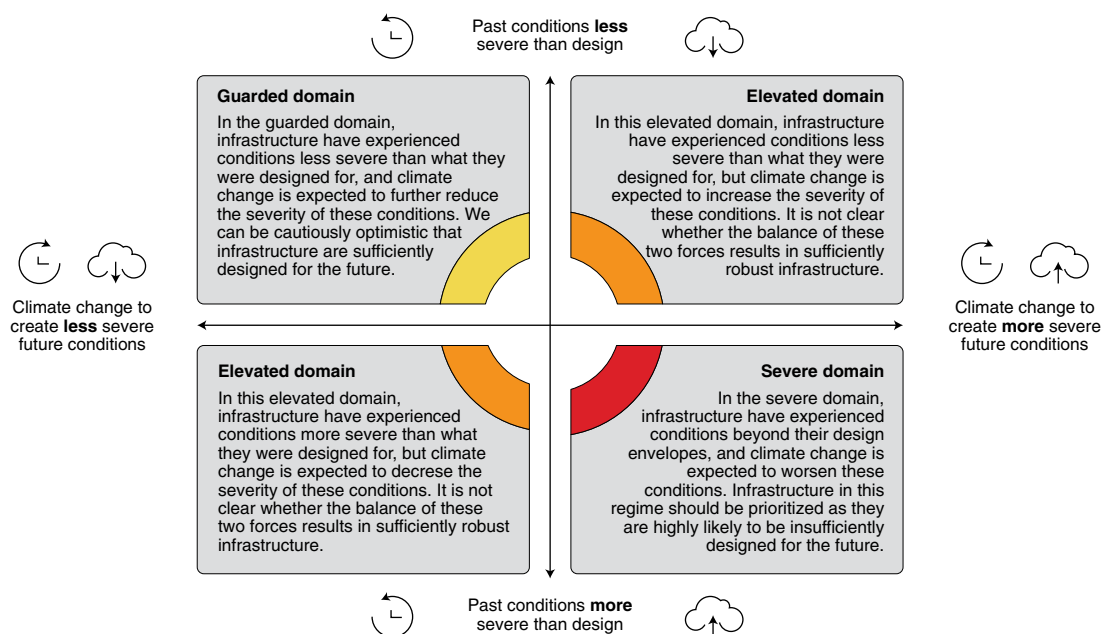


Fig. 1 | Infrastructure decision-making domains defined by past and future climate uncertainty. Past conditions are represented along the vertical dimension, and future conditions are represented along the horizontal dimension.

and the conditions under which that asset were initially designed for have become worse, then there's certainly cause for alarm (severe domain). In contrast, if climate change is likely going to result in less severe conditions, and the conditions under which the asset was initially designed are better, then the asset's design might be sufficient; that is, appropriately designed for the environmental hazard (guarded domain). The elevated domains are particularly problematic because the conditions for which the asset was originally designed are moving in the same directions as climate—either infrastructure was over-designed for what was needed but climate is getting worse, or infrastructure was under-designed for what was needed and climate is getting better. In such cases, there is uncertainty about whether interventions are needed. These domains highlight how blanket policies that call for more robust upgrades across the board do not address how assets are prioritized and may ultimately deploy scarce resources away from highest risk assets. These are not just hypotheticals, for even just the uncertainty from modelling choices to update hazard estimates under climate change could lead to decisions that considerably increase the cost of required infrastructure for a specific location⁹.

Decisions about how to upgrade and prepare infrastructure for climate change must also consider other variables beyond the uncertainty embedded in past and

future climate conditions. For instance, a road with a stormwater management system may have been under-designed in the past, leading to repeated flooding, but the transportation agency may have recognized this failure and reconstructed the asset. Conversely, the design may have been correctly or even over-designed in the past, but inadequate maintenance may have degraded the asset's capacity. Another important consideration is the deference afforded to engineers and construction managers in the field that allows them to modify designs to exceed minimum requirements given the conditions they are seeing during construction. A bridge engineer may use their judgement on-site to add more erosion control measures when they notice that the terrain or conditions are likely to lead to more intense hazards. Finally, changes in population and technology, changes in the surrounding impervious landscape area as well as the installation or degradation of local green infrastructure can all affect performance. All of these variables can make assessments about the current robustness of infrastructure difficult. The coupled uncertainty around infrastructure's robustness and climate change create a paradigm where the certainty-based approaches that are at the heart of infrastructure decision-making today are limited in their capacity to steer these critical systems into the future.

Future directions

Unlike traditional infrastructure design, the equations and mathematical relationships representing climate adaptation are not yet fully defined, and the field of resilience is rapidly evolving to fill this challenge. Several important approaches are emerging. First, decision-making must consider safe-to-fail designs where the impacts and management of failure are considered during the design process instead of the fail-safe approaches that we rely on today¹⁰. Given the limited resources to modernize infrastructure as well as its vast scale, obdurate nature and limitations for robustness against the broad range of climate outcome severity, 'failure' in some form will be inevitable, so we must plan for it. In the course of that planning, we'll learn about weaknesses, tolerances, values and incorporating equity into resilience decisions.

Next, we must embrace resilience decision-making under deep uncertainty. Robust decision-making and infrastructure design under deep uncertainty^{11–13} are a class of methods that facilitate the evaluation of performance across the entire plausible range of futures and enable stakeholders to choose adaptive pathways that minimize the costs of choosing incorrectly. More rigorous approaches to understanding what vulnerability of infrastructure means—not purely as technical systems but as social–ecological–technological systems—are becoming viable through multi-discipline

frameworks informed by new data with computational and communication capabilities (such as high-resolution dense sensor networks that include smartphones) as well as recognition that resilience begins with people, governance and ecosystem services¹⁴. Presently, analyses of infrastructure vulnerability to climate change often simply overlay climate change forecasts on infrastructure asset maps. However, merely co-locating the hazard with the infrastructure misses that failure most often occurs when design conditions are exceeded, not simply because the asset has increased exposure; additionally, failure is often not collapse but some temporary reduction in supply and service^{3,4,8}. More research is needed to inform infrastructure decisions with an understanding of failure dynamics, how failure cascades, how failures affect people and services, and how governance, social networks and ecosystem services (including natural infrastructure) can be supported to attenuate risks and reduce the reliance on technological systems towards improving resilience. But infrastructure stakeholders also need updated standards and methods for climate change adaptation that are simple enough to be adopted but rigorously manage a growing list of uncertainties.

The future will be defined by increasing complexity, and infrastructure managers

must be equipped with new tools and competencies to navigate their systems through this emerging world. Climate change, and the concurrent uncertain forces that are expected to characterize the future (such as technology, finance, social needs and so on), require adaptive capacities that embrace the unknown¹⁵. Infrastructure managers must be committed to design and operational processes that can help them understand the uncertainty in the environment around them, and change their systems in response. Climate change will force infrastructure managers to rethink the future of their systems. As such, the broad community of climate researchers can help lead the development of new knowledge required to determine how societal needs are reliably met through infrastructure in a warming world. 

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