Climate Resilience Analysis Framework: Testing the resilience of natural and engineered systems

Bree Bennett, Lu Zhang, Nick Potter, and Seth Westra

Goyder Institute for Water Research
Technical Report Series No. 18/02

www.goyderinstitute.org

Goyder Institute for Water Research Technical Report Series ISSN: 1839-2725

The Goyder Institute for Water Research is a partnership between the South Australian Government through the Department for Environment and Water, CSIRO, Flinders University, the University of Adelaide, the University of South Australia and the International Centre of Excellence in Water Resource Management. The Institute enhances the South Australian Government's capacity to develop and deliver science-based policy solutions in water management. It brings together the best scientists and researchers across Australia to provide expert and independent scientific advice to inform good government water policy and identify future threats and opportunities to water security.

Enquires should be addressed to: Goyder Institute for Water Research
Level 4, 33 King William Street
Adelaide, SA 5000
tel: 08 8236 5200
e-mail: enquiries@goyderinstitute.org

Citation

Bennett, B., Zhang, L., Potter, N.J., and S. Westra, 2018, *Climate Resilience Analysis Framework: Testing the resilience of natural and engineered systems*, Goyder Institute for Water Research Technical Report Series No. 18/02.

Introduction

Australia's variable and changing climate presents significant challenges to the performance of natural and engineered systems across the municipal, agricultural, energy, mining, industrial, transport and environmental sectors. In many cases, it is desirable that these systems operate successfully across a range of climate and weather conditions, and can withstand weather and climatic extremes. This capacity to tolerate change to weather and climate is referred to here as the system *resilience*[1].

This document steps you through a framework for testing the resilience of natural and engineered systems, and supports the identification of options to strengthen resilience where needed.

Who is this framework for?

The framework is relevant for anyone interested in understanding how weather and climate affects a given system, and/or developing options that maximize system resilience. The framework is most suited to projects that:

- Focus on long-term planning;
- Are at a scale to warrant detailed quantitative analysis of system resilience;
- Have a quantitative system model available or have the capacity to develop such a model; and
- Have complex relationships between weather and climate drivers and the overall system, such that system resilience cannot be assessed using simpler methods.

Potential example applications include municipal water supply planning, irrigation system design, environmental flow management or energy systems planning that rely on one or multiple climate-dependent sources (e.g. hydroelectric, solar or wind).

Depending on the scope of the analysis, the framework will be relevant to individuals in policy, planning, engineering design and system operation roles.

What type of problems can this framework help me with?

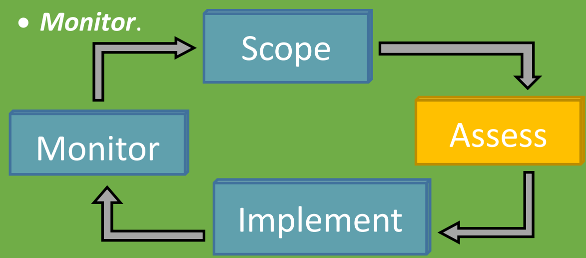
In each step of the framework you treat the system as the central concern of your analysis. Here the 'system' is a combination of physical and operating characteristics that translates weather and climate inputs into some desirable outcome (e.g. water and/or energy security, agricultural productivity, ecosystem services, etc.). This emphasis means that the framework can be used to address a range of system-centric problems. These include:

- Testing the resilience of an existing system;
- Assisting in designing new systems or augmenting existing systems; and
- Supporting the development and assessment of system management options as part of an adaptation pathways approach (see box above).

HOW THE RESILIENCE ANAYLSIS FRAMEWORK FITS IN THE ADAPTATION PLANNING CYCLE

There are many adaptation planning frameworks available in the literature (see further reading), but almost all contain the following elements:

- Define the ***scope*** of the investigation;
- ***Assess*** the current system and adaptation options under potential future conditions;
- ***Implement*** the chosen options; then
- ***Monitor***.



For the ***assess*** step, adaptive planning cycles can accommodate a range of evaluation methods. This includes the climate resilience analysis framework described herein. The climate resilience analysis framework provides a rigorous quantitative analysis method for undertaking the evaluation step in certain applications. For example, in cases where a natural or engineered system sits within the identified planning scope or may be considered as an adaptation option.

Key features of the framework

The framework builds on bottom-up approaches (e.g. Prudhomme et al. 2010), and decision-centric approaches for managing climate uncertainty (e.g. Brown 2011, Culley et al. 2016, McPhail et al. 2018), with further details on a similar framework provided in Poff et al. (2016).

The framework has been specifically designed to:

- Recognize that systems are inherently complex and that links with climate are often non-trivial;

[1] There are numerous definitions for resilience in the literature, including a more narrow definition that requires considers the ability of a system to recover from shocks. Here we use the broader definition, which is equivalent to the inverse of vulnerability; i.e. a resilient system is one that has low vulnerability to a range of climate stressors.

- Emphasize the importance of system understanding by numerically ‘stress testing’ systems against a range of hypothetical and projected climate states;
- Provide a basis for iterative dialogue between decisions makers, system modelers and climate experts about model uncertainty and the implications of different design and operation options;
- Allow exploration of the implications of deep uncertainty by combining climate projections (via top-down approaches) with hypothetical climate scenarios (via bottom-up approaches) that cover a wide range of possible climatic changes;
- Enable rapid update of impact assessments under new lines of evidence (e.g. if new climate model projections become available); and
- Provide a basis for adaptive planning (including supporting the development of adaptive pathways).

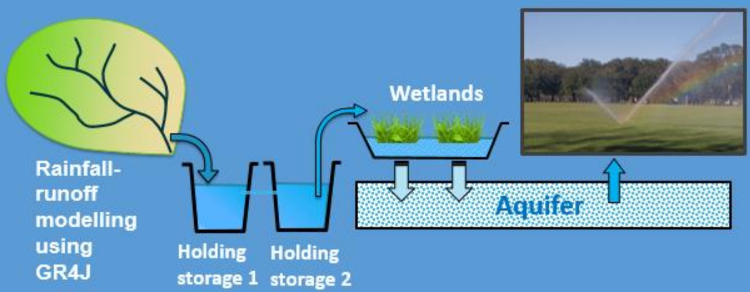
Available tools and resources

The framework is accompanied by an open-source R-package, *fore*SIGHT, to support you throughout the system specific analysis steps (e.g. system stress testing). The tool is described in Bennett et al. (2017) and available on the Comprehensive R Archive Network (https://cran.r-project.org) with accompanying help tutorials. For a more detailed illustration of the framework and tools applied to a managed aquifer problem, refer to Potter et al. (2018).

Box 1: Parafield stormwater capture and managed aquifer recharge scheme

Adelaide is expected to face a warmer and drier climate in the future, with water resources identified as a key sector for adaptation. The City of Salisbury in the Northern Adelaide region has augmented its traditional water supply since 2003 via a managed aquifer recharge (MAR) scheme. As a part of its larger water resource system it is important to evaluate the resilience of the MAR system across a wide range of weather and climate conditions.

To evaluate system resilience, the climate resilience analysis framework was applied to the MAR scheme. The system captures stormwater from a 16 km^2 residential and industrial catchment, which passes through two storage basins and wetlands for cleaning and sediment reduction. Four wells inject and extract water from the aquifer for reuse for industrial and irrigation uses. A system model including a rainfall-runoff model was coded in R, with volumetric reliability chosen as the performance measure.



System stress tests were conducted using the *fore*SIGHT software. Initial tests were conducted to determine which of a range of climate variables produced the most change in system performance. These tests indicated that system resilience is most sensitive to changes in mean annual rainfall, potential evaporation (especially through influencing demand), mean number of wet days (rainfall intermittency) and rainfall seasonality. The identification of the specific aspects of future change that can influence system performance is a defining feature of the framework. Following variable identification, the system can then be ‘stress tested’ to a range of possible changes in each variable (and variable combinations). This can be combined with a traditional ‘top-down’ climate impact assessment to inform which future changes to climate variables are more likely. For the case study, the climate model projections show that future climate conditions would lead to a deterioration in performance, with volumetric reliability expected to decrease from 72% under current climate conditions to as low as 22% under the worst-case future climate projections by 2085 based on the stress test.

The combination of system stress testing with traditional climate impact assessments enables an evaluation not only of *how vulnerable a system is* to climate change, but more usefully, *why this vulnerability exists*—which in turn may assist with identifying possible options for improving system resilience. For example, a finding that the loss of performance is due to changes in rainfall intermittency may suggest augmentation of system storage size or pump capacity may improve system resilience, but a finding that loss of performance is due to increases in evapotranspiration may lead to demand management as the preferred option. For the Parafield case study, multiple climate variables including changes to total annual rainfall, potential evapotranspiration, intermittency and seasonality were all found to contribute to a decrease in system performance, suggesting that a multi-pronged solution may be needed.

To determine the potential for system augmentation to mitigate these changes, a number of different hypothetical infrastructure scenarios (e.g. increase in number of injection wells, augmentation of holding storage) were assessed in the context of overall system resilience. This analysis revealed that increasing detention time, surface storage capacity and changing the number of injection wells led to a moderate improvement in performance. However, because of the complex nature of future climate changes identified during the stress testing phase, it is likely that no single system augmentation option will be sufficient to address the considerable reduction in system performance in isolation; rather, any system augmentations should be considered in combination and potentially in conjunction with demand management and consideration of alternative water sources to maintain a suitable reliability of supply.

The Climate Resilience Analysis Framework

This framework represents a general approach for assessing the resilience of existing natural and engineered systems, and supports the development of options for improving system resilience. In this context, a system is defined as the interaction of physical characteristics (e.g. natural characteristics and built infrastructure) with any relevant operating characteristics (e.g. operating rules) to fulfill one or several functions.

The framework is illustrated in Figure 1 and contains the following five elements:

- The system is the central concern of the analysis, and thus requires an assessment of how the system should perform. You can define 'system performance' in a number of ways, including binary success/failure criteria or quantitative performance measures, as well as across multiple economic, social and/or environmental measures;
- A climate 'stress test' is then applied to the system to assess the rate of system performance degradation and/or identify situations under which it can fail;
- Multiple 'lines of evidence' are then used to understand possible future climate changes. Lines of evidence may include climate model projections (by combining global climate models with dynamical and/or statistical downscaling, or bias corrections), historical climatic changes, expert judgement and/or analogues from paleo records;
- Performance of multiple alternative options for strengthening system resilience (e.g. infrastructure augmentation, land use planning, operations, demand management, etc.) can then be analyzed and compared; and
- Decision-analytic approaches are then used to determine the preferred system management option. This analysis can proceed in multiple ways, depending on user preference and interpretation of climate uncertainty (e.g. probabilistically or through scenarios).

Throughout the process there are a number of points to check in with system and climate experts. Therefore, to ensure that this framework has the ability to inform decision making it is advised that it is underpinned by a stakeholder engagement strategy.

What follows is a detailed description of how to implement the five-step framework for a system. You may find that some iteration between Steps 2 to 4 is required to meet individual needs of your investigation.

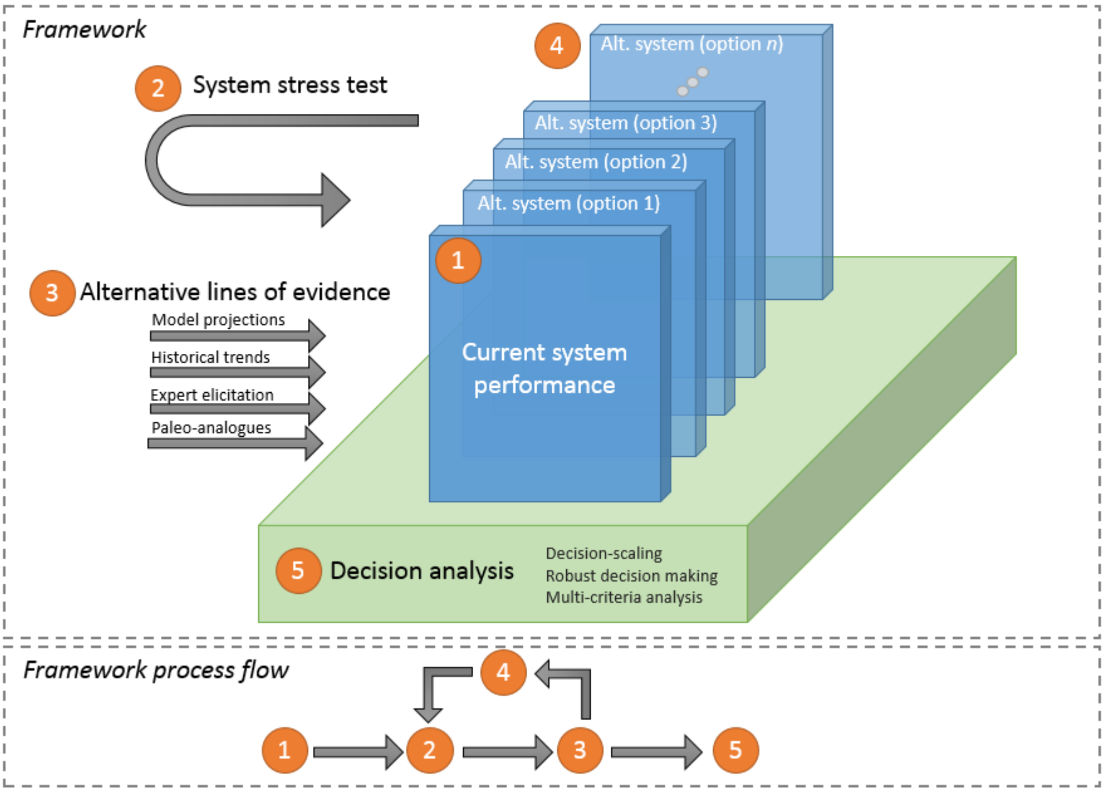


Figure 1: Elements of the climate resilience analysis framework (top) and framework process flow (bottom)

Step 1: Define the problem and system performance measures

In this Step you will describe and analyze the system under consideration. The aim is to define the problem(s) you are attempting to solve in order to achieve sustainable management of the system. Firstly, the system domain needs to be identified. This includes the system's physical and operational characteristics, as well as the system boundaries. The system domain forms the central reference point for the remainder of the framework.

Defining the system domain includes consulting decision makers and seeking expert knowledge from system operators (e.g. utilities, government agencies). These discussions should be a creative exploration of the system domain, recognizing that how a system is defined (e.g. where the boundaries are set) can often strongly determine the assessment of system resilience or the availability of options to improve performance.

Performance measures can then be developed to quantify system performance. These can represent a range of social, economic and environmental measures of the system. Performance measures represent the system values important to stakeholders and often we need to consider hidden costs, such as opportunity costs, and trade-offs of various kinds. Measures can include average performance (e.g. average annual net profit) or probability-based measures (e.g. probability of system failure).

Typical questions to ask in this step include:

- What is the purpose of the system?
- How is the system defined, and what are the system boundaries?
- How can system performance be measured? Are there clear success/failure criteria or is performance represented using multiple measures?
- What non-climate factors should be considered as part of understanding overall system performance (e.g. population growth, energy pricing, and system outages due to maintenance issues)?
- What alternative system management options may be available and should be considered?

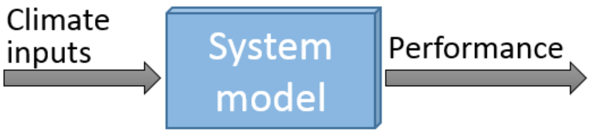
You can consider alternative system management options at this point or return to this in Step 4. Depending on the system boundaries and options available to decision makers, alternative system management options may include modification of operating rules, system re-optimization, infrastructure augmentation, economic signaling (e.g. modification of resource prices) and so on.

Following the identification of key performance measures, possible climate conditions that may affect system performance should be established. Potential climate conditions may include seasonality, extremes, annual totals and timing of variables such as rainfall, temperature and evapotranspiration.

Questions to consider include:

- What are the specific weather and climatic conditions that could affect system performance? What climate conditions could present risks to the system?
- How have climate variables been used in the decision making?
- What range of climatic change could the system be expected to experience? Within what climate bounds should the system be evaluated?

In light of this investigation, choose (or develop) a suitable numerical system model based on the identified performance measures and the set of climate conditions. The 'system model' in this context is a model that translates changes in the climate conditions into the system performance, and it may represent the combination of multiple separate computer models (e.g. hydrology, reservoir operation and demand models).



The system model is used to evaluate system performance across a wide range of scenarios and system management options in Steps 2 to 4. Hence it is critical that the model is able to capture the system's response to current and alternate climates, and is able to be easily adjusted to represent alternate system management options. An initial sensitivity analysis is recommended to understand the model's intrinsic behavior.

Outcomes: Problem scope defined, performance measures set & system model developed

Step 2: Stress test the system

In this Step you will evaluate how system performance responds to changes in the weather and climate variable properties identified in Step 1.

Begin with a preliminary investigation of the climate variable properties identified in Step 1. This investigation also relies on the chosen system model. Preliminary investigation questions include:

- Do changes in the *a priori* identified climate variable properties produce changes in system performance?
- Does the identified range of changes from Step 1 encompass the changes projected by global climate models?

CHECK IN POINT

Check in with your system and climate experts to confirm whether the climate variable properties identified in Step 1 are producing logical changes in system performance.

Once the sensitivity of the system to the selected climate variables is confirmed, generate perturbed time series that cover the range of plausible climate conditions identified in Step 1. These sets of perturbed time series are used to drive the system model and are termed ‘scenarios’. Options for generating scenarios include:

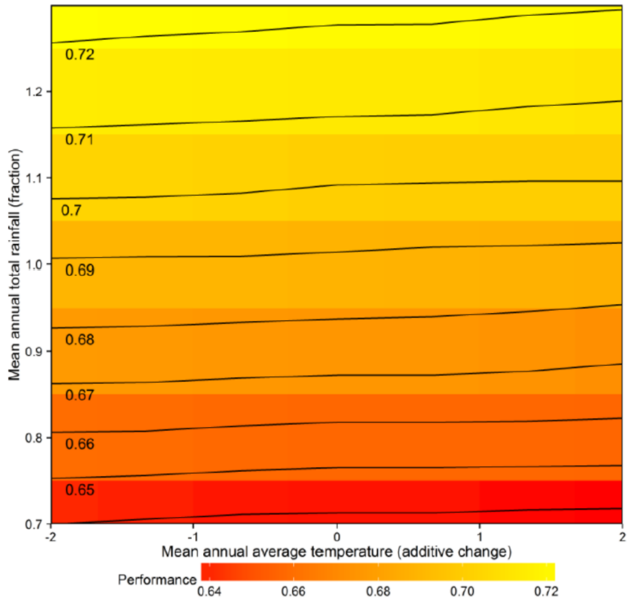
- Simple scaling: multiplicative/additive changes to observed climate time series
- Stochastic generation: time series are generated using a stochastic generator with the required properties

Next use all the sets of perturbed climate time series to drive the system model and generate the system performance measures.

Now you have collated the system performance for all sets of perturbed climate time series, visualize the system performance across the range of investigated changes as a system performance map.

Options for visualizing system performance maps include:

- Binary pass/fail regions (if the system has distinct performance thresholds)
- Heat maps/contours plots of the system performance



Example system performance map

The system’s response to the range of perturbed time series provides insight into the system’s sensitivity to changes in the climate variables and the characteristics of those variables (e.g. averages, extremes). Use the outcomes of this stress test for system diagnosis where unacceptable performance is encountered. A thorough understanding of the reasons for unacceptable system performance will be required in Step 4.

CHECK OUT POINT

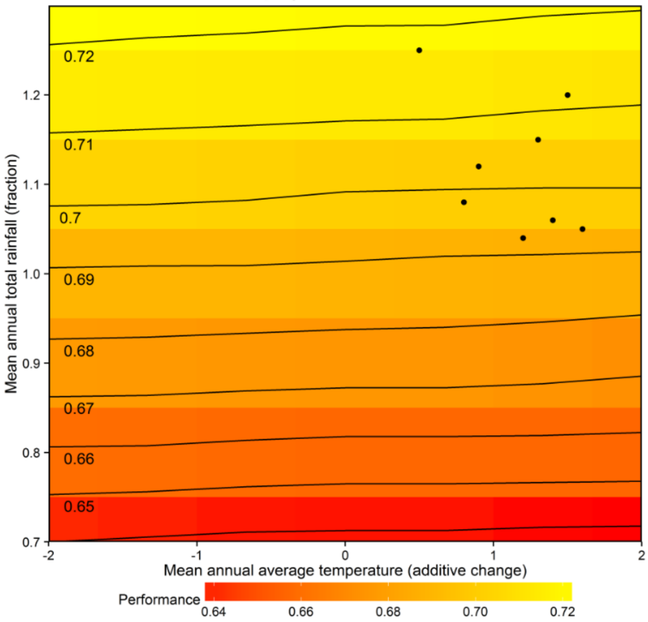
If you find your system is very resilient consult with your stakeholders to check if you need to proceed to Steps 3 – 5.

Outcomes: Quantitative understanding of the system and its sensitivities to climate variation

Step 3: Climate projections and other lines of evidence

In Step 2 you identified critical variables that affect the system's vulnerability. Now you can place this system understanding in context with climate projections from global climate models and other lines of evidence. This is done by superimposing the climatic changes projected by GCMs or other sources of climate information on to the system performance maps produced in Step 2.

Use the system sensitivities and thresholds at which the system is pushed beyond acceptable operating conditions uncovered in Step 2 as practical guidance on what information on projected change should be considered. This can be done in consultation with climate experts.



Selected climate projections shown as black dots on system performance map

CHECK IN POINT

This is a good time to consult the project stakeholders to see what time periods (e.g. time slices) are relevant to your system.

Now superimpose downscaled and bias-corrected GCM projections onto the system performance maps. This provides an indication of the plausibility of the climate conditions causing system failure.

Other sources of climate information relevant to the problem specifications can also be visualized, such as the observed historical climate variability, the limits of engineering specifications (e.g. 1-in-100 year floods from which the system may have been originally designed), expert knowledge, and/or paleo-climate information.

CHECK IN POINT

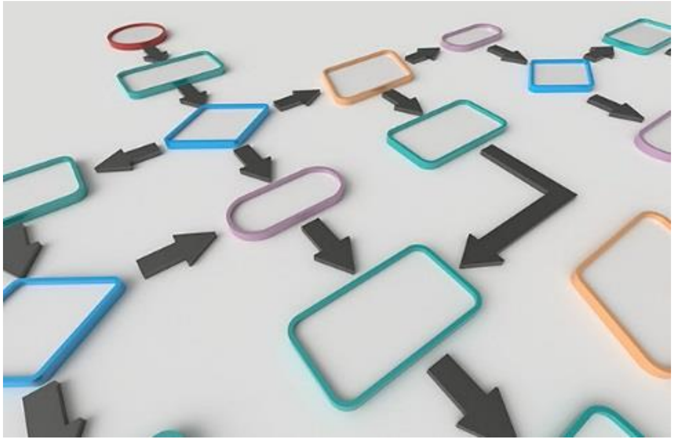
This is a good time to consult climate experts about possible change to key climate variables.

- How well do the climate models represent the processes and climate variables your system is most sensitive to?
- What other 'lines of evidence' would be useful in light of the sensitivities uncovered in Step 2

A key consideration is how to interpret alternative 'lines of evidence'. Whereas Step 2 involved stress testing the system against climate time series (or 'scenarios') that represent hypothetical alternative climate states, in this step we are concerned with identifying parts of the climate space that are more or less likely, for example through the use of projections from climate models. The question of whether or not different lines of evidence can be interpreted as probabilistic statements of the future has important implications on which decision making tools are most appropriate (Step 5), and particularly whether approaches that account for 'deep uncertainty' are needed.

Outcomes: System performance maps incorporating other lines of evidence

Step 4: System management options



This Step revisits the potential system management options and analyses each option in turn.

In Step 2 you gained a deeper understanding of the sensitivities and behaviour of the system. Here this deeper understanding and diagnosis of existing performance sensitivities becomes critical in evaluating system management options.

SYSTEM MANAGEMENT OPTIONS

Remember there may be a large number of alternative options to achieve the same objective. Some examples of options include:

- modification of operating rules
- system re-optimisation
- infrastructure augmentation
- economic signaling (e.g. modification of resource prices)

In light of the investigation in Step 2 reflect on the identified system management options identified in Step 1. If necessary iterate with your stakeholders/system operators.

CHECK IN POINT

Check in with your stakeholders regarding system management options.

Again this should be a creative and explorative process in which it is important to think laterally. It is useful to keep the problem definition developed in Step 1 in mind. It may be necessary to iterate on the problem definition or performance measures in Step 1 depending on the findings of Steps 2 and 3.

EXPLORATORY PROCESS

Examples of questions useful for this exploratory process include:

- What alternative system management options are available?
- Should a variation of operating rules be investigated?
- Should additional or alternative performance metrics be considered?
- How constrained is the system?
- Are any of the system management options similar in the treatment of the identified climate variables?

At the end of this exploratory process you should have an agreed set of system management options that require further evaluation.

At this point, you will need to repeat Steps 2 to 3 for all agreed system management options. At the end of this process you will have visualized the system performance as system performance maps incorporating other lines of evidence for each agreed system management option.

Outcomes: System performance maps incorporating other lines of evidence for all considered system management options

Step 5: Decision analysis

The final outcome of this Step is to arrive at a preferred option that can be implemented within the parameters identified in Step 1.

Based on the analysis carried out in Steps 2 to 4, the various system management options must be evaluated. This includes considering their feasibility, costs, benefits and potentially political will to investigate alternative infrastructure investments. There may also be a need to balance economic benefits with environmental and social values.

Use the system performance ‘stress test’ carried out in Step 2 alongside the alternate climate information overlaid in Step 3 to characterize system resilience. This way, it becomes more apparent which climate states will present the most challenges, and indicates how much change in climate can occur before the system is no longer able to provide the expected services. Combining this with the alternative options identified in Step 4, the conditions at which an option becomes preferable can be determined, enabling the development of adaptive pathways.

Questions that may assist in your decision analysis include:

- Under what conditions does a system management option become preferable?
- What are the trade-offs between system management options?
- Can an adaptation pathway be developed?

Decision-centric approaches can be tailored depending on whether alternate climate futures are interpreted probabilistically (in which case approaches such as cost-benefit analyses, and/or quantitative risk assessments may be appropriate) or as scenarios (in which case robustness approaches may be required). The scenario-based approach is becoming increasingly accepted given the recognition that climate models are unlikely to accurately represent multiple key physical processes that are likely to be relevant to a given system, requiring a focus on ‘what-if’ scenarios rather than ‘best estimates’ of future climate.

Regardless of the approach taken to decision making under uncertainty, the analysis in Steps 1-5 provides a holistic view of key modes of system vulnerability, a ‘multiple lines of evidence’ view of future climate, and a detailed exploration of alternative system design options that may increase system resilience. The combination of this information can form the basis for a final recommendation, which may include the ‘do nothing’ option, implementation of alternative system management options, or the identification of key trigger points at which action is required as part of an adaptive pathways approach.

CHECK OUT POINT

You’re done.

Outcomes: Assess system resilience across a range of system management options and determine final recommendations

Glossary

Adaptation

The process of adjustment to actual or expected future climate and its effects (IPCC, 2014).

Bottom-up approach

Bottom-up climate assessment begins in the vulnerability domain. It takes important system characteristics and local capacities into account before the sensitivity and robustness of possible adaptation options are tested against climate projections (e.g. GCM outputs).

Climate change

Climate change refers to a change in the climate's state that can be identified (e.g. via statistical tests) and that persists for an extended period, typically decades or longer (IPCC, 2014).

Climate projection

Climate projections are typically derived using climate models and are the simulated response of the climate system to a scenario of concentrations of greenhouse gases and aerosols or future emissions.

Deep uncertainty

The "condition in which analysts do not know or the parties to a decision cannot agree upon (1) the appropriate models to describe interactions among a system's variables, (2) the probability distributions to represent uncertainty about key parameters in the models, and/or (3) how to value the desirability of alternative outcomes" (Lempert et al., 2006).

Downscaling

The process by which coarse GCM climate projections are transformed into higher resolution climate information.

Global climate model (GCM)

GCMs are numerical representations of the global climate system that are based on the fundamental physical, biological and chemical properties of its components, the interactions of these components and feedback processes.

Resilience

The capacity of a system to cope with disturbance, hazardous event or trend, responding or reorganizing so as to still retain essentially the same function, structure, identity, and feedbacks as well as retaining capacities for adaptation (IPCC, 2014).

Top-down approach

Top-down approaches for climate impact assessment begin by downscaling climate model projections and then using these downscaled projections to drive various models in order to develop expectations for changes in hydrology, vegetation, social systems, etc.

Vulnerability

Vulnerability is the degree to which a system, or element of a system, may adversely react as a result of the occurrence of a hazardous event. This concept implies some risk combined with the system's ability to cope and the level of economic and/or social liability associated with an event's occurrence.

References and further reading

Adaptation

NCCARF (2017).CoastAdapt: Coastal Climate Adaptation Decision Support (C-CADS). National Climate Change Adaptation Research Facility, Gold Coast. (available online at https://coastadapt.com.au/coastal-climate-adaptation-decision-support-c-cads, accessed 13 November 2017).

Department of Environment, Water and Natural Resources (2012). Prospering in a changing climate: a climate change adaptation framework for South Australia (available online at http://www.environment.sa.gov.au/files/sharedassets/public/climate-change/prospering-in-a-changing-climate-adaptation-framework-sa.pdf, accessed 13 November 2017).

Haasnoot, M, J. H. Kwakkel, W.E. Walker and .J. ter Maat (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world, Global Environmental Change, Volume 23, Issue 2, 2013, Pages 485-498, ISSN 0959-3780, https://doi.org/10.1016/j.gloenvcha.2012.12.006.

Siebentritt, M. A. and M. Stafford Smith (2016). A User's Guide to Applied Adaptation Pathways Version 1, Seed Consulting Services and CSIRO (available online at www.adaptationpathways.net).

Wilby, R. L., and S. Dessai (2010) Robust adaptation to climate change, Weather, 65(7), 180–185.

Bottom-up

Brown, C., and R. Wilby (2012) An alternative approach to assessing climate risks, Eos Trans. AGU, 93(41), 401–402, doi:10.1029/2012EO410001.

Culley, S., S. Noble, A. Yates, M. Timbs, S. Westra, H. R. Maier, M. Giuliani, and A. Castelletti (2016), A bottom-up approach to identifying the maximum operational adaptive capacity of water resource systems to a changing climate, Water Resour. Res., 52, doi:10.1002/2015WR018253.

Ghile, Y. B., M. Ü. Taner, C. Brown, J. G. Grijsen, and A. Talbi (2014), Bottom-up climate risk assessment of infrastructure investment in the Niger River Basin, Clim. Change, 122(1–2), 97–110, doi:10.1007/s10584-013-1008-9.

Prudhomme, C., R. L. Wilby, S. Crooks, A. L. Kay, and N. S. Reynard (2010), Scenario-neutral approach to climate change impact studies: Application to flood risk, J. Hydrol., 390, 198–209.

Climate change

Intergovernmental Panel on Climate Change (2014), Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

CRAFT case studies and tools

Bennett, B., S. Culley, S. Westra, and D. Guo (2018) An R package for evaluating system performance and vulnerability under hydroclimate variability and change using a scenario-neutral approach (in prep).

Bennett, B., Culley, S., Westra, S., Guo, D. and Maier H. (2018) foreSIGHT: Systems Insights from Generation of Hydroclimatic Timeseries, R package version 0.9.6. Available from https://CRAN.R-project.org/package=foreSIGHT.\

Potter, N.J., Zhang, L., Bennett, B., Westra, S. (2018) Case study for Climate Resilience Analysis Framework and Tools (CRAFT): Managed aquifer recharge at Parafield Airport, Goyder Institute for Water Research Technical Report Series No. 18/03.

Decision scaling

Brown, C. (2011) Decision-scaling for robust planning and policy under climate uncertainty, World Resour. Rep., World Resour. Inst., Washington D.C. (Available online at http://www.worldresourcesreport.org.)

Brown C., Y. Ghile, M. Laverty and K. Li (2012) Decision scaling: Linking bottom-up vulnerability analysis with climate projections in the water sector. Water Resour Res 48:1–12, doi:10.1029/2011WR011212.

Poff, N.L., C.M. Brown, T.E. Grantham, J.H. Matthews, M.A. Palmer, C.M. Spence, R.L. Wilby, M. Haasnoot, G.F. Mendoza, K.C. Dominique and A. Baeza (2016), Sustainable water management under future uncertainty with eco-engineering decision scaling, Nature Clim. Change, 6(1), 25-34.

Turner, S.W.D., D. Marlow, M. Ekström, B. G. Rhodes, U. Kularathna, and P. J. Jeffrey (2014), Linking climate projections to performance: A yield-based decision scaling assessment of a large urban water resources system, Water Resour. Res., 50, 3553–3567, doi:10.1002/2013WR015156.

Robustness

Lempert, R. J., D.G. Groves, S.W. Popper and S.C. Bankes (2006). A general, analytic method for generating robust strategies and narrative scenarios. Management science, 52(4), 514-528, doi: 10.1287/mnsc.1050.0472

McPhail, C., H.R. Maier, J.H. Kwakkel, M. Giuliani, A. Castelletti and S. Westra (2018), Robustness metrics: How are they calculated, when should they be used and why do they give different results? Earth's Future, doi: 10.1002/2017EF000649 (accepted 19 Decmeber 2017).

Whateley, S., S. Steinschneider, and C. Brown (2014), A climate change range-based method for estimating robustness for water resources supply, Water Resources Research, 50(11), 8944-8961.

Stochastic generation

Guo, D., S. Westra, and H. R. Maier (2016), An inverse approach to perturb historical rainfall data for scenario-neutral climate impact studies, J. Hydrol., doi:10.1016/j.jhydrol.2016.03.025

Top-down

Chiew, F.H.S., Teng, J., Vaze, J., Post, D.A., Perraud, J.-M., Kirono, D.G.C., Viney, N.R. (2009) Estimating climate change impact on runoff across south-east Australia: method, results and implications of modelling method. Water Resour. Res., 45, W10414, doi:10.1029/2008WR007338

Acknowledgements

This work undertaken as part of the Goyder Institute 'Climate resilience analysis framework and tools' project (project number CA.16.01).

The Goyder Institute for Water Research is a partnership between the South Australian Government through the Department for Environment and Water, CSIRO, Flinders University, the University of Adelaide, the University of South Australia, and the International Centre of Excellence in Water Resource Management.