Official Journal of the World Water Council
Water Policy



Water Policy Vol 23 No S1, 144 doi: 10.2166/wp.2021.266

# Screening for nonstationary analysis

Paul H. Kirshen
School for the Environment, University of Massachusetts Boston, 100 Morrissey Blvd, Boston, MA 02125, USA
E-mail: paul.kirshen@umb.edu

## ABSTRACT

Adjustments in the designs of water resources systems due to climate change and other nonstationarities are warranted because the benefits of effective adaptation are well recognized. Therefore, the time and resources invested in these analyses are well worth the effort. Before a major investment in an effort is made, however, it is reasonable to determine if the problem is of sufficient complexity or the value of additional information is high enough to warrant the inclusion of complex, sophisticated methods that explicitly include nonstationarity and associated decision-making under deep uncertainty. There exist several planning level conditions such as the lifetime of the project, its criticality, and its reversibility that may indicate detailed analysis is not needed. There are also sequential analysis and screening steps that can be applied to determine the complexity of the methodology needed. Finally, the use of decision analysis can also help determine if additional, detailed analysis, or data collection are necessary. The use of one or several of these methods should be considered as initial steps before undertaking a vulnerability assessment and developing an adaptation strategy for a water resources system.

**Key words:** Climate change, Decision-making, Nonstationarity, Preliminary analysis, Screening analysis, Water resources planning

## HIGHLIGHTS

- Including nonstationarity in the design of water resources systems may require considerable resources and finances to apply but given the high cost of failures of most water-based systems and the generally high benefit–cost ratios of adaptation, the expense and effort of appropriate planning are certainly justified. There are circumstances, however, when even though nonstationarity is acknowledged, a full detailed assessment of it is not necessary.
- The decision on the complexity of the analysis can be based upon a project's lifetime, criticality, reversibility, flexibility/adaptability, robustness, and the use of forward design standards.
- Top-Down and Bottom-Up screening methodologies also exist to assist in the analysis decision. Some rely upon determining if a system is operating below capacity and/or its historical performance, assessing the climate sensitivity of the needs of stakeholders, and changes in the design conditions.
- Several recent methods such as the World Bank Decision Tree Process and Climate Risk Informed Decision Analysis (CRIDA) include screening as part of their complex processes.
- The use of decision analysis can help determine if additional, detailed analysis, or data collection are necessary.

## INTRODUCTION

It is widely recognized that all human and natural systems are sensitive to climate; thus as the climate changes, the services provided by these systems also change. The adjustment to the impacts of these services changes is known as adaptation. Water resources and coastal systems are some of the most sensitive systems to climate change because of their strong linkages to climatic driving forces and because of the many important services and also threats they provide to human and natural systems. Here, we focus upon the analysis of their services to human systems, but similar analysis can be applied to natural systems. Similar analysis can also be applied to respond to other nonstationary drivers such as demographic and land use changes; again not discussed here.

The impacts of climate change upon the services of water resources and coastal systems and their adaptation to the impacts have been the subject of intense research and analysis at least since the late 1980s and are now considered for most new projects and existing projects. Both top-down (e.g., scenario analysis) and bottom-up (e.g., context first) approaches can be applied. In all cases, however, the major challenge is incorporating the uncertainties of the nonstationary climate changes into the analysis. It is not possible to confidently describe them with probability functions (Mendoza *et al.*, 2018). If this was possible, then adaptation planning to threats and opportunities would become a less complex challenge and the well-known and established systems analysis approaches described in Maass *et al*. (1962), Major (1969), Loucks & van Beek (2017), and others could be applied – some with proven success (Brown *et al.*, 2015). Of course, as recently pointed out by Loucks (2021), there remain significant challenges in inserting the results of sophisticated water resources analyses into management policies.

Since climate change unfortunately will result in more threats to water resources and coastal systems than opportunities, here we only focus upon managing the threats though, of course, similar analysis could be applied to capturing any limited opportunities associated with climate change. Opportunities might include increased annual rainfall in presently humid areas, longer growing seasons, and increased offshore winds for renewable energy. Of course, unfortunately many of these opportunities may be accompanied by more droughts, more plant disease, and more intense tropical storms.

As noted above, there exist many approaches to analyze system vulnerabilities and adaptation options with some of them included in this volume. These approaches continue to evolve as the field of water resources systems analysis expands to meet these new challenges (Kasprzyk, *et al.*, 2018) but some have already had some successful and impactful applications (Mauroner *et al.*, 2021). Many of them require considerable resources and finances to apply but given the high cost of failures of most water-based systems and the generally high benefit–cost ratios of adaptation, the expense and effort of appropriate planning are certainly justified. The challenge is applying the correct method to the problem; guidance to this is also presented in this volume.

There are circumstances, however, when even though nonstationarity is acknowledged, a full detailed assessment of it is not necessary. This chapter starts with a discussion of these cases when a detailed assessment of nonstationarity may not be warranted based upon planning conditions, and then moves to sequential screening methods to assist in determining the level of nonstationarity analysis that should be considered, and concludes with the use of decision analysis to aid in this decision.

## PLANNING CONDITIONS

There are situations where even though nonstationarity is recognized, it may not be necessary to carry out a detailed assessment of its consequences. These situations can be characterized by a project's lifetime, criticality, reversibility, flexibility/adaptability, robustness, and the use of forward design standards. There will be, of course, cases where multiple conditions exist. In any case, however, if there is any doubt, a more complex method of nonstationarity analysis must be used given the large vulnerabilities of some systems and the significant positive benefits of reasonable adaptation strategies.

### Project lifetime

If an asset is not threatened now and, based upon a preliminary analysis of the more extreme range of climate change threats, will never be impacted over the planning horizon, then a detailed nonstationarity analysis is not needed. It may be needed, however, if the inputs necessary for that system to function or its outputs are threatened by climate change. For example, an electrical generation station far from the flood zone may never be threatened and thus no analysis is needed unless its cooling water supply is threatened or the demands on it might increase if other power plants do not function and more demands are placed on it.

Similarly, if a project has a short lifetime, is not exposed now to a threat, and will be upgraded before the estimated earliest time when it may be threatened, then nonstationarity analysis can be implemented later as part of the new design. The caveats about its inputs and outputs being threatened as above also apply.

If the project lifetime or the planning period is relatively short – perhaps 20–30 years – then the project can be designed with trend analysis applied to recent data. For example, Serago & Vogel (2018) suggest exploiting historical trends in discharge data to update flood design discharges to reflect current conditions.

### Criticality

If an asset is not critical to system performance or there are many alternatives to it or adaptive capacity is high, then detailed analysis is also not needed. A simple case is a road segment which, if flooded, only results in minor consequences because there are many alternative routes to destinations. This is in contrast to a road that is the sole connection of the neighborhood to medical facilities.

### Reversibility

Hobbs *et al*. (1997) report upon the results of a workshop that identified project characteristics that may warrant the consideration of complex nonstationary analyses because they are sensitive to climate change. These include:

- Options involving commitments to resources that have long-lived effects and are costly to alter or are irreversible.
- The benefits and costs of options are large and could be altered by climate change.
- The resource commitment is a unique part of the system for which there are no ready substitutes so adjustments to changed conditions are difficult to make later on.

### Flexibility/adaptability

The American Society of Civil Engineers Manual of Practice (MOP) on Climate-Resilient Infrastructure (American Society of Civil Engineers, ASCE, 2018) examines how to consider nonstationarity in infrastructure design. While recognizing that there are many situations when complex design approaches are necessary, there are also situations where less complex methods may be applicable.

The most relevant may be the Observational Method (OM) historically used in the geotechnical field where uncertainty conditions are high. The approach is to identify system changes during the design phase that can be implemented over time as the uncertain conditions change over the project lifetime or as stated in the MOP:

> 'The Observational Method [in ground engineering] is a continuous, managed, integrated, process of design, construction control, monitoring and review that enables previously defined modifications to be incorporated during or after construction as appropriate. All these aspects have to be demonstrably robust. The objective is to achieve greater overall economy without compromising safety' (page 52).

Implementing such a process requires an accompanying observation system. The article also points out that the data collected from the system can also resolve some of the uncertainties of the performance of future systems, i.e. some of the uncertainties can be reduced. Projects most suitable for OM include those with multiple stages or construction processes and in situations where the changes are gradual such as sea level rise. In situations with possibly rapid changes, it may not be possible to have obtained the observational data in time to act.

The steps involved in the OM include:

1. 'Project design is based on the most-probable weather or climate condition(s) rather than the most unfavorable. The most-credible unfavorable deviations from the most-probable conditions are identified.
2. A course of action or design modification is devised (in advance) for every foreseeable unfavorable weather or climate deviation from the most-probable condition(s).
3. The performance of the project is observed over time (using preselected quantities) and the response of the project to observed changes is assessed.
4. Design and construction modifications (previously identified) can be implemented in response to observed changes' (page 53).

The modification to a system at any one time can be the construction of an element of a type different from previous modifications. For example, a levee may initially be modified by adding more material to it, but then modified by building a flood wall on top of it or implementing means to accommodate any flooding that overtops the levee.

An example of this is the recent decision of the City of Boston USA not to plan to install a massive harbor-wide barrier system to protect it from present and future coastal flooding (Kirshen *et al.*, 2018, 2020; Climate Ready Boston, 2021). It was found that the system was not cost-effective, and after a few decades of operation, the gates would have to close perhaps as frequently as once per week because of sea level rise – resulting in increased chance of operational failure of the gates, and ecological, recreational, and shipping impacts. It was not necessary to analyze this system in more detail for its performance under nonstationarity conditions because one alternative to the barrier was shore-based systems such as a shoreline elevated with parks and open space (nature-based solutions) or protected by floodwall or levees. These engineered systems can be implemented relatively quickly when needed, can be expanded over time as climate changes, are more cost-effective than a harbor-wide barrier system under a range of climate change scenarios, and provide many social and ecological co-benefits. Detailed nonstationarity analysis is not needed for selecting their initial elevations because of the existence of reasonable engineering principles for their selection based upon possible future flood elevations, economies of scale, and site design constraints. The major concern is ensuring that space is reserved for the shore-based systems so they can be implemented when needed.

As noted, one of the disadvantages of the approach is that many of the costs of modifying a project in an urban area such as access, disruption, interference with other infrastructure systems can be high. In addition, it is not possible to modify some systems so their expansion can be staged. Still, some of these can be avoided if they are recognized in the planning phase and options preserved to act on future possible conditions. For example, development could be limited in an area where a future adaptation plan may have to be implemented.

### Robustness

Detailed nonstationarity analysis also may not be necessary if it is shown that the reasonable solutions over time to the climate stress are relatively insensitive to different climate change scenarios. For example, in an analysis of water supply and conservation alternatives to meet the present and future demands in Amman Jordan, Ray *et al.* (2012) showed that the set of surface water and groundwater resources, imported water, reclaimed water, water conservation, and other sources to meet future demands did not change significantly over time given a range of climate change scenarios. However, the relative quantities of the sources varied over time.

### Forward design standards

Complex adaptation analysis also may not be needed if previous reasonable analysis has been codified and can be followed in the design process. An example of this is the requirements of Federal Executive Order (EO) 13690. As reported in ASCE (2018), the EO set minimum flood protection requirements for federally funded buildings and infrastructure. It gave flexibility to select one of three approaches for establishing a Design Flood Elevation:

1. Climate-Informed Science Approach (CISA) – use best available, actionable hydrologic and hydraulic data, and methods that integrate current and future changes in flooding based on climate science and other factors or changes affecting flood risk to determine the vertical flood elevation and corresponding horizontal floodplain in a manner appropriate to policies, practices, criticality, and consequences.
2. Freeboard Value Approach (FVA) – use the present Base Flood Elevation (or 1 percent annual flood determined using best available data) and an additional height to calculate the freeboard value. The additional height will depend on whether or not the action is a critical action.
3. The 0.2-percent-annual-chance Flood Approach (0.2 PFA) – use the 0.2-percent-annual-chance flood elevation (also known as the 500-year flood elevation).

In situations where previous analysis has been carried out, its application could be straightforward. For example, in Boston, USA, the City's planning and permitting authority, the Boston Planning and Development agency, requires that 2 feet of freeboard be added to the elevation of the highest sea level rise projection and associated storm flooding determined by a scientific organization for critical facilities and buildings with ground floor residential units and one foot for all other building types (Boston Planning & Development Agency, 2017).

Related to this is use of traditional design approaches using products that have been enhanced to include future climates. ASCE (2018) contains several methods for enhancing precipitation Intensity–Duration–Frequency relationships and flood frequencies (and some methods are also reviewed in this volume). If the designer is confident that one of the scenarios of the enhancement is reasonable or at least adjustments to the design can be made if it turns out not to be sufficiently accurate, then the enhanced relationships can be used in the design process.

## SCREENING METHODOLOGIES

### Asian Development Bank (ADB)

ADB (2013) offers guidance to investigate the complexity of climate changes stresses. ADB suggests a stakeholder workshop to address what might be the changes caused by climate change and how will these affect utilities and services in the context of the Pressure:State:Reponse framework. They present some principles for ranking stresses. For example, if a system is currently operating below capacity, then vulnerability is likely to be low. Conversely, if already operating at peak capacity, and occasionally fails under severe weather events, then vulnerability is likely to be high. An example of the outcome of such a process could be as in Figure 1.

### US Agency for International Development (USAID)

USAID (2014) recommends a two-step Scoping and Assessment process to determine the vulnerability of a system to climate and other stresses. There are several intermediate steps in the process to decide if a more detailed analysis is necessary. The Scoping step consists of the following:

- 'Frame the planning process by identifying the development goals important to the country, community, or sector you are working with; and identify inputs and enabling conditions necessary to achieve those development goals.
- Consider the impacts of climate and non-climate stressors on those inputs, and consider the needs and opportunities for addressing the various stresses affecting inputs and undermining development' (page 9).

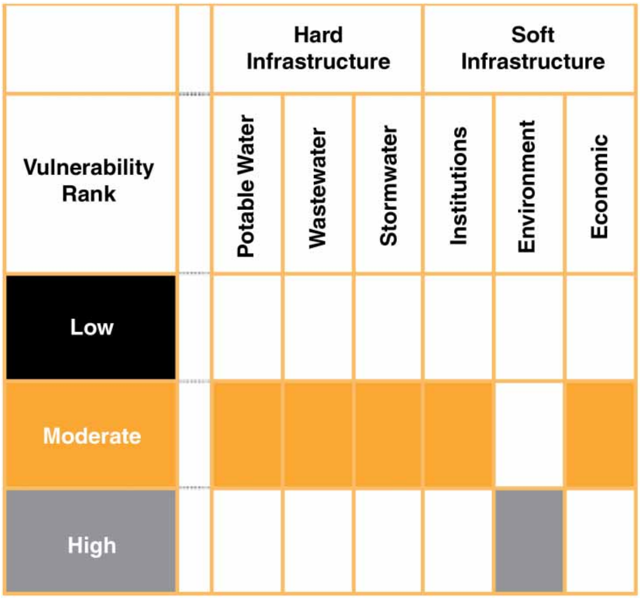



**Fig. 1** | Example of the outcome of vulnerability ranking (ADB, 2013).

This is procedure may result in either complex or less complex solutions or perhaps the need to immediately move a more detailed vulnerability assessment – but if there is not a need right now, the next step is the Assessment step.

The Assessment step includes the analyses of exposure to the threat, sensitivity to the threat, and adaptive capacity to manage the threat. These analyses result in the vulnerability of the system. The level of detail and hence the complexity of the method depends on factors such as the information needed to make the decision, the time and resources available, and the importance of the decision.

### US Climate Resilience toolkit

The above screening approaches can be characterized as bottom-up because they start with a set of questions about existing capacity and performance. In contrast, the US Climate Resilience Toolkit (2021) presents a top-down, staged approach based upon the exposure-sensitivity-adaptive capacity approach to investigate a system's vulnerability to climate change and subsequent adaptation strategies. Initially stakeholders, using scenarios of climate change projections, determine if weather and climate threatens valued assets. If so, the next step is to determine the vulnerability – they recommend setting priority for action based upon how close in time and/or condition an asset is to a tipping point – 'a point when incremental change in a system results in a new, irreversible response'.

### Federal Highway Administration

Once an asset has been shown to be possibly exposed to a threat and is deemed critical, then an examination can be made of its sensitivity to the threat. Federal Highway Administration (2017) describes several methods of screening for sensitivity. These include:

#### Historical performance and agency knowledge

If performance of assets has been lowered in past weather events, particularly extreme weather events, then it indicates climate sensitivity. Maintenance records correlated with weather events are also useful. Discussions with design and maintenance staff can also yield insights.

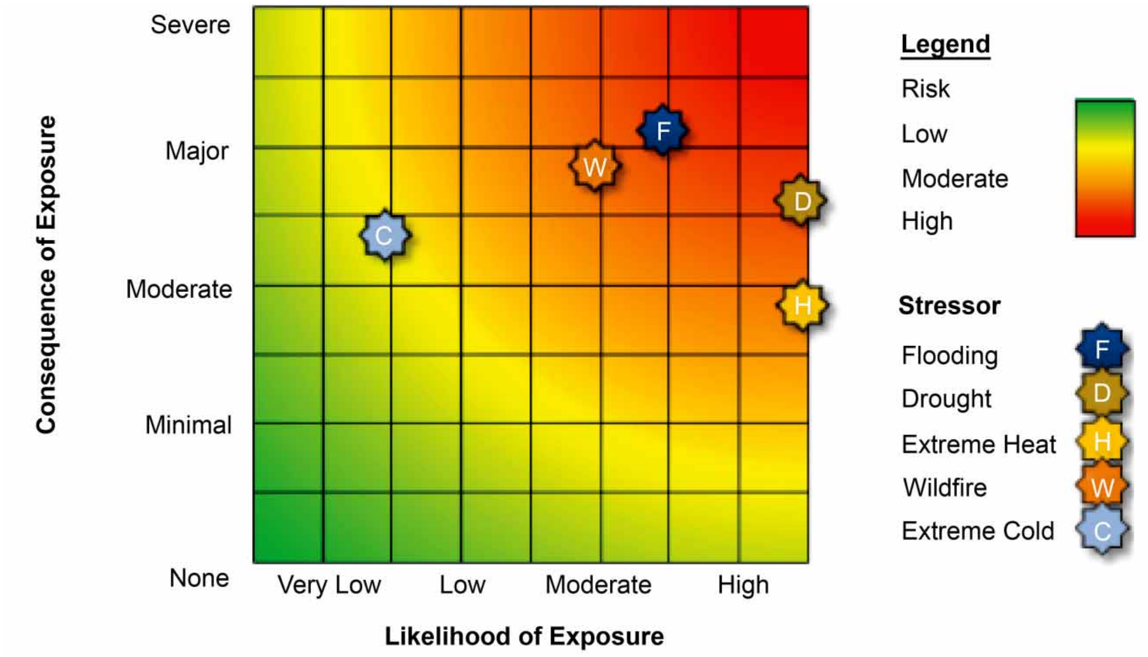
### Infrastructure design standards and guidelines

Many smaller scale assets are designed for particular events and frequencies. If possible changes in the events are known, then a comparison can indicate sensitivity. For example, in Boston, USA, most of the storm drainage network was designed approximately 100 years ago using around 4 inches of rainfall in 24 h. Recent analysis indicates that this value is now over 5 inches (Douglas *et al.*, 2016). If a more complex system has been designed using maximum expected present value net benefits that analysis can also be recalculated with current information.

The sensitivity can also be weighed by a qualitative assessment of the probability of the damage to the asset from an event – that is, the risk. Shown in Figure 2 is an example of this applied to a particular transportation asset.

### World Bank decision tree framework

The entire four phase methodology of the bottom-up, Context First process of The Decision Tree Framework of Ray & Brown (2015) is described in this volume so here only the screening phases (1 and 2) are summarized. Phase 1 is known as Project Screening. In this phase, a thought-exercise is carried out to determine the initial possibility that the project may be sensitive to nonstationary climate and other drivers. The process is guided by the Climate Screening Worksheet in Appendix B of Ray & Brown (2015). This leads the project analyst to




CAMPO developed risk summary fact sheets for each asset studied that explain the extreme weather risks it faces. This is an example Risk Summary Matrix for SH 71E at SH21. Flooding and drought present the greatest risks to this asset, while wildfire and extreme heat present moderate risks. Though flooding is projected to occur less often that drought, it would have greater consequences for the asset. (Source: CAMPO)

**Fig. 2** | Example of consequence of exposure (sensitivity) weighted by likelihood of exposure to estimate risk (FHWA, 2017).

consider the 'Four C's' of the project: 'available project design choices; the consequences or performance metrics that will be used to evaluate the project's success; the connections through which choices and consequences are linked; and finally, the uncertainties that affect the conclusions that can be drawn about the profitability of the project'. If the result of this guided process is that the project may be significantly affected by future climates, then the project undergoes more extensive and complex analysis in Phase 2 to determine if a full detailed analysis of the project's vulnerability and adaptation options under deep uncertainty is carried out. If not significantly impacted by future climates, but perhaps instead by other uncertain drivers, then project analysis can proceed without consideration of a nonstationary climate.

Phase 2, known as Initial Analysis, recommends 'Rapid Project Scoping' to assess the systems sensitivity to climate change. It requires the use of a computer-based water resources model of the major elements of the system – this could be a complex watershed model or a less complex tool based upon, e.g., Excel. While this may require 1–2 months of time to complete, it is inexpensive compared to the actual design, construction, and operation of a large water resources project – even more valuable when the benefits lost or harm due to construction are also included. Details are given in Ray & Brown (2015).

The Phase 2 process is carried out in seven steps that result in the elasticities of stakeholder-defined Performance Indicators (PI) to the nonstationary climate inputs, then probability density functions (PDFs) of changes on PIs due to hydrologic changes, and eventually the risks and probabilities of changes of the PIs as a function of possible climate changes. The PI values can then be compared to acceptable thresholds of them. If the PI values are not acceptable, then the project is climate sensitive and must be analyzed in more detail with a DMDU method. This methodology can also be carried out for other nonstationary drivers such as population change if desired.

### Climate risk informed decision analysis (CRIDA)

This process (Mendoza *et al.*, 2018) for inclusion of nonstationary analysis into decision-making starts with a bottom-up assessment of the system to determine if it may fail under certain climate and other conditions – the stress test of Brown *et al.* (2012) performed with a water resources system model. This is then compared to the uncertainty of this occurring in a figure such as Figure 3. If the outcome of this preliminary analysis (known as the 'Level of Concern') falls in Quadrants I or II of Figure 3, then existing analytical planning methods can be used that do not rely heavily upon nonstationary inclusion.

The previous analysis of Kirshen *et al.* (2018, 2020) used in the comparison of harbor-wide barriers versus shore-based Natural-Based Solutions to protect metro Boston from present and increased coastal flooding falls into Quadrant II of Figure 3.

### Hobbs *et al.* (1997)

Based upon the results of using decision analysis to determine adaptation strategies (see the below section on 'Decision Analysis'), Hobbs *et al.* (1997) developed a five step procedure on when to apply decision analysis. The procedure can also be used to determine when detailed nonstationarity analysis can be used.

1. Determine if the project has characteristics that may make it sensitive to climate change (already mentioned in the above section on 'Planning Conditions'): 'irreversibility; playing a unique role in the system; long lived benefits and costs that would be significantly affected by climate change; and the ability to delay a decision to obtain more information on climate change'.
2. Assuming a climate change scenario, perhaps more extreme than average, determine if the projects net benefits would change significantly.
3. Determine the loss of net benefits if a decision was made assuming no climate change but climate change occurred (i.e. regret).

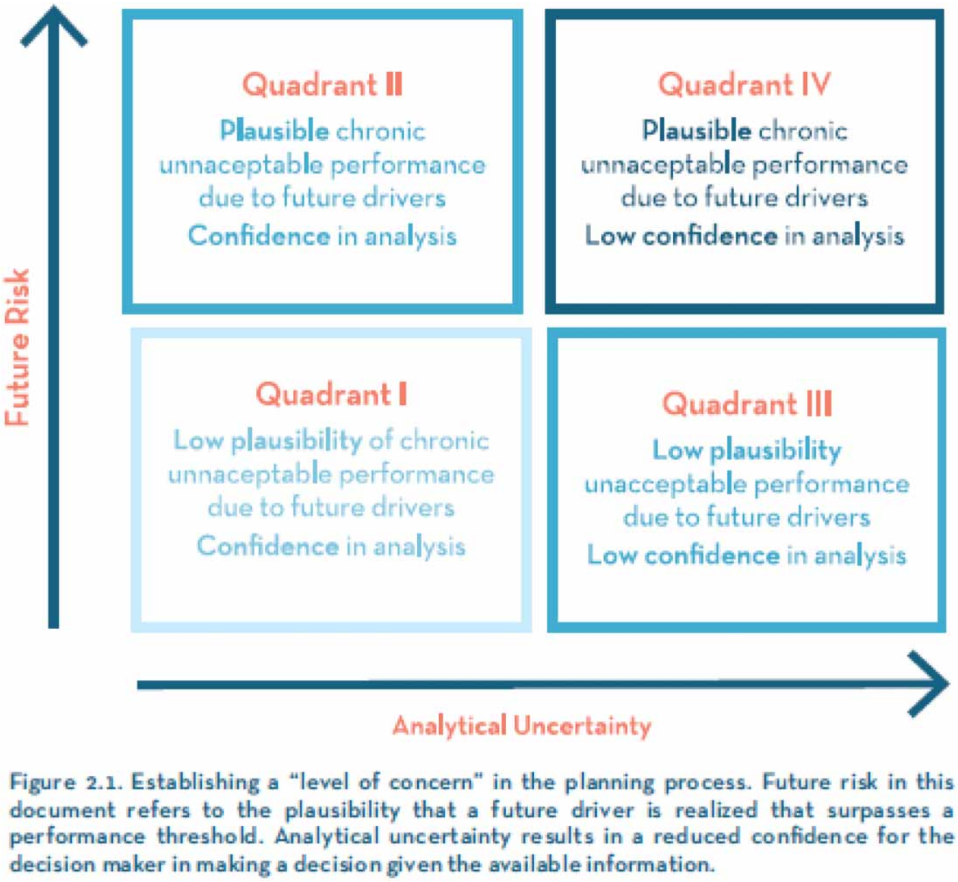



**Fig. 3** | The CRIDA level of concern matrix (Mendoza *et al.*, 2018).

4 and 5. If results of (3) are significant, then construct a decision tree with multiple climate change scenarios and with the option of delaying the project to wait for additional information. The decision tree approach follows below.

## DECISION ANALYSIS

The Decision Analysis process breaks a problem out into a systematic display of all relevant choices. Oftentimes it is combined with the use of Bayes' Law so the impact and value of additional information can be added to the decision process; in some cases, the most reasonable solution is to pay for and/or delay to obtain more information. Decision trees are also commonly used to illustrate all the various decision pathways, the probabilities and economic consequences of various outcomes occurring, and provide a structured approach to making a decision (de Neufville, 1990). These processes can be used to help decide on the complexity of the method warranted for vulnerability and adaption planning.

In a now classic paper, Hobbs *et al.* (1997) uses decision analysis to determine the value of including climate change uncertainty in a water resources management strategy with an example of the Great Lakes in the USA. With the goal or objective of minimizing cost, the expected cost of ignoring uncertainty is the difference between the expected value of making the decision assuming no climate change and the expected value of making the decision assuming the possibility of climate change occurring and this is factored into the decision process. In the case study, using Bayes' Law to include information on the possibility of climate change given observations 20 years in the future, it is shown that it is better to wait 20 years to review the monitoring than take a construction action now. This method results in not only the most reasonable decision to make given what is known now, but also the value of information. Based upon the results of research on the case studies, Hobbs *et al.* (1997) recommended the five step approach described in the 'Screening Methodologies' section above.

In another application of decision analysis, Rosner *et al.* (2014) developed an adaptation planning process that considers the possibilities and consequences of both stationary and nonstationary future conditions. This is done by explicitly analyzing the consequences of analyzing flood trends and making either Type I or Type II errors. Type I errors occur when it is concluded a trend exists when it does not and results in over-preparedness and thus more expensive than necessary. Type II error is rejecting a trend when it actually exists and results in under-preparedness, and consequently additional damages. Such an approach could be used to help decide if more detailed analysis of trends or similar climate changes is necessary in water resources adaption planning. As shown in Figure 4, the decision tree used in this process includes branches with the possibilities of these types of errors occurring with their probabilities related to the significance level of the null hypothesis and the power of the alternative hypothesis. It is shown in an example that consideration of both types of errors occurring results in a better decision than ignoring the possibilities. Bayesian analysis could also be added to this process to investigate the value of additional information. While not directly including decision-making regarding climate change, Hecht *et al.* (2020) show how to include ecosystem impacts as well into this type of analysis.

## SUMMARY

The impacts of climate and other changes on the services provided by water resources systems must be considered in examining the operation of existing systems and those in the planning phase. Adjustments in their designs may be warranted because the benefits of effective adaptation are well recognized. Therefore, the time and resources invested in these analyses are well worth the effort. Before a major investment in an effort is made, however, it is reasonable to determine if the problem is of sufficient complexity or the value of additional information is high enough to warrant the inclusion of complex, sophisticated methods that explicitly include

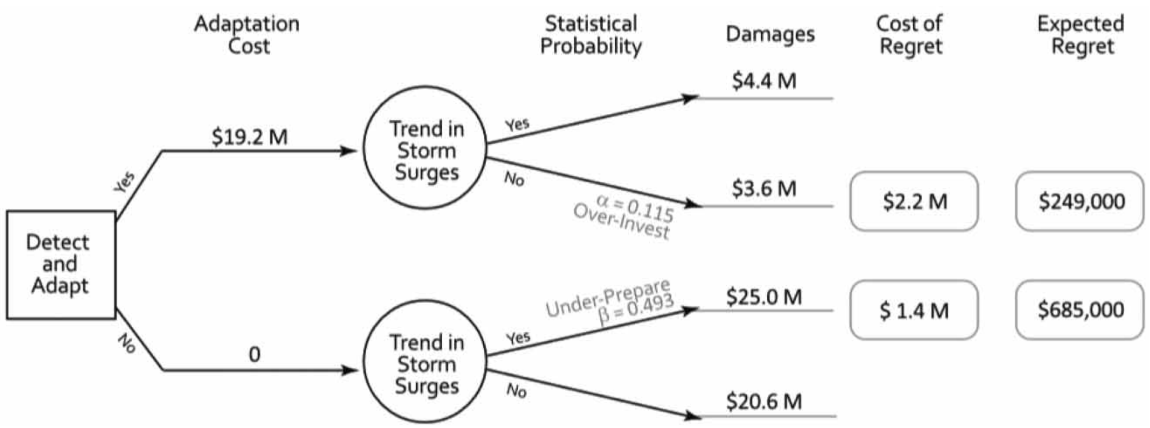



**Fig. 4** | Decision tree for risk-based coastal flood adaptation in a nonstationary world case study. A decision point is denoted by a square, a chance outcome by a circle. Alpha, probability of Type I Error, Beta, probability of Type II error.

nonstationarity and associated decision-making under deep uncertainty. There exist several planning level conditions such as the lifetime of the project, its criticality, and its reversibility that may indicate detailed analysis is not needed. There are also sequential analysis and screening steps that can be applied to determine the complexity of the methodology needed. Finally, the use of decision analysis can also help determine if additional, detailed analysis, or data collection are necessary. The use of one or several of these methods should be considered as initial steps before undertaking a vulnerability assessment and developing an adaptation strategy for a water resources system.

## ACKNOWLEDGEMENTS

The author appreciated the helpful comments and suggestions of Eugene Stakhiv. He also benefitted from conversations with Richard Vogel and Jory Hecht.

## REFERENCES

American Society of Civil Engineers (2018). In: *Climate-Resilient Infrastructure, Adaptive Design and Risk Management, Manual of Practice 140*. Ayyub, B. (ed.). ASCE Committee on Adaptation to a Changing Climate, Reston, VA.

Asian Development Bank (2013). *Increasing Climate Change Resilience of Urban Water Infrastructure*. Asian Development Bank, Mandaluyong City.

Boston Planning and Development Agency (2017). *Climate Resiliency Guidance*. Available at: http://www.bostonplans.org/getattachment/5d668310-ffd1-4104-98fa-eef30424a9b3 (accessed April 30, 2021).

Brown, C., Ghile, Y., Laverty, M. & Li, K. (2012). Decision scaling: linking bottom-up vulnerability analysis with climate projections in the water sector. *Water Resources Research 48*, 9. doi:10.1029/2011WR011212.

Brown, C. M., Lund, J. R., Cai, X., Reed, P. M., Zagona, E. A., Ostfeld, A., Hall, J., Characklis, G. W., Yu, W. & Brekke, L. (2015). The future of water resources systems analysis: toward a scientific framework for sustainable water management. *Water Resources Research 51*, 6110–6124. doi:10.1002/2015WR017114.

Climate Ready Boston (2021). *Resilient Boston Harbor*. Available at: https://www.boston.gov/environment-and-energy/resilient-boston-harbor (accessed April 30, 2021).

De Neufville, R. (1990). *Applied Systems Analysis*. McGraw-Hill, New York.

Douglas, E., Kirshen, P., Hannigan, R., Herst, R., Palardy, A., DeConto, R., Fitzgerald, D., Hay, C., Hughes, Z., Kemp, A., Knopp, R., Anderson, B., Kuang, Z., Ravela, S., Woodruff, J., Barlow, M., Collins, M., DeGaetano, A., Schlosser, C., Ganguly, A., Kodra, E. & Ruth, M. (2016). *Climate Change and Sea Level Rise Projections for Boston*. The Boston Research Advisory Group, for Climate Ready Boston, City of Boston.

Federal Highway Administration (2017). *Vulnerability Assessment and Adaptation Framework*, 3rd edn. Federal Highway Administration, Cambridge, MA.

Hecht, J., Vogel, R., McManamay, R., Kroll, C. & Reed, M. (2020). Decision trees for incorporating hypothesis tests of hydrologic alteration into hydropower-ecosystem tradeoffs. *J. Water Resources Planning and Management 146*(5). https://ascelibrary.org/doi/abs/10.1061/%28ASCE%29WR.1943-5452.0001184.

Hobbs, B., Chao, P. & Venkatesh, B. (1997). Using decision analysis to include climate change in water resources decision making. *Climatic Change 37*(1), 177–202.

Kasprzyk, J., Smith, R., Stillwell, A., Madani, K., Ford, D., McKinney, D. & Sorooshian, S. (2018). Defining the role of water resources systems analysis in a changing future. *Journal of Water Resources Planning and Management 144*(12). https://ascelibrary.org/doi/10.1061/%28ASCE%29WR.1943-5452.0001010.

Kirshen, P., Borrelli, M., Byrnes, J., Chen, R., Lockwood, L., Watson, C., Starbuck, K., Wiggin, J., Novelly, A., Uiterwyk, K., Thurson, K., McMann, B., Foster, C., Sprague, H., Roberts, H., Jin, D., Bosma, K., Holmes, E., Stromer, Z., Famely, J., Shaw, A., Hoffnagle, B. & Herst, R. (2018). *Feasibility of Harbor-Wide Barrier Systems: Preliminary Analysis for Boston Harbor*. Sustainable Solutions Lab, University of Massachusetts, Boston.

Kirshen, P., Borrelli, M., Byrnes, J., Chen, R., Lockwood, L., Watson, C., Starbuck, K., Wiggin, J., Novelly, A., Uiterwyk, K., Thurson, K., McMann, B., Foster, C., Sprague, H., Roberts, H., Jin, D., Bosma, K., Holmes, E., Strummer, Z., Famely, J., Shaw, A., Hoffnagle, B. & Herst, R. (2020). Integrated assessment of storm surge barrier systems under present and future

climates and comparison to alternatives; a case study of Boston USA. *Climatic Change 162*(2), 445–464. doi:10.1007/s10584-020-02781-8.
Loucks, D. P. & van Beek, E. (2017). *Water Resources Systems Planning and Management: An Introduction to Methods, Models and Applications*. Springer, Switzerland.
Loucks, D. (2021). Science informed policies for managing water. *Hydrology 8*, 66.
Maass, A., Hufschmidt, M., Dorfman, R., Thomas, H., Marglin, S. & Fair, G. (1962). *Design of Water-Resource Systems: New Techniques for Relating Economic Objectives, Engineering Analysis, and Governmental Planning*. Harvard Univ. Press, Cambridge, Mass.
Major, D. C. (1969). Benefit-cost ratios for projects in multiple objective investment programs. *Water Resources Research 5*(6), 1174–1178.
Mauroner, A., Timboe, I., Matthews, J., Taganova, J. & Mishra, A. (2021). *Planning Water Resilience from the Bottom-Up to Meet Climate and Development Goals*. UNESCO and AGWA, Paris, France and Corvallis, USA.
Mendoza, G., Jeuken, A., Matthews, J., Stakhiv, E., Kucharski, J. & Gilroy, K. (2018). *Climate Risk Informed Decision Analysis (CRIDA)*. UNESCO, Paris, and International Center for Integrated Water Resources Management, Alexandria, VA.
Ray, P. & Brown, C. (2015). *Confronting Climate Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework*. World Bank, Washington, DC.
Ray, P., Kirshen, P. & Watkins, D. (2012). Staged climate change adaptation planning for water supply in Amman, Jordan. *Journal of Water Resources Planning and Management*. *138*, 403–411.
Rosner, A., Vogel, R. & Kirshen, P. (2014). A risk-based approach to flood management decisions in a nonstationary world. *Water Resources Research*, published online March 7, 2014.
Serago, J. & Vogel, R. (2018). Parsimonious nonstationary flood frequency analysis. *Advances in Water Resources 112*, 1–16.
US Agency for International Development (2014). *Climate-Resilient Development: A Framework for Understanding and Addressing Climate Change*. US Agency for International Development, Washington, DC.
US Climate Resilient Toolkit (2021). Available at: https://toolkit.climate.gov/ (accessed April 30, 2021).

First received 18 November 2021; accepted in revised form 18 November 2021. Available online 30 November 2021