The centrality of engineering codes and risk-based design standards in climate adaptation strategies

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ABSTRACT

Engineering codes, design standards and analytical criteria for hydraulic structures are the final determinative specifications for designing and constructing a water resources project. As such, they are the authoritative and legally accepted standards for project design and construction. Engineering codes and standards are developed to optimize public safety and performance by focusing on structural reliability, which includes a wide range of extreme conditions that encompass most contemporary climate uncertainties, and which are likely to overlap some portion of future climate non-stationary conditions. Current practices of risk-based planning and design standards have evolved incrementally, responding to each catastrophic natural disaster, whether it is geotechnical, floods, droughts or hurricanes. Design standards and building codes encompass an accumulation of changes that progressively reflect changing climate conditions, most notably because they focus on climate extremes. Design standards and embedded 'safety factors' that are based on extremes are likely to encompass a good deal of an anticipated non-stationary climate regime and its associated uncertainties. Modern risk analysis methods and risk-based standards, codes and methods comprise an important part of a progressive autonomous adaptation to climate change. They represent an essential component of 'no regrets' climate adaptation.

Key words: Engineering codes, 'No regrets' climate adaptation, Risk-based design standards, Risk tolerance, Safety factors

INTRODUCTION

New and ageing infrastructure will require huge investments in public infrastructure over the next 30 years because of growing populations, increased trade, prosperity and adaptation to climate change. Global estimates for water-related infrastructure investment requirements are nearly $200 billion/yr. (Oxford Economics, 2017). These investments can serve as the foundation of a 'no regrets' climate adaptation strategy. 'No regrets' adaptation connotes that the benefits of a selected option are justified regardless of whether the projected impacts of future climate change materialize and can be economically justified by existing benefit–cost procedures (Prabhakar et al. 2009, OECD, 2018a, 2018b).

Whatever actions ultimately lead to the decarbonization of the global energy system, it will be many decades before they have a discernible effect on the climate (Pielke et al., 2007). Historical emissions dictate that climate change is unavoidable, even under the most favorable assumptions. Hence, the anticipated adverse impacts of climate change require a focus on adaptation that will require innovative technological solutions that increase

robustness, resilience and reliability of coastal protection, flood protection, irrigation, water supply and hydropower projects and systems.

Even the most optimistic emissions projections show global greenhouse gas concentrations rising for the foreseeable future (IPCC, 2021). Virtually, every climate impact projected to result from increasing greenhouse gas concentrations – from rising storm damage to declining biodiversity – already exists as a major concern. Existing engineering methods that deal with the extremes of contemporary (stationary) climate variability can serve as a platform for a new class of risk-based methods that will more effectively deal with a non-stationary and more uncertain climate (Stakhiv, 2011; Read & Vogel, 2015; Read & Vogel, 2016; François et al., 2019; Hecht & Vogel, 2020; Vogel & Castellerin, 2017).

Public engineering practices, i.e., that engineering conducted under the auspices of sanctioned public institutions, are bound by numerous overlapping laws and regulations that are conservative and generally risk-averse. Large public works projects (dams, flood control systems, urban drainage systems, wastewater treatment, water supply and irrigation systems) are often legally required to perform and provide services with a high degree of reliability – as close to 'fail-safe' as possible, since communities depend on service reliability and public safety of these water management systems. Public engineering is always accompanied by a dense dendritic network of laws, administrative regulations and public review procedures that guide project planning and design procedures. These engineering planning and design practices are translated into stringent building codes, design standards and analytical criteria (Retief et al., 2013; Ayyub, 2018, 2019).

According to the U.S. Office of Management and Budget, Circular No. A-119 (OMB, 1998), a standard consists of technical definitions, procedures and/or guidelines that specify minimum requirements or instructions for design of infrastructure or equipment. This can be done by specifying either the methods or the results; the latter is termed 'performance specifying'. Most importantly, a standard provides standardization or agreement within an industry or water management sector, which translates to a commonly understood frame of reference among planners, design engineers, manufacturers and contractors.

A code is a standard that has been enacted into law by a local, regional or national authority having jurisdiction, so that the engineer or contractor is legally obligated to comply with the code. Noncompliance can result in being prosecuted. The code may be an industry, government or voluntary professional consensus-based standard. Codes are generally accepted sets of rules that tell engineers what they need to do. Standards provide the 'how to' instructions for implementing codes.

Engineering codes and standards are constantly evolving, as knowledge increases, albeit slowly because of legal liability implications and extensive peer-review and testing processes. Hence, new knowledge and rapid advances in technology are not readily assimilated into engineering practice. Designing infrastructure for future climate uncertainties using novel and untested analytical methods further complicates this matter. Determining an engineer's liability in any future design failure becomes ever more difficult, because of the uncertainties associated with widely varying sources of data generated by climate models and climate scenarios, or unproven design theories for structures at the cutting edge of the profession.

Professional legal liability for infrastructure failure is an even more important reason for carefully vetted and institutionally accepted design procedures and standards (Peck & Hoch, 1985; Hatem, 1989). Averting failure is at the heart of engineering design and explains, to a large degree, why engineering standards and codes that institutions designed to protect the populace from natural and man-made hazards are fundamentally conservative (Petroski, 2006).

Design engineers are legally liable for infrastructure failure if they diverge significantly from acceptable practices and standards (Seemann, 1991). Hence, any changes, such as those associated with incorporating the largely uncertain effects of global warming and climate non-stationarity, require a considerable degree of testing,

peer review and formal acceptance by professional engineering societies, federal agencies, ministries and multi-lateral lending institutions, such as the World Bank and Asian Development Bank (Ittmann, 2020). In general, contemporary laws protect structural engineers who have designed at the accepted professional level of competence but not necessarily at the state of the art (Peck & Hoch, 1985).

It is important to recognize that technologies devised to solve practical water management problems preceded the development of scientific knowledge and associated predictive techniques. Hydraulic engineering (water infrastructure) achievements preceded the science of hydrology by several millennia and began with water development of ancient civilizations in Mesopotamia, Egypt, India, China and Greece aimed at controlling floods and the flow of water, initially for agricultural needs (irrigation) and later for communal water supply (Koutsoyiannis, 2014). Hence, conservative safety factors embedded within design standards that are in use today, are the result of millennia of trial and error and adjustments after many failures (Petroski, 1985, 2006). During these millennia (3000BC–present), climate varied considerably, encompassing higher global temperatures, and lengthy periods of floods and droughts.

Accounting for engineering liability has been true since the times of Hammurabi (1754 BCE), whose code consisted of 282 laws, a number of which dealt harshly with design failure and engineering liability, following the biblical 'eye for an eye' compensation standard: https://avalon.law.yale.edu/ancient/hamframe.asp:

- 227. If a builder builds a house for a man and does not make its construction firm, and the house which he has built collapses and causes the death of the owner of the house, that builder shall be put to death.
- 228. If it causes the death of the son of the owner of the house, they shall put to death a son of that builder.
- 229. If it causes the death of a slave of the owner of the house, he shall give to the owner of the house a slave of equal value.

Adaptation of infrastructure to climate change calls for upgraded risk-based engineering design standards and codes, along with new approaches and frameworks for water management planning, since climate change directly affects the hydrologic basis of planning and design. Climate change introduces many new uncertainties that will stretch the limits of knowledge and risk-based design. Public acceptance of risk and quantifying their degree of risk tolerance is an important component of devising new risk-based standards. Risk acceptance and tolerance by the public is a social construct requiring the acquiescence of, and affirmation by the public, via legislation and approval of professional engineering societies (Institute for Water Resources, 2010; Olsen, 2015; WFEO, 2015; Engineers Canada, 2018).

Design standards, codes and derivative regulations that govern infrastructure design are scientifically well-grounded and often finely negotiated in concert with ministries, agencies and professional societies and are legally balanced, making them slower to adapt (Vrouwenwelder, 2008; Ayyub, 2018). Project planning guidelines, such as embodied in the U.S. Water Resources Council's 'Principles and Standards' (US Water Resources Council, 1983), which precede project design, incorporate specific legislated rules and procedures and, in that sense, can be considered as both codes and standards, as they are legally required for federally funded projects in the U.S. (Major & Stakhiv, 2020).

It should be recognized that many water infrastructure design procedures and standards, already encompass and compensate for a considerable portion of climate and weather extremes and hydrologic uncertainties through various design redundancies and 'safety factors' (Matalas & Fiering, 1977; Auld, 2008; Ayyub, 2018). In reality, the combination of standards, codes and built-in engineering safety factors that aim to deal with a wide range of uncertainties can be viewed as a collective foundation of a 'no regrets', precautionary approach to building more resilient infrastructure (OECD, 2018a, 2018b). Therefore, it can reasonably be posited that this historically conservative engineering approach implicitly and explicitly incorporates many, but not all, aspects of 'robust' and

'resilient' design features called for by many advocates of climate vulnerability assessments and 'robust decision making' (Hallegatte *et al*., 2012; Lempert, 2019).

UNIFORMITY OF ENGINEERING STANDARDS AND PROCEDURES

Averting failure is the key underlying theme of engineering practice – and is at the heart of engineering design, which is why engineering design standards are conservative by nature, building in redundancies and safety factors to deal with uncertainties and unknowns. Engineering standards are at the nexus of rapid change and orderly processes for adapting to those changes. As Petroski (2006) states: '[S]uccessful design is not the achievement of perfection but the minimization and accommodation of imperfection' and '[E]ngineering is achieving function while avoiding failure'. Acknowledging and estimating the imperfections of our knowledge (uncertainty) and the risks of failure are at the core of hydrologic and hydraulic engineering. Continuous testing and upgrades are embodied in the most recent ensemble of engineering design standards – all of which are subject to constant improvements and updating of techniques, based mainly on failures due to an unending series of highly publicized catastrophic events.

Planning and designing public works infrastructure within the context of any modern public decision-making setting require a high degree of safety, reliability, procedural uniformity, analytical replicability and legal account-ability to the public, as part of a lengthy series of steps in a typically cumbersome and complicated publicly conducted planning and review process. In any publicly financed planning endeavor, the first level of accountabil-ity rests with meeting publicly stated needs and demands for water-related services, incorporating public inputs into the formulation and selection of options for meeting those demands. Planners must honor those publicly derived choices.

The second level of accountability is following established procedures that are uniformly applied, transparent and analytically replicable. The third level of accountability rests with legally and administratively established rules for the proper operation and maintenance and reliable service delivery and performance of a selected pro-ject. The fourth, and most critical level of accountability to the public, is ensuring the reliability and safety of the project, which requires explicit definition and modeling of potential pathways of failure and public acceptance of 'tolerable' risks, residual risks and consequences of failure.

It is important to note, also, that water resources-based infrastructure systems are not stand-alone systems. They are usually part of a larger network of interdependent systems, and thus considered as 'critical infrastructure' – which if it fails, can result in a domino effect of other dependent infrastructure failures. Modern society is highly dependent on many kinds and levels of networks – many of which interact with one another and are highly inter-dependent. Critical infrastructure systems are the lifelines for our health, safety and prosperity. They are our nerve systems facilitating communications, transportation, trade and financial transactions.

Once any of these critical components fail – say the energy grid, as it did during Hurricane Maria in Puerto Rico on July 20, 2017, there often follows a series of devastating cascading effects on cities and communities. Hos-pitals, water treatment plants, commercial centers, ports, waterways, transportation and industry are all adversely affected. More than three years after the disaster, Puerto Rico had not fully recovered, and its economy and social welfare systems will take years to recover to pre-Maria conditions (GAO, 2021). The potential failure of 'critical infrastructure' has a heightened level of accountability for the engineering profession, which is why engineering codes and standards go through such rigorous peer review and testing before they become embedded as 'best management practices'.

The core advantages of engineering codes and standards are central to 'best management practices' – i.e., uni-formity of approach, replicability of analyses and consistency in outcomes of engineering design and throughout

the globe, wherever hydraulic structures may be constructed. Such codified standards and practices serve as the basis for enhanced transparency and public trust and accountability.

INTERNATIONAL PRINCIPLES AND GUIDELINES FOR RISK-BASED DESIGN STANDARDS

Principles for risk analysis and risk-based structural reliability analysis have evolved for over 100 years, are now encoded in a series of guidelines developed by the International Organization for Standardization (ISO, 2015). Most of the ISO standards are derived from and represent the experience and best management practices of leading public engineering agencies, as they are formulated by select committees of practicing professionals. ISO standards exist for environmental management, health and safety, food safety, energy management, etc. https://www.iso.org/standards.html.

There is a great deal of overlap between the uniformity within ISO standards with the more detailed engineering professional standards and agency design regulations. For example, while new ISO standards are being formulated for flood risk assessment (Yunika *et al.*, 2017), they are based on the experience and existing guidelines of national agencies such as the Dutch Rijkswaterstaat, the Corps of Engineers or Japan's Ministry of Land, Infrastructure and Transportation. A similar situation exists with the European Flood Directive of 2007, which set in motion a cascading suite of new rules, regulations, prescribed analytical procedures and design standards (Tsakiris, 2015; Yannopoulos *et al.*, 2015).

In 2009, IS0 published a standard for risk management (ISO 31000:2009). The criteria for risk assessment proposed in ISO 31000 largely spring from a probabilistic logic, considering many aspects of standard risk analysis techniques (Purdy, 2010; Lalonde & Boiral, 2012). ISO also published a series of guidelines for adaptation to climate change (ISO 14090:2019). This specifies principles, requirements and guidelines for adaptation to climate change, which include the integration of adaptation within and across organizations, understanding impacts and uncertainties and how these can be used to inform decisions.

There are many professional engineering societies in each country, setting specific codes and standards for planning and design, as there are international bodies such as the International Commission on Large Dams (ICOLD, 2020). ICOLD leads the profession in setting standards and guidelines to ensure that dams are built and operated safely, efficiently, economically and are environmentally sustainable and socially equitable. ICOLD sets the standards for dam design construction and safety for most of the world's engineering agencies.

Of equal interest are the engineering profession's approaches to planning and design under climate uncertainty. In particular, the World Federation of Engineering Organizations (WFEO, 2015) issued a set of 'Principles for Engineers in Climate Adaptation'. These principles were further embellished and encoded by 'Engineers Canada' (2018). Engineers Canada is the national organization of the provincial and territorial associations that regulate and license the practice of engineering in Canada. Similar policy statements and standards are being developed in the U.S. by the American Society of Civil Engineers (ASCE). ASCE Policy 360 deals with climate change (https://www.asce.org/advocacy/policy-statements/ps360–climate-change/). ASCE also published a 'Manual of Practice' for 'Climate-Resilient Infrastructure: Adaptive Design and Risk Management' (Ayyub, 2018).

PLANNING VS DESIGN CONSIDERATIONS

Planning water resources projects, by its nature, encompasses a great deal of information and projections about future conditions, including population, economic growth, land use, etc. Each projection carries varying degrees of uncertainty. Uncertainty is an inherent feature of any future-oriented planning effort. Risk and uncertainty analysis are about quantifying, to the extent possible, the major uncertainties that influence key decisions for selection of the project alternative best suited to solve a particular problem; i.e., how large should the project be (reservoir

capacity, levee height, pipeline diameter, channel depth, etc.), and whether it is economically feasible and environmentally acceptable.

Existing engineering standards and criteria, on the other hand, generally represent a combination of, and tradeoff between costs and socially established risk tolerance norms, such as the well-accepted 100-year flood protection standard used for flood insurance purposes and flood protection. There are many other quantified standards to protect against the extremes of natural hazards phenomena, such as earthquakes, floods, hurricanes and droughts, such as the 'probable maximum flood (PMF)', 'probable maximum hurricane', 'design flood' or 'probable maximum precipitation' (Auld, 2008; Ayyub, 2018). More recently, because of climate change uncertainties, risk analysis and management has evolved and broadened to incorporate such broad concepts as 'resilience' and 'robustness' as project planning objectives, in addition to existing and long-held engineering criteria of 'safety' and 'reliability'.

It is no longer acceptable to merely protect against a defined natural hazard event using proven engineering standards. Risk management strategies and solutions should also ensure that communities are able to withstand unforeseen events that are outside the established 'norms' (robust solutions), but also are able to rebound quickly by restoring critical infrastructure services and resuming commercial and economic activities after a devastating event (resilient solutions). In the past, the focus on 'reliability' was a substitute for robustness and resilience in that hydraulic structures not only had to withstand 'loads' that surpassed the historical extremes (robust designs), but also provided a high degree of performance, in terms of delivery of reliable services, whether it be water supply, hydropower, flood control, irrigation or wastewater management under a variety of extreme events.

Risk-based design for planning and designing future water resources projects (hydraulic structures) typically has three important components:

- Probabilistic analysis of future demands on the services of the structure – i.e. services required under a variety of future conditions of growth and development.
- Probabilistic analysis of the reliability of services of the structure provides under various conditions (flood protection, water supply, environmental flows, hydropower, etc.).
- Probabilistic reliability analysis of the structure itself in determining how the structure may withstand different environmental loads.

The first two, future demands and reliability of service delivery, are typically conducted as part of planning processes that are an integral part of project justification. Is the project economically feasible? Does it address ecological and social objectives? Does it meet all the legal and community constraints? Project design methods, on the other hand, have been developed to achieve a reasonable balance between functionality, performance, safety and economic feasibility of such structures. The reliability-based design aims to achieve a consistent and acceptable probability of structural failure across a range of conditions. The risk-based design considers the expected consequences of failure as a principal basis for decision-making and design (Retief et al., 2013; Diamantidis et al., 2016; Sykora et al., 2017).

There is a conceptual divergence, however, between the risk-based analytical approaches used as part of the project planning, with optimization of associated economic justification processes, and that of subsequent engineering design of the selected 'optimized' option. Because of the differences in the many institutional and legislated requirements underlying water resources management, for the same problem set, different planning processes of various agency or ministry project selection frameworks would not necessarily lead to the same outcomes in terms of project capacity, performance, costs or basic design. However, because of the greater uniformity in engineer design procedures, the actual design of any selected project would likely be more consistent in many different settings because of greater uniformity within engineering design practices.

At the core of the differences in analytical procedures and decision rules between project feasibility planning and engineering design is the importance of societal or community 'safety'.

Project feasibility planning centers on economic justification analyses and decision rules, e.g., maximize net economic benefits, while project design focuses on minimizing failure risk and loss of life (Yoe, 2017). An example of this duality is to be found in the most recent Corps of Engineers planning and design guidelines.

The Corps' most recent engineering and design guidance (U.S. Army Corps of Engineers, 2019a) lays out the following principles.

A risk-informed approach will be used for all dam and levee designs for new projects, modifications, improvements, rehabilitation or repairs. Risk assessments are the cornerstone for the application of a risk-informed decision-making approach. The following are the overarching principles to follow:

(a) *Hold life safety paramount*. While seeking to manage risk to people, property and the environment, USACE will consider risk to life safety as priority. Tolerable risk guidelines will be used as the risk-informed decision goal for life safety.
(b) *Risk-informed decision-making*. Decisions for risk management actions will be commensurate with the level of risk that exists when a dam or levee is present to ensure wise federal investments.
(c) *Ensure open and transparent engagement*. USACE will engage project sponsors in all design activities related to their dams and/or levees.
(d) *Learn and adapt*. Risk assessments will be used to evaluate if designs must be up-scaled (i.e., use more stringent design criteria) or downscaled (i.e., use less stringent design criteria) using a risk-informed approach as compared to solely considering traditional standards.
(e) *Do no harm*. Risk-informed designs should not increase the risk to the population and property above the risk the population currently experiences.

Indeed, the (Corps' 2019a) most recent guidance on risk analysis and risk tolerance ('Interim Approach for Risk-Informed Designs for Dam and Levee Projects'), while advocating risk-informed decision-making that balances multiple factors, still prioritizes life safety as paramount. This contrasts with the associated planning guidance that was published by the Corps of Engineers (U.S. Army Corps of Engineers, 2019b) for how to conduct risk assessments for flood risk management (FRM) studies. That planning guidance (ER 1105-2-101) emphasizes selecting a project scale that maximizes net economic benefits, subject to environmental constraints.

The two complementary guidance documents essentially disaggregate the notion of 'risk and tolerable risk' into two distinct components: the design phase which emphasizes safety of lives associated with failure of the designed structures and the planning phase which emphasizes project feasibility based on economic damages associated with the causative flood event. The engineering design guidance is much more risk-averse by highlighting risk analytic procedures that address the reliability of the structure to ensure that it does not fail under a wide range of extreme hydrologic loading conditions.

Under economic optimization procedures, adding resilience and robustness elements to a project or a system that would encompass a broader range of future climate uncertainties, as a way of preventing damages from more frequent and/or more damaging events/hazards would typically add additional project costs (Liu & Son, 2020). For such design entails either expanding the size/capacity of a project and/or additional engineering safety factors to account for extreme future climate uncertainties, which inevitably increase project costs – often beyond the level of initially optimized financial or economic feasibility.

Other important differences between planning and design lie in the numerous economic evaluation and decision criteria. In project planning and justification, the use of expected annual damages (EADs) in a traditional benefit–cost procedure essentially has a two-fold effect in minimizing large or extreme events. The EADs

approach required by U.S. law, and commonly used by agencies such as the Corps of Engineers, minimizes or suppresses the costs of and avoidance benefits of large events, whereas the use of a high discount rate deflates the impact of future large events, beyond a 15–25-yr planning horizon (Stakhiv, 2011).

Thus, there is always a tradeoff between risk reduction and cost increases, while minimizing residual risks. One of the underlying goals of project planning, then, becomes the identification and reduction of 'residual risks' of both service failure and/or hydraulic failure through a variety of mitigative actions, which also impose added risks, uncertainties and costs. Also, from an equity standpoint, one must identify the sectors of the population that will bear those residual risks, and what array of mitigation and/or compensation measures are provided as part of the plan.

The U.S. Army Corps of Engineers (USACE) and Bureau of Reclamation (BoR), two of the foremost U.S. federal agencies that develop standards for water-related infrastructure, have accelerated their revisions of many planning and design standards, to rely more on risk-based analysis to accommodate climate uncertainties and design more robust and resilient projects (BoR, 2019). The U.S. General Accountability Office (GAO, 2013), the performance monitoring arm of the federal government, evaluated the USACE and BoR climate change adaptation programs and found that both agencies 'have assessed water resource and infrastructure vulnerabilities and taken steps to develop guidance and strategies to adapt to the effects of climate change'.

The U.S. Department of Transportation is another very important standard-setting agency. They have also tackled the issue of climate uncertainties in revising their numerous standards for roads, bridges and culvert designs. The Transportation Research Board (TRB) of the National Research Council prepared a 'Guide for Design Practices' (TRB, 2019) for hydrologic and coastal infrastructure to deal with climate uncertainties.

ENGINEERING DESIGN AND HYDROLOGIC NON-STATIONARITY

A changing climate is likely to lead to a suite of non-stationary and historically unforeseen conditions that serve as the basis for altering not only project planning procedures, but also engineering design criteria and standards (Milly *et al.*, 2008; IPCC, 2021). According to the most recent IPCC assessment (2021), the frequency, intensity and duration of extreme events (rainfall, runoff, temperature, snow, ice, etc.) are likely to change over time, though it is highly uncertain as to which direction these changes may occur, and at what locations or what magnitudes. Numerous studies have diverged on the frequency, duration and extremity of floods and drought – both regionally and globally depending on which the general circulation model was used, which development scenario was selected and in which continent or region the changes occurred (Pechlivanidis *et al.*, 2017; Kettner *et al.*, 2018).

Projecting climate impacts on hydrological processes is unavoidably prone to a concatenation of uncertainties stemming from selection greenhouse gas emission scenarios, climate models and their parameterization, downscaling techniques, bias correction methods, hydrological model structure and parameters. The uncertainties propagate in very complex and sometimes unknown ways, effectively rendering the outcomes useless for longterm water project design decisions (Wilby & Dessai, 2010; Pielke & Wilby, 2012; Pechlivanidis *et al.*, 2017).

The suite of periodic IPCC reports, beginning in 1990 through 2021 created a climate model, scenario-driven 'top-down' analytical paradigm. This was deemed by many engineering practitioners as unsuitable for most water resources management problems – particularly those related to site-specific infrastructure design (Kundzewicz & Stakhiv, 2010; Stakhiv, 2011; Retief *et al.*, 2013; Sykora *et al.*, 2017; Sykora *et al.*, 2018; Underwood *et al.*, 2020).

Hence, several significant adjustments are required in both the planning and design paradigms currently in use by engineering institutions, to deal with site-specific project analysis under non-stationary climate conditions. These include:

- Top-down vs bottom-up climate downscaling/decision-scaling: bridging the gap between climate-driven scenario analysis and hydrologic non-stationarity at the project level.
- Designing 'robust' structures and resilient systems under existing economic optimization and benefit–cost procedures.
- Factoring in non-stationary hydrology – non-stationary extremes for the design, non-stationary mean and variance for planning.
- Bridging gap between the decision criteria associated with the planning paradigm and design paradigm: minimizing risk-cost vs minimizing hydraulic failure and maximizing safety.

Recent methods that aid planning of water infrastructure to bridge some of these gaps, and to enhance project robustness, resilience and reliability have been developed by such leading institutions as the World Bank, Asia Development Bank, Corps of Engineers and UNESCO (Ray & Brown, 2015; Mendoza *et al*., 2018; Watkiss *et al*. 2020). These methods are extensions of existing institutionally accepted planning protocols, that focus on the added uncertainties of climate change and non-stationarity, under the rubric of 'climate risk-informed decision-making'. The basic purpose is to decide ('decision-scaling') under what circumstances progressively more detailed levels of climate analysis should be used, or whether existing analytical methods, planning protocols and design standards are sufficient for the problem at hand.

The key for planning and engineering design is the abstraction of an empirical hydrologic data set that is the basis for site-specific project-level analysis and converting it to a functional distributional form or type of empirical non-parametric distribution (Beven, 2016). The next step is to transform that selected probability distribution, reflecting stationary climate conditions, into a non-stationary distribution of extremes, used for design (Salas *et al*., 2018; Serago & Vogel, 2018). Unfortunately, there are still many epistemic (lack of knowledge) and scientific uncertainties in each step of the process, that need to be resolved. Engineers have found practical ways of circumventing these uncertainties, even as they undertake various permutations of accepted statistical analyses to better inform their decisions.

It becomes a matter of choice and judgment as to how to treat those uncertainties, including the selection of formal probabilistic and statistical frameworks to deal with climate non-stationarity (Beven, 2016). As Mondal & Mujumdar (2017) and Salas *et al*. (2018) have shown, there are many choices available to the practicing engineer, but agency procedures require a uniform, standardized approach to these issues, which have not yet been formalized to any significant degree.

As a partial practical substitute, however, there is some comfort in recognizing that current design standards are based on the analysis of continually updated historical records under the hypothesis of stationarity (Kunkel *et al*., 2013; Olsen, 2015; Ayyub, 2018; USACE, 2021). This has been a practical and effective approach to deal with repeatedly large but unpredictable events, because simultaneously, many federal and state design manuals, as well as the underlying precipitation and runoff data sets are periodically upgraded. The practical implications of these progressive upgrades are that the risk level of infrastructure that is being designed with today's upgraded standards and data may not necessarily change much in the future (Serinaldi & Kilsby, 2015).

Additionally, Serinaldi & Kilsby (2015) dispute the notion that it is important for engineering design to explicitly incorporate climate non-stationarity into contemporary design. They argue that non-stationary models introduce additional sources of uncertainty; that misspecification of non-stationary models can lead to physically inconsistent results and non-stationary models can provide no practical enhancement of the credibility of results. They advocate an approach that emphasizes the 'risk of failure' during the design life of a project as a more realistic measure of the risk for design purposes, and a more understandable one for decision-making purposes. Read & Vogel (2015, 2016) essentially arrive at the same conclusion.

The key substantive and operational distinction, however, is that hydrologic and hydraulic engineers continuously make important design decisions that affect the populace of future generations. Critical decisions cannot wait for better data about future climate conditions from improved computational technologies. Hence, their decisions are based on a body of time-tested 'best management practices' that have undergone not only periodic and intensive practical peer review by their respective professional societies, along with progressive updating of design criteria and standards, but also the most important consequential and pragmatic reviews of all – the failure or non-failure of their designs and creations.

As an example, the reconstruction of infrastructure that occurred after such catastrophic events as Hurricane Katrina in New Orleans, 2005, or Hurricane Maria in Puerto Rico, 2017, could not wait for a better explication of climate uncertainties. Design decisions were made according to prevailing standards, new data and better models, based on best engineering judgment, given the new set of physical circumstances and societal risk tolerance criteria. The new criteria were determined in cooperation between the U.S. Congress, the engineering profession via the Hurricane Katrina Interagency Performance Evaluation Task Force (Link & Harris, 2007) and academic inputs, such as the recommendations of National Academy of Sciences (National Research Council, 2009). Collectively, those standards and analytical methods represented a major advancement of the state-of-art in engineering design for climate adaptation.

RISK ANALYSIS, RESIDUAL RISK AND TOLERABLE RISK

Engineering standards, criteria and regulations reflect each society's accepted levels of 'risk tolerance'. 'Tolerable level of risk' is a phrase describing a level of risk that has been associated with a national, corporate, regulatory or otherwise socially determined level of acceptable risk. A 'tolerable risk' is a previously unacceptable risk whose severity has been reduced to a point where it is tolerated by way of a social consensus. In effect, it is a 'residual risk' after all acceptable and cost-effective risk management measures have been implemented for a particular situation (Institute for Water Resources, 2010, 2017).

For example, the U.S. Congress could, hypothetically, establish the 0.2% annual exceedance frequency as the tolerable level of risk for FRM in vulnerable urban areas. After all, the 1.0% annual exceedance frequency (100-year flood) is the legal standard for flood insurance purposes and floodplain management in the U.S. Then all urban FRM projects must protect against floods with a recurrence interval of 500 years, or less, as a matter of national policy (Institute for Water Resources, 2017). The problem remains of how to quantify a '500-year flood' under non-stationary climate conditions – i.e., what will be the actual flood volume or discharge 50 years hence? Generally speaking, studies have shown that stationary models tend to underestimate extreme floods relative to non-stationary models (Šraj et al., 2016; Mondal & Mujumdar, 2017; Salas et al. 2018).

Different nations, like Netherlands or Japan, set their societal risk tolerance levels using different premises and methods to justify their standards for flood control or earthquake management. Both nations are very risk-averse due to their physiographic circumstances which subject the populace to a wide range of natural hazards and other vulnerabilities. A good part of the Netherlands is below sea level. Hence, their risk tolerance level is very low, manifesting itself as very stringent engineering design standards for sea walls, levees and other flood control infrastructure (François et al., 2019). In the Netherlands, standards for levee and dike design, range anywhere from the 300- to 10,000-year flood depending on location. Japan is a flood-prone mountainous nation that is also subjected to typhoons, tsunamis and earthquakes, so their design standards must offer a higher degree of safety and structural reliability to protect against infrastructure failure.

Most of the 'residual risk', i.e., that risk which cannot be ameliorated through structures, zoning policies or insurance, is largely borne by individuals, homeowners and small businesses. Yet the degree of 'residual risk' is rarely quantified or explained to the public in terms they could understand. Residual risk is almost always

underestimated because it is difficult to quantify a cascading series of highly interdependent measures, each of which has its own reliability characteristics and risk of failure, including human error (Perrow, 1984). For example, a local flood protection system is a collection of fragmented measures, including disparate building codes, zoning ordinances and structural measures that are implemented over a long period of time and loosely coordinated by multiple authorities. That combination of measures comprises the definition of a 'brittle system' (Fiering, 1982), whose risks of failure are hard to quantify (Haimes *et al.*, 1995).

ADAPTING CONTEMPORARY ENGINEERING RISK MANAGEMENT PRACTICES TO CLIMATE UNCERTAINTIES

It is understandable that forecasting climate change is a highly uncertain technical endeavor. Yet, these uncertainties need to be managed in some uniform and replicable manner, to ensure planning and design transparency for the public, despite difficulties in identifying and quantifying many of these uncertainties. It is even more difficult to convey this uncertain information to the public and decision-makers. Recognizing that there is a great deal of conjecture about uncertainty estimation in the hydrologic sciences, the engineering profession has devised different ways of dealing with such analytically thorny and largely intractable theoretical issues through a series of risk management practices. These practices have evolved to provide more practical and indirect means for resolving and addressing the accumulation of uncertainties through a variety of best management practices and risk management measures.

There are several parallel paths that are currently being undertaken by the water resources engineering profession as part of climate-related risk management practices (Auld, 2008):

1. Update and revise engineering codes and standards that are directly affected by climate-induced changes in hydro-climatological design criteria (e.g., 1% chance flood; 'design flood'; PMF; 'probable maximum hurricane', etc.).
2. Increase safety factors commonly used in design to account for known climate uncertainties.
3. Periodically revise planning and engineering guidance and regulations to account for new information, analytical techniques, design methods and technologies.
4. Develop new analytical techniques that can effectively deal with climate non-stationarity.

All of these upgrades of standards and other pathways are being vigorously pursued by many federal agencies in both Europe and the U.S. Safety factors and design redundancies are another direct way that engineers have always used to deal with uncertainties of natural hazards, modeling and data collection. Since uncertainty analysis is a well-accepted part of engineering practice that encompasses codes, standards and associated regulatory processes, it should be possible to deal with the growing uncertainty of future climate-related design values by identifying and increasing safety factors when evidence points towards the likelihood of increased climate risks over the lifespan of a given structure (Yen & Tung, 1993; Tung, Yen & Melching, 2006; Sykora *et al.*, 2017; Sykora *et al.*, 2018). These safety factors inherently account for increased project and system robustness, used to minimize the risk of a major catastrophe from occurring.

A primary example of current risk-based analytical methods that can be adapted readily to analyze climate non-stationarity are the Corps of Engineers procedures for flood damage analysis, based on a Monte-Carlo simulation of multiple combinations of flood discharges and stages (Kalyanapu *et al.*, 2011). The Flood Damage Reduction Analysis (HEC-FDA) software developed by the Corps' Hydrologic Engineering Center provides the capability to perform an integrated hydrologic engineering and economic analysis during the formulation and evaluation of FRM plans (U.S. Army Corps of Engineers, 2021). The software computes EAD and equivalent annual damages, and computes the annual exceedance probability (AEP) and conditional non-exceedance probability as required for levee certification, and implements the risk analysis procedures described in EM 1110-2-1619 (https://www.hec.usace.army.mil/software/hec-fda/).

In the Corps' HEC-FDA procedures, risk analysis is applied to both economic performance measures (project net benefits and benefit–cost ratio) and to engineering performance measures (probability of flooding). Figure 1 provides a graphical view of the Monte-Carlo sampling procedure that provides a distribution of damages accounting for multiple sources of uncertainty. The U.S. National Research Council (NRC, 2000), in a review of Corps' risk analysis procedures, found that '*while the measures of economic performance in the method are generally practical and informative, there are too many types of engineering performance measures to be clearly understood by most citizens. Standardization to one or two key measures of engineering performance measures would represent an improvement*'.

The NRC committee also recommended that the Corps use AEP as the performance measure of engineering risk. This is a measure of the likelihood that people will be flooded (including the probability of failure of flood damage reduction structures, such as levees) in any given year, considering the full range of floods that can occur and all sources of uncertainty. In effect, Read & Vogel (2015) recommended a similar approach noting that even for stationary processes, the common application of an average return period is problematic because it does not account for a planning horizon and is an average value that may not be representative of the time to the next flood. Read and Vogel introduce 'reliability' as a substitute for 'return period', as a more useful term to explain the risk of failure during the life of a project. Reliability is defined as the probability that a system will remain in a satisfactory state during its lifetime, i.e., that an exceedance event will not occur within a project life of n years.

Design standards and computational methods based on extremes represent a progressively incremental 'autonomous adaptation' to climate change and associated uncertainties. A segment of the engineering profession suggests that traditional risk-based design methods may currently be more useful than non-stationary approaches because it is much too difficult to realistically accommodate all the uncertainties associated with climate change. In fact, many authors argue that factoring in these uncertainties, many of them 'unknown unknowns', simply makes the analyses more complex and bewildering for the public and political decision-makers (Serinaldi & Kilsby, 2015; Underwood *et al*., 2020).

For instance, 'freeboard' is included in the hydrologic design as a typical safety factor to improve the reliability of levees and embankments, which might fail to deliver the intended level of safety in a changing climate. 'Freeboard' is defined by the Federal Emergency Management Agency (FEMA, 2020) as a factor of safety usually
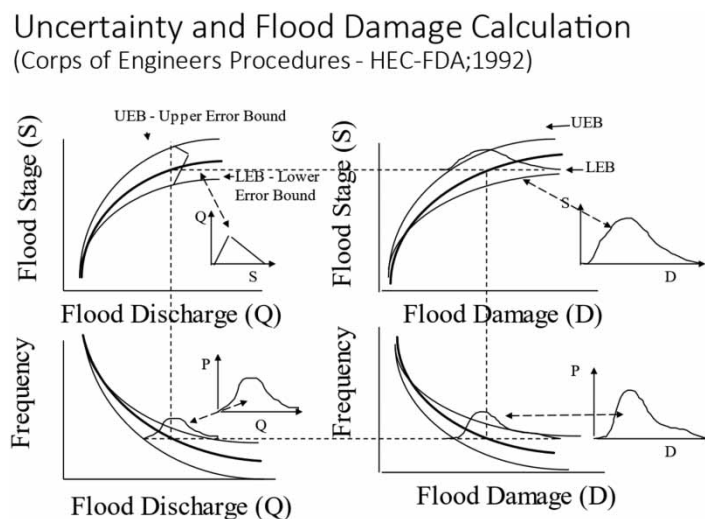
Fig. 1 | HEC-FDA uncertainty and flood damage calculation procedure.

expressed in feet above a flood level for purposes of floodplain management. 'Freeboard' tends to compensate for the many unknown factors which could contribute to flood heights greater than the height calculated for a selected design flood and floodway conditions, such as wave action, bridge and channel constrictions, or the evolving hydrological effects of urbanization of a watershed.

Figure 2 shows how freeboard (typically 3 feet) compensates for the uncertainties and unknowns of engineering analysis – both the hydrologic and hydraulic computations. Freeboard assures that the 100-year design flood can be contained within the 95% confidence bounds. It also can be viewed as potentially protecting against a flood of up to a 500-year return period, under stationary climate assumptions.

Another way of adding a 'safety factor' within the current stationary climate 'design flood' paradigm, is by selecting a 'suitable' flood frequency distribution for analyzing a potential project. The choice of an appropriate probability distribution and parameter estimation method plays a vital role in at-site frequency analysis. U.S. federal agencies are required by law to use the Log-Pearson type 3 (LP3) distribution (England et al., 2018), while the U.K. and Japan recommend the generalized extreme value (GEV) distribution (Kazama et al., 2010). Castellarin et al. (2012) reviewed applied statistical methods for flood frequency analysis in Europe. According to their review, the GEV was among the recommended distributions used by Austria, Italy, Germany and Spain.

The selection of an appropriate probability distribution is essential for accurately delineating floodplains and capitalizing national flood insurance funds, as well as selecting the appropriate scale of flood protection infrastructure. Correctly characterizing the flood frequency distribution has the greatest direct influence on the choice of a particular flood management strategy – i.e., deciding whether structural or non-structural flood protection is appropriate for a particular location.

Stakhiv (2011) shows how, for a given set of annual flood peak data in a particular watershed, the selection of a probability distribution can dramatically alter the underlying risk analysis and risk tolerance assumptions for any particular location or choice of an alternative project design. Figure 3 shows a hypothetical comparison between the GEV and LP3 probabilities for flood frequency analysis for the same set of real data of a watershed. It shows that for a given discharge of 25,000 cubic feet per second, that the LP3 shows a recurrence interval of 100 years,
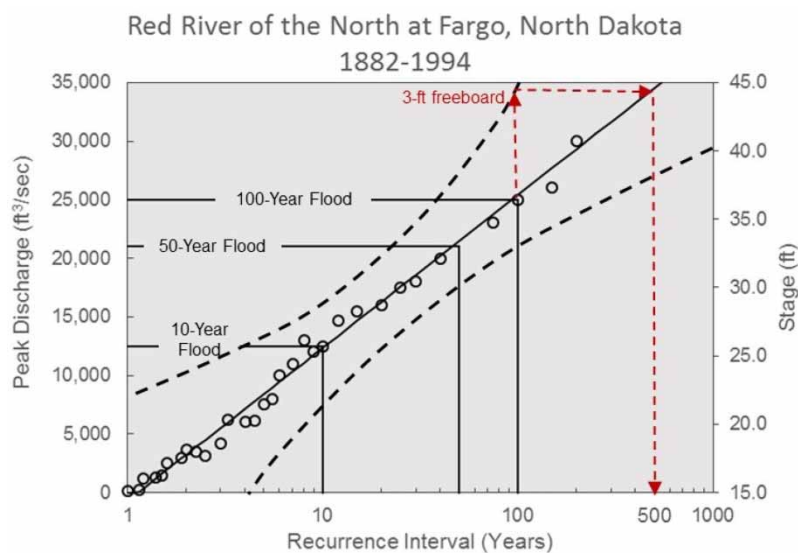

**Fig. 2** | The role of 'freeboard' as a safety factor in design of flood protection.

whereas for the same discharge, the GEV shows approximately a 47-year recurrence interval. Conversely, a 100-year discharge computed by GEV equates to a 225-year discharge with LP3.

In this instance, selecting the GEV distribution for levee design or flood plain delineation would partly address concerns about non-stationarity in the future by halving the frequency of a 100-year event computed by the LP3 method. This outcome is consistent with the expectation of increased flood frequencies under many climate scenarios generated by the IPCC (2021). When freeboard is added to the design as an additional safety factor, this would be the equivalent of indirectly adding robustness and reliability to a selected flood control option, solely based on upgrading current codes and standards, without having to resort to inherently difficult and somewhat technically dubious climate scenario analyses (Anagnostopoulos *et al.*, 2010; Kundzewicz & Stakhiv, 2010).

Another way of partially addressing the uncertainties of climate non-stationarity, via engineering codes and standards, equivalent to adding 'freeboard', is the concept of 'flood allowances' employed by many European nations. A 'flood allowance' is defined as 'the maximum change in peak flows to allow for future impacts of climate change' (COST, 2013). Table 1 shows how various European nations use flood allowances to adjust for climate non-stationarity. Several procedures exist to adjust design flow estimates for the combined influence of climate change and land use. Considering the effect of climate change on design flood estimates, a safety margin of 20% is applied in the U.K., as recommended by DEFRA (2009), to compensate for climate change with a time horizon until 2085.

Vogel *et al.* (2011) computed the equivalent of flood allowance factors, in the form of flood magnification and recurrence reduction factors for the U.S. They developed a simple statistical model that could both mimic observed flood trends and the frequency of floods in a non-stationary world. Using historical flood data across the U.S., they calculated flood magnification factors in excess of 2–5 for many regions of the U.S., particularly urban areas with higher population densities. Similarly, they computed recurrence reduction factors which showed that what was once considered the 100-year flood may become much more common in many watersheds.

However, trends in flood peaks do not necessarily imply climate change, as they can arise from many other anthropogenic factors such as land use alterations, urbanization or riverine structures (bridges, constrictions and channel alterations). Vogel *et al.* (2011) found that large increases were generally observed in regions with higher population densities subject to land use changes both in urban areas and upstream watersheds. In particular, they found that '[N]onstationarity in floods can result from a variety of anthropogenic processes including changes in land use, climate, and water use, with likely interactions among those processes making it very difficult to attribute trends to a particular cause'.
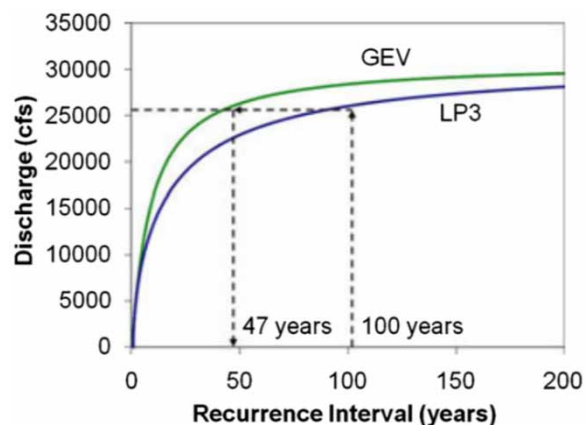
Fig. 3 | Comparison of GEV and LP3 distributions on flood return periods (Stakhiv, 2011).

Table 1 | Summary of existing European guidelines on climate change adjustment factors on design floods and design rainfall (COST, 2013).

Country	Region	Variable	Guideline	Reference
Belgium	Flanders	Design floods	30% increase	Boukhris & Willems (2008)
Belgium	National	Design rainfall	30% increase	Willems (2011)
Denmark	National	Design rainfall	20, 30 and 40% increase for return periods 2, 10 and 100 years	Arnbjerg-Nielsen (2008)
Germany	Bavaria	Design flood with 100-year return period	15% increase	Hennegriff *et al.* (2006)
Germany	Baden-Württemberg	Design floods	Increase between 0 and 75% depending on location and return period	Hennegriff *et al.* (2006)
Norway	National	Design floods	0, 20 and 40% increase based on region, prevailing flood season and catchment size	Lawrence & Hisdal (2011)
Sweden	National	Design rainfall	Increase between 5 and 30% depending on location	SWWA (2011)
United Kingdom	National	Design floods	20% increase for 2085	DEFRA (2006)
United Kingdom	National	Design rainfall	10, 20 and 30% increase for 2055, 2085 and 2115	DEFRA (2006)

As another example of codes and standards, that are periodically adjusted, is the critically important concept of 'probable maximum precipitation' (PMP). The PMP is theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location. It is used to develop inflow flood hydrographs, known as PMF, as the design standard for high-risk flood-hazard structures, such as dams and nuclear power plants (England *et al.*, 2014; Wright *et al.*, 2019). The procedures to estimate PMP were standardized by the World Meteorological Organization (WMO) in 1973 and revised in 1986 and 2009 (WMO, 2009). In the U.S., PMP estimates are published in a series of Hydrometeorological Reports (e.g., HMR55A, HMR57 and HMR58/59) by the National Weather Service since the 1950s (Kunkel *et al.*, 2013).

The examples above show that design-related codes and standards that assume a stationary climate are periodically adjusted and upgraded as information becomes available reflecting, to a certain extent, existing climate trends and non-stationary processes. A reasonable case can be made that since the information is inherently focused on climate extremes that are experienced regularly, this updating factor alone could reasonably be considered to account for a significant portion of future uncertainties arising from climate non-stationarity. When additional precautionary measures such as flood allowances, freeboard and other safety factors are used in design to account for other uncertainties linked to hydrologic and hydraulic models and urbanization, it is also reasonable to assume that most of the significant climate uncertainties associated with hydrologic non-stationarity could be accommodated in project design through periodic adjustment of existing design codes and standards.

Further following Auld's (2008) paths to updating engineering risk management strategies, there is yet another, even more fundamental approach that implicitly deals with future uncertainties. Water management functions can be partitioned into five basic categories, each addressing a different set of uncertainties and each offering different ways of dealing with climate variability and uncertainties within their respective evaluation and decision-making processes and engineering standards. Each has corresponding well-documented standardized

decision frameworks and associated analytical procedures in the form of engineering regulations, manuals and other guidance. Different water management strategies employ various combinations of the categories listed below (Rogers, 1997; Stakhiv, 2011):

- *Planning new investments* for capacity expansion (reservoirs, irrigation systems, levees, water supply, waste-water treatment and interconnecting systems).
- *Operation and adaptation* of existing systems to accommodate new uses increased demands (e.g., reservoir reregulation and water allocation for ecology, population).
- *Maintenance and major rehabilitation* of existing systems (e.g., dams, barrages, irrigation systems, canals, pumps, etc.).
- *Modifications in processes and demands* (water conservation, pricing, regulation, policies and legislation) for existing systems and water users.
- *Introducing new efficient technologies* (desalting, biotechnology, drip irrigation, wastewater reuse, recycling, solar energy, materials and pumps).
- *Monitoring and regulation of existing systems* to improve performance, increase efficiencies and monitor critical thresholds.

Project maintenance and major repair and rehabilitation offer a good example of a practical engineering approach that obviates the need for a 'top-down' climate scenario approach, taking advantage of the life-cycle properties of infrastructure, and the recognition that water management functions are not static (Rogers, 1997). Rogers demonstrates that, because major rehabilitation of long-lived infrastructure projects normally occurs every 20–30 years, these are the opportunities to integrate new data, technologies, different designs, upgrade materials and analytical techniques as well as adjusting operating rules that can adjust to emerging demands and updated hydrologic data.

More importantly, Rogers (1997) noted that climate uncertainty was not the significant factor in projects whose capacity could be incrementally expanded (e.g., water and wastewater treatment plants, irrigation systems, pumping stations and water conveyance pipelines), finding that the economic discount rate was the more decisive factor in such analyses. Hence, projects that require major rehabilitation (dam spillways, levees and aqueducts) and those that may require incremental capacity expansion because of increased demands can essentially employ conventional analytical procedures that are periodically updated, incorporating the latest data, science and technological upgrades and design standards (Ehsani *et al.*, 2017).

Roger's findings also buttress the conceptual basis of an 'adaptation pathways' approach, which is based on incremental adjustments to infrastructure expansion, built on a form of 'threshold analysis' (Haasnoot *et al.*, 2013; Walker *et al.*, 2013; Mendoza *et al.*, 2018). Performance threshold-based design is essentially standard engineering practice – a 'bottom-up' process where the known or reasonably suspected performance vulnerabilities of existing or proposed infrastructure are identified so that potential conditions that expose those vulnerabilities can be quantified and addressed.

Similarly, Stakhiv (2011) demonstrated that many adaptive management adjustments can be made to existing infrastructure, in terms of monitoring, regulating and operating water-based delivery systems. For example, there are many opportunities for updating drought and flood contingency plans based on new information that could improve the overall resiliency, robustness and reliability of existing water management systems.

As an example, Figure 4 shows the Corps of Engineers' various operating procedures and manuals that govern reservoir management, that are part of a reservoir 'Master Manual' (U.S. Army Corps of Engineers, 2017). A water control manual is the guiding document that specifies how the Corps of Engineers operates their reservoirs. Each reservoir operates following congressionally mandated purposes, and the manuals specify how those multiple water management objectives are balanced. They also provide details on the reservoir's watershed characteristics, data collection networks, forecasting methods and stakeholder coordination.

It should be noted that the popularly advocated 'no regrets' climate adaptation practices inherently encompass current engineering 'best management practices', including contemporary risk-based design, safety factors and freeboard considerations that are routinely incorporated into the design of dams and flood works (Bhave et al., 2016). Especially when the impacts of future changes remain highly uncertain, bottom-up 'no regrets' actions may offer the most realistic adaptation option. In this sense, undertaking infrastructure planning and design under upgraded risk-based methods within a traditional stationarity-based framework may be the most sensible approach to 'no regrets' climate adaptation.

CONCLUSIONS

Adaptation to climate change is currently the most practical and rational approach to dealing with the uncertainties of future climate, since international mitigation policies cannot effectively change the trajectory of global warming over the next few decades (Pielke et al., 2007).

Current practices of risk-based planning and design standards have evolved incrementally, responding to each catastrophic natural disaster, some of which may be the precursors of a changing climate regime. Design standards and building codes encompass an accumulation of changes that reflect changing climate conditions over the past five decades, most notably because they are largely based on addressing climate extremes. These extremes may encompass the anticipated core of changes of a non-stationary climate regime, thereby indirectly addressing a large part of future unknown climate uncertainties. Risk analysis methods that form the basis of evolving design standards, progress in step with perceived climate changes, highlighting extreme events.

The combination of standards, codes and built-in engineering safety factors that aim to deal with a wide range of uncertainties, can be viewed as a collective foundation of a 'no regrets', precautionary approach to building more resilient infrastructure (OECD, 2018a, 2018b).

Planning and design are essentially separate functions with different objectives and decision criteria. The 'planning' function is centered on an evaluation framework that optimizes economic performance metrics for providing reliable water-based services, whether they be flood damage reduction, municipal water supply or hydropower. Once a suitable project is selected, project 'design' criteria focus on avoiding project and system failure and incorporate design safety factors and redundancies to account for a wide range of uncertainties.

A practical approach to climate adaptation and associated climate uncertainties would be to apply existing best management practices. These include adapting contemporary design procedures; risk management approaches with provisions for robustness, resiliency and adaptive management – i.e., nominal, 'no regrets' adjustments to changes in desired performance and service levels and technological adaptations with updates based on new
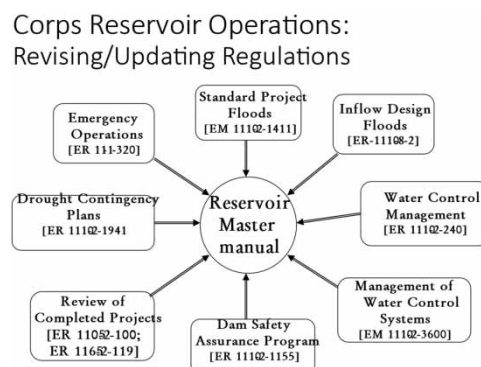
Fig. 4 | Updating reservoir master manuals (Stakhiv, 2011).

data and monitoring. Part of the ensemble of 'best management practices' includes climate adjustment factors, such as 'flood allowances', and upgrading design safety factors for critical components of infrastructure.

In particular, U.S. federal agencies have taken this route, and agencies such as the U.S. Army Corps of Engineers, the Bureau of Reclamation and the Federal Highway Administration have all updated both their planning and design procedures, employing a broader array of risk analytic tools and procedures that explicitly account for climate-related uncertainties. In addition, they have worked on better coordinating the risk-analytic methods used to assess and quantify uncertainties associated with climate change.

The core advantages of engineering codes and standards are central to 'best management practices' – i.e., uniformity of approach, replicability of analyses and consistency in outcomes of engineering design and throughout the globe, wherever hydraulic structures may be constructed. Such codified standards and practices serve as the basis for enhanced transparency and public trust and accountability.

Many other nations and international lending institutions, such as the World Bank and Asian Development Bank have upgraded their climate analysis procedures, have international engineering organizations in the form of new guidance for risk analysis and infrastructure planning, as well as developing new codes and standards for structural design.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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