Chapter 6

Stress-Testing Adaptation Options

Robert L. Wilby

Abstract This technical contribution discusses ways of testing the performance of adaptation projects despite uncertainty about climate change. Robust decision making frameworks are recommended for evaluating project performance under a range of credible scenarios. Stress-testing options help to establish conditions under which there may be trade-offs between or even failure of project deliverables. Stress-tests may be undertaken for specified portfolios of management options, using models of the system being managed (including inputs and drivers of change), and then assessed against decision-relevant performance indicators with agreed options appraisal criteria. Field experiments and model simulations can be designed to test costs and benefits of adaptation measures. Simple rules may help to operationalize the findings of trials—such as ‘plant 1 km of trees along a headwater stream to cool summer water temperatures by 1 °C’. However, insights gained from field-based adaptation stress-testing are limited by the conditions experienced during the observation period. These may not be severe enough to represent extreme weather in the future. Model simulations overcome this constraint by applying credible climate changes within the virtual worlds of system models. Nonetheless, care must be taken to select meaningful change metrics and to represent plausible changes in boundary conditions for climate and non-climate pressures. All stress-testing should be accompanied by monitoring, evaluation and learning to benchmark benefits and confirm that expected outcomes are achieved.

Keywords Climate change · Adaptation · Stress test · Weather generator · Field experiments

R. L. Wilby (✉)

Geography and Environment, Loughborough University, Loughborough L11 3TU, UK

e-mail: r.l.wilby@lboro.ac.uk

© The Author(s) 2022

Climate Adaptation Modelling, Springer Climate,
https://doi.org/10.1007/978-3-030-86211-4_6

Introduction

How can we be confident that investments in adaptation projects will deliver intended benefits *despite* deep uncertainty about climate variability and change?

This technical contribution discusses ways of evaluating the performance of adaptation measures. However, it is important to begin by acknowledging that climate change is not the only risk faced by human and natural systems. There are also concerns about resource depletion, biodiversity loss, environmental degradation, and especially human health. These are being driven by profound changes in demography, technology, global trade, public debt and urbanisation. Agencies are grappling with all these ‘megatrends’ whilst at the same time striving to meet policy goals around social cohesion, economic prosperity, national security and environmental sustainability. Nexus concepts are helpful in exposing the trade-offs that exist between climate change and connected policy areas. For instance, the climate-water-food-energy nexus should frame national and global efforts to achieve net zero emissions *whilst* simultaneously adapting to unavoidable climate change. Hence, this paper emphasizes the importance of adaptation planning that is integrated and mindful of multiple drivers of environmental change—we must avoid what some term ‘climate exceptionalism’ in our thinking.

Another important point of departure is to recognize that all 17 themes of the United Nations Sustainable Development Goals are intrinsically water-related. The hydrological community has traditionally been solution-orientated, but our generation faces perhaps the greatest array of water challenges in human history (Wilby 2019: 1464). Hence, this paper unashamedly views adaptation through a water lens, notwithstanding the above call for integrated planning and assessment. The next section describes a framework that emphasizes clarity about intended adaptation and/or development outcomes from the start. Two ways of evaluating attendant adaptation measures and investments are then discussed. By such ‘stress-testing’ we are seeking to better understand how various options might perform under credible climate *and* non-climate scenarios of system change. Fortunately, new tools and techniques are being developed to enable this via dedicated field experiments and systems modelling—each will be discussed in turn. Finally, some concluding remarks and practical recommendations will be offered.

Robustness and Resilience Frameworks

Conventional approaches to adaptation begin with climate model information as the basis for planning. Unfortunately, this ‘predict-then-act’ framework is soon confounded by growing uncertainties at each stage of the analytical chain: from the emissions scenario, to climate model selection, regional downscaling techniques, impacts modelling, ending with adaptation options appraisal (Wilby and Dessai

2010). Faced by wide ranges of uncertainty in outcomes, decision-makers may be forgiven for taking no action, delaying investments, or calling for further information.

A more fruitful strategy is to first accept that uncertainty is a fact of life—it may be better *characterized* by more research but is seldom *reduced* to a point where there is certainty about the consequences of a future action. By embracing the uncertainty, we are satisficing rather than optimising investments: some say we are seeking to minimize regret or maximize resilience through robust decision making (Weaver et al. 2013). Hence, robustness and resilience frameworks focus on testing decisions; climate model information is applied much later in the workflow to identify conditions under which there may be trade-offs or even break-points in performance. By concentrating on project goals and understanding key vulnerabilities, it is possible to target time and resources in more productive ways (ADB 2020). In situations where adaptation is a secondary objective there could be scope for light touch climate proofing (e.g., designs and materials for roads that will be upgraded every 10 years or so). Where addressing climate risks is the primary objective, or where there are long-lived investments, with risk of lock-in, high levels of precaution, or major economic consequences, detailed assessment is warranted (e.g., coastal defences to protect infrastructure from rising sea levels).

Robust decision making frameworks for adaptation option appraisal typically comprise of four main elements. These are as follows: (1) portfolios of management options; (2) models of the system being managed (including inputs and drivers of change); (3) project performance metrics; and (4) options appraisal criteria. Moreover, decision-centric frameworks are participatory and iterative in ways that enable managers and analysts to reach a shared understanding of key system vulnerabilities and adaptation goals (Fig. 1).

Let us imagine that authorities and private sector organisations have the legal power and/or responsibility for delivering a service—such as reliable water supplies—over a planning horizon that is potentially vulnerable to climate change. Ideally, these actors and their stakeholders will co-develop a portfolio of management options such as water saving measures, new or upgraded reservoirs and water

Fig. 1 An adaptation option appraisal framework. Adapted from Yates et al. (2015)

transfer schemes, source protection, environmental flows, artificial recharge, effluent reuse, water allocation and pricing controls.

Physical experiments or system models (see below) can then be used to evaluate (i.e., stress test) how such measures or combinations of measures perform under specified scenarios of change. These drivers may describe the future in narrative or numerical terms, but they must be credible and internally consistent. For instance, a hotter-drier climate change scenario might imply vegetation die-back, wildfires, or more dust on snow episodes that favour earlier snowmelt and more rapid rainfall-runoff. In other words, the stress-testing may need to be multi-dimensional to gain a more comprehensive view of direct and indirect climate risks, as well as non-climate threats (e.g., Ray et al. 2018).

Measures of system behaviour should also be meaningful to the decision-making context. Any trade-offs between outcomes should be apparent, such as reduced flood risk to property but less frequent or extensive rejuvenation of floodplain habitats (e.g., Poff et al. 2015). Moreover, it may not be economically or technically feasible to manage impacts from most extreme scenarios, so plans are needed for managing ‘tolerable’ risks against adaptation costs (e.g., Borgomeo et al. 2016). Ideally, multiple co-benefits will be measured too.

Finally, control experiments or counterfactual simulations are needed to benchmark outcomes ‘with’ versus ‘without’ adaptation. Options may be appraised using cost–benefit analysis and various adaptation pathways may be considered to schedule measures according to emergent climate and non-climatic pressures on the system. This presupposes a commitment to long-term monitoring of relevant drivers, well-defined trigger points for decisions, with monitoring of adaptation outcomes (e.g., Gell et al. 2019). Project goals or priorities will likely evolve, so the whole adaptation framework must be dynamic and open-ended. The following section gives more detail on the physical experiments and systems models than can be used to stress-test options.

Stress-Testing Methods

Physical Experiments

Given deep uncertainty about regional climate change and impacts, adaptation measures are needed that are low-regret, evidence-based and likely to deliver co-benefits to people and/or the environment. Field trials can be an effective way of obtaining such evidence as well as demonstrating adaptations in practice (Wilby et al. 2010). This strategy has been successfully used before, such as when developing measures to counteract the harm caused by acid rain or commercial afforestation/deforestation to headwater ecosystems. However, field experiments can be time

and resource intensive, so they have to be carefully designed to test specific interventions—often using space-for-time substitutions to yield results quicker than the pace of climate change.

For example, the Loughborough University Temperature Network (LUTEN) was established in 2011 to test a superficially straightforward adaptation measure: riparian shade management to ‘keep rivers cool’ (Johnson and Wilby 2015). In practice, the efficacy of shading rivers depends on a host of factors, not least the season, the location and area of any tree-planting along the river network, choice of species, their rates of growth, channel dimensions relative to tree height, and amount of local shading by the landscape.

Hence, a high-density network of paired air and water thermistors was installed in the Rivers Dove and Manifold, Midlands, UK, to gather data on space–time variations in these primary variables. The initial 36 test sites were chosen to represent a wide range of catchment, channel and bankside conditions, including open moorland, heavily wooded and deep Limestone gorge sections. Downstream water temperatures are further influenced by weirs, tributaries, ephemeral and perennial springs.

Long-term monitoring with modelling of shade revealed that approximately 1 km of riparian tree cover would lower daily maximum water temperatures by 1 °C in summer (Johnson and Wilby 2015). Moreover, the benefit of shade (relative to open reference sites) is greatest under hotter/drier/sunnier conditions. For instance, when air temperatures (T_a) are 25 °C, T_w can be ~3 °C cooler at sites with 77% compared with 43% upstream shade (Fig. 2). Such a thermal benefit might appear modest, but this could be the difference between lethal/sub-lethal conditions for biota during heatwaves.

The detailed field surveys further revealed significant local cooling by spring flows in middle and lower reaches of the rivers. Cool refugia like these should be carefully protected from non-climatic pressures such as trampling by cattle and fine sediments, as part of a broader programme of measures. Practicalities around land ownership, cost-benefits and maintenance of the riparian zone have to be resolved too. Nonetheless, simple rules of thumb like ‘1 km for 1 °C’ help to operationalize the findings of the fieldwork.

Field experiments are ultimately constrained as a stress-testing tool by the range of weather conditions encountered during the period of observation (see: Wilby and Johnson 2020). Record homogeneity may also be affected by non-climatic changes.

Fig. 2 Daily maximum water temperature (T_w) estimates for partially shaded (left) and open (right) sites.

For example, since the LUTEN monitoring began, there have been relatively few hot dry summers (until 2019) under which the thermal benefits of shade could be observed. Weir removals from mid-reaches of the drainage network had meanwhile impacted local river flow depths and velocities. Hybrid empirical-models (such as the logistic function in Fig. 2) can be fit to field data then used to extrapolate conditions at sites under climate change (such as higher T_a), but there are a host of associated stationarity assumptions. Alternatively, plot-scale or laboratory experiments (e.g., mesocosms) can apply changes in temperature, rainfall, water quality and even carbon dioxide concentrations under controlled conditions to assess outcomes with and without adaptations. However, these kinds of trial may be limited by the number of permutations of factors that can be practicably explored.

Systems Modelling

Systems modelling offers another means of evaluating adaptation options plus scope for more comprehensive, integrated assessment of risks. The technique involves running simulations with and without adaptations, given varied inputs representing the range expected boundary conditions. For example, Yates et al. (2015) took down-scaled daily precipitation and temperature scenarios and then simulated the Denver Water, CO supply system using the Water Evaluation And Planning System (WEAP) with, and without, measures intended to protect reservoir storage during droughts. Hydrological model parameters were adjusted in line with climate scenarios to reflect potential changes in snowpack, land cover and soil properties. Accompany narratives described plausible drivers of the hydrology like ‘fewer cold winters reduce mortality amongst infecting beetle populations’ to adjust the vegetated area and evapotranspiration rate. With just three narrative scenarios it was shown that modest (but practically significant) adaptation benefits would be achieved.

Others implement more exhaustive stress-testing of adaptation measures, such as allowances (or headroom) for climate change in flood defence infrastructure (Broderrick et al. 2019), portfolios of options to reduce the probability of water use restrictions (Borgomeo et al. 2016), or raising levees and changing reservoir operations to reduce flood damages and meet ecological objectives (Poff et al. 2015). Response surfaces are typically produced by simulating performance metrics (e.g., change in 20-year flood) for a few dimensions of future climate ‘space’ (e.g., change in the mean and seasonality of precipitation) with climate model scenarios overlain to indicate likelihood (as shown in Fig. 3).

Methodological differences arise when specifying the variable(s) and credible range(s) of adjustments to these variables for stress-testing. To really expose system vulnerabilities to climate change, it may be necessary to look beyond changes to mean temperature and precipitation to more subtle shifts in seasonality, persistence or extreme weather (e.g. Culley et al. 2019). Plausible ranges for changes may be defined via stochastic weather generation of very large ensembles/rare events, or from the limits of widely adopted climate model ensembles (e.g. CMIP5 or CMIP6), via

Fig. 3 Response surfaces for changes (%) in 20-year flood magnitude with incremental changes in the mean (x axis) and seasonality (y axis) of the annual precipitation cycle for selected catchments in Ireland based on CMIP5 models and four Representative Concentration Pathways. Source: Broderick et al. (2019).

expert panels and meta-analyses, or by a combination of approaches. For example, H++ scenarios for heat waves, droughts, floods, windstorms and cold snaps were developed from climate change scenarios at the margins or beyond the 10th to 90th percentile range of the 2009 UK Climate Change Projections (Wade et al. 2015).

High-end H++ scenarios of sea level rise were initially used to stress-test adaptation pathways for flood risk management within the Thames Estuary 2100 Plan. Now, credible maximum sea level change scenarios are informing the planning and testing of designs for new nuclear build in the UK. Under these highly precautionary circumstances, transparency about lines of evidence and working assumptions is essential; governance structures are also needed to ensure periodic review of evolving science, especially around key uncertainties about future meltwater contributions to sea level rise from the Antarctic and Greenland ice sheets.

Conclusions and Recommendations

This technical contribution asserts that deep uncertainty about the future climate and other major drivers of global change are not impediments to adaptation planning and options appraisal *provided* that decision-led (rather than scenario-led) frameworks are implemented. Stress-testing of physical (field-based) or virtual (model-based) systems under climate change, with and without adaptation, can reveal the efficacy of adaptations, as well as key system vulnerabilities and residual risks. Expert elicitation and ranking of options performance under different storylines may also be applied but there was insufficient space to discuss qualitative methods here (see for example, Brown et al. 2015). Regardless of the approach taken, it is essential that portfolios of adaptation options and decision-relevant metrics are co-produced by analysts,

with competent authorities and stakeholders. These are effective entry points for stress-testing options.

Field experimentation is most informative when adaptation outcomes are observable under extreme weather or controlled laboratory conditions. Likewise, systems modelling credibility depends on plausible narratives of change with which to bound simulation inputs and model parameters. In either case, strong counterfactuals are needed to assess outcomes, especially where there are potentially confounding signals from non-climatic pressures. Stress-testing also requires long-term monitoring, evaluation and learning to benchmark performance metrics and to confirm that expected project outcomes are achieved. Additionally, further work will be needed to monetize climate risks and adaptation benefits.

References

- Asian Development Bank (ADB) (2020) Principles of climate risk management for climate proofing projects. ADB Sustainable Development Working Paper Series No.69. Metro Manila, Philippines
- Borgomeo E, Mortazavi-Naeini M, Hall JW, O'Sullivan MJ, Watson T (2016) Trading-off tolerable risk with climate change adaptation costs in water supply systems. *Water Resour Res* 52:622–643
- Broderick C, Murphy C, Wilby RL, Matthews T, Prudhomme C, Adamson M (2019) National assessment of climate change allowances for future flood risk using a scenario-neutral framework. *Water Resour Res* 55:1079–1104
- Brown I, Berry P, Everard M, Firbank L, Harrison P, Lundy L, Quine C, Rowan J, Wade R, Watts K (2015) Identifying robust response options to manage environmental change using an ecosystem approach: a stress-testing case study for the UK. *Environ Sci Policy* 52:74–88
- Culley S, Bennett B, Westra S, Maier HR (2019) Generating realistic perturbed hydrometeorological time series to inform scenario-neutral climate impact assessments. *J Hydrol* 576:111–122
- Gell PA, Reid MA, Wilby RL (2019) Management pathways for the floodplain wetlands of the southern Murray Darling Basin: lessons from history. *Rivers Res Appl* 35:1291–1301
- Johnson MF, Wilby RL (2015) Seeing the landscape from the trees: Metrics to guide riparian shade management in river catchments. *Water Resour Res* 51:3754–3769
- Poff NL, Brown CM, Grantham TE, Matthews JH, Palmer MA, Spence CM, Wilby RL, Haasnoot M, Mendoza GF, Dominique KC, Baeza A (2015) Sustainable water management under future uncertainty with eco-engineering decision scaling. *Nat Clim Chang* 6:25–34
- Ray PA, Bonzanigo L, Wi S, Yang YCE, Karki P, Garcia LE, Rodriguez DJ, Brown CM (2018) Multidimensional stress test for hydropower investments facing climate, geophysical and financial uncertainty. *Glob Environ Chang* 48:168–181
- Wade S, Sanderson M, Golding N, Lowe J, Betts R, Reynard N, Kay A, Stewart L, Prudhomme C, Shaffrey L, Lloyd-Hughes B, Harvey B (2015) Developing H++ climate change scenarios for heat waves, droughts, floods, windstorms and cold snaps. Committee on Climate Change, London, p 145
- Weaver CP, Lempert RJ, Brown C, Hall JA, Revell D, Sarewitz D (2013) Improving the contribution of climate model information to decision making: the value and demands of robust decision frameworks. *Wiley Interdis Rev Clim Change* 4(1):39–60
- Wilby RL (2019) A global hydrology research agenda fit for the 2030s. *Hydrol Res* 50:1464–1480
- Wilby RL, Dessai S (2010) Robust adaptation to climate change. *Weather* 65:180–185
- Wilby RL, Johnson MF (2020) Climate variability and implications for keeping rivers cool in England. *Clim Risk Manage* 30:100259

Wilby RL, Orr H, Watts G, Battarbee RW, Berry PM, Chadd R, Dugdale SJ, Dunbar MJ, Elliott JA, Extence C, Hannah DM, Holmes N, Johnson AC, Knights B, Milner NJ, Ormerod SJ, Solomon D, Timlett R, Whitehead PJ, Wood PJ (2010) Evidence needed to manage freshwater ecosystems in a changing climate: turning adaptation principles into practice. *Sci Total Environ* 408:4150–4164

Yates D, Miller KA, Wilby RL, Kaatz L (2015) Decision-centric adaptation appraisal for water management across Colorado's Continental Divide. *Clim Risk Manag* 10:35–50

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.