Coping with the wickedness of public policy problems: Approaches for decision-making under deep uncertainty

Kwakkel, JH; Haasnoot, M; Walker, WE

DOI
10.1061/(ASCE)WR.1943-5452.0000626

Publication date
2016

Document Version
Accepted author manuscript

Published in
Journal of Water Resources Planning and Management

Coping with the wickedness of public policy problems: approaches for decision-making under deep uncertainty

Jan H. Kwakkel (corresponding author)
j.h.kwakkel@tudelft.nl
+31 (0)15 27 88487
Faculty of Technology, Policy and Management
Delft University of Technology
Jaffalaan 5
2628 BX Delft, the Netherlands

Warren E. Walker
w.e.walker@tudelft.nl
Faculty of Technology, Policy and Management
Delft University of Technology
Jaffalaan 5
2628 BX Delft, the Netherlands

Marjolijn Haasnoot
Marjolijn.Haasnoot@deltares.nl
Deltares,
P.O. Box 177,
2600 MH Delft, the Netherlands

Faculty of Technology, Policy and Management
Delft University of Technology
Jaffalaan 5
2628 BX Delft, the Netherlands

In many planning problems, planners face major challenges in coping with uncertain and changing physical conditions, and rapid unpredictable socio-economic development. How should society prepare itself for this confluence of uncertainty? Given the presence of irreducible uncertainties, there is no straightforward answer to this question. Effective decisions must be made under unavoidable uncertainty (Dessai et al. 2009; Lempert et al. 2003). In recent years, this has been labeled as decision-making under deep uncertainty. Deep uncertainty means that the various parties to a decision do not know or cannot agree on the system and its boundaries; the outcomes of interest and their relative importance; the prior probability distribution for uncertain inputs to the system (Lempert et al. 2003; Walker et al. 2013); or decisions are made over time in dynamic interaction with the system and cannot be considered independently (Haasnoot et al. 2013; Hallegatte et al. 2012). From a decision analytic point of view, this implies that there are a large number of plausible alternative models, alternative sets of weights to assign to the different outcomes of interest, different sets of inputs for the uncertain model parameters, and different (sequences of) candidate solutions (Kwakkel et al. 2010).

Decision-making under deep uncertainty is a particular type of wicked problem (Rittel and Webber 1973). Wicked problems are problems characterized by the involvement of a variety of stakeholders and decision-makers with conflicting values and diverging ideas for solutions (Churchman 1967). What makes wicked problems especially pernicious is that even the problem formulation itself is contested (Rittel and Webber 1973). System analytic approaches presuppose a separation between the problem formulation and the solution. In wicked problem situations this distinction breaks down. Solutions and problem formulation are intertwined with each other. Depending on how a problem is framed, alternative solutions come to the fore; and, vice versa, depending on the available or preferred solutions, the problem can be framed differently. Even if there is agreement on the difference between observed and desired outcomes, rival explanations for the existence of this difference are available, and hence different solutions can be preferred. An additional factor adding to the wickedness is that decision-makers can ill afford to be wrong. The consequences of any decision on wicked problems can be profound, difficult if not impossible to reverse, and result in lock-ins for future decision-making. Planning and decision-making in wicked problem situations should therefore be understood as an argumentative process, where the problem formulation, a shared understanding of system functioning and how this gives rise to the problem, and the set of promising solutions, emerge gradually through debate among the involved decision-makers and stakeholders (Dewulf et al. 2005).

When even the problem formulation itself is uncertain and contested, planning and decision-making requires an iterative approach that facilitates learning

across alternative framings of the problem, and learning about stakeholder preferences and tradeoffs, all in pursuit of a collaborative process of discovering what is possible (Herman et al. 2015). Modeling and optimization can play a role in facilitating this learning. They can help in discovering a set of possible actions that is worth closer inspection, and make the tradeoffs among these actions more transparent (Liebman 1976; Reed and Kasprzyk 2009).

Under the moniker of 'decision-making under deep uncertainty', a variety of new approaches and tools are being put forward. Emerging approaches include (multi-objective) robust decision-making (Kasprzyk et al. 2013; Lempert et al. 2006), info-gap decision theory (Ben Haim 2001), dynamic adaptive policy pathways (Haasnoot et al. 2013), and decision scaling (Brown et al. 2012). A common feature of these approaches is that they are exploratory model-based strategies for designing adaptive and robust plans or policies. Although these frameworks are used in a wide variety of applications, they have been most commonly applied in the water domain, in which climate change and social change are key concerns that affect the long-term viability of current management plans and strategies. Liebman (1976) recognized that water resources planning problems are wicked problems in which modeling, simulation, and optimization cannot be straightforwardly applied. In recent years, this observation has been reiterated (Herman et al. 2015; Lund 2012; Reed and Kasprzyk 2009).

If decision-making under deep uncertainty is a particular type of wicked problem, to what extent do the recent methodological advances address some of

the key aspects of what makes wicked problems wicked? To answer this question, we look at two exemplary approaches for supporting decision-making under deep uncertainty — (multi-objective) robust decision-making and dynamic adaptive policy pathways. We first briefly outline each approach, and then discuss some of the ongoing scientific work aimed at integrating the two approaches. This sets the stage for a critical discussion of these approaches and how they touch on the key concerns of supporting decision-making in wicked problem situations.

Robust Decision-Making

Robust Decision-Making (RDM) (Lempert et al. 2006) emphasizes an iterative approach to planning in which candidate strategies are tested across a very large number of scenarios and, in light of insights gained from this model-based scenario analysis, candidate strategies can be improved. The overarching concern is with the development of a strategy that produces satisficing results in as large a set of scenarios as possible. In RDM, the first step is a generic policy analytic activity that aims at conceptualizing the system under study, the key uncertainties pertaining to the system, the main policy levers, and the outcomes of interest. The second step is case generation, or exploratory modeling (Bankes et al. 2013). In this step, the behavior of one or more models of the system under study is systematically explored across the identified uncertainties, and the performance of candidate strategies is assessed. The third step is scenario discovery (Bryant and Lempert 2010). Using statistical machine learning algorithms, the results of the exploratory modeling are analyzed to reveal the conditions under which strategies perform poorly. These conditions reveal

vulnerabilities of the strategies, in light of which they can be modified. The fourth step is tradeoff analysis, in which the performance of the different strategies are compared across the different outcome indicators, thus providing an additional source of information that can be used in redesigning strategies. The steps can be iterated until a satisficing robust strategy emerges.

Multi-objective Robust Decision-Making (MORDM) (Kasprzyk et al. 2013) is an extension of Robust Decision-Making that adds a multi-objective optimization search for solutions prior to performing the exploratory modeling and scenario discovery. The multi-objective optimization is used to generate a set of promising planning alternatives that illustrate the key tradeoffs on the relevant objectives. Robust Decision-Making is subsequently used to assess the robustness of each of these planning alternatives to a wide range of deeply uncertain futures. Kasprzyk et al. (2013) also discuss various visual analytics techniques that can be used to assess the tradeoffs across multiple objectives and the robustness of the various alternatives. A key point of the visual analytics is that both RDM and MORDM aim at facilitating a discussion among stakeholders and decision-makers, rather than dictating a single optimal solution (Singh et al. 2015).

RDM has been applied to strategic planning problems in a diverse set of fields, including economic policy (Seong et al. 2005), climate change (Lempert et al. 2003; Lempert et al. 1996), flood risk management (Fischbach 2010), sea level rise (Lempert et al. 2012), energy resource development (Popper et al. 2009), and water resources management (Groves 2005; Groves and Lempert 2007;

Lempert and Groves 2010; Matrosov et al. 2013; Matrosov et al. 2013). MORDM has been applied to water resources planning management (Herman et al. 2014; Kasprzyk et al. 2013) and ecosystem management (Singh et al. 2015).

Dynamic Adaptive Policy Pathways

The Dynamic Adaptive Policy Pathways (DAPP) (Haasnoot et al. 2013) approach is based on the concept that, in light of deep uncertainties about the future, one needs to design dynamic adaptive plans. Such plans contain a strategic vision of the future, commit to short-term actions, and establish a framework to guide future actions. It is a fusion of adaptive policymaking (Hamarat et al. 2013; Kwakkel et al. 2010; Walker et al. 2001) and adaptation tipping points (Haasnoot et al. 2012; Kwadijk et al. 2010; Offermans 2012).

The first step in DAPP is to describe the setting, including objectives, constraints, major uncertainties, and a definition of success, and to assess current and future vulnerabilities and opportunities. The specified uncertainties are used to generate an ensemble of plausible futures in the form of (transient) scenarios. Next, the conditions under which the status quo starts to perform unacceptably (adaptation tipping points) are assessed for the relevant uncertainties using expert judgment and/or model simulations. The timing of an adaptation tipping point ('use-by date') is derived from linking the use-by conditions with scenarios, or from the changing performance over time resulting from transient or semi-static model simulations. This reveals if and when policy actions are needed to reach the desired outcomes. Based on this problem analysis, policy actions are identified to address vulnerabilities and seize opportunities, and their conditions

and timing of adaptation tipping points is assessed based on their efficacy in reaching the desired outcomes over changing conditions or time. Once the set of policy actions is deemed adequate, alternative pathways can be designed and evaluated. A pathway consists of a concatenation of policy actions, where a new policy action is activated once its predecessor is no longer able to meet the definition of success. Based on the evaluation of the pathways, a manageable number of preferred pathways can be identified. These preferred pathways can be improved through contingency planning, which requires the specification of 'corrective', 'defensive', and 'capitalizing' actions, and an associated monitoring system with trigger values that would result in the implementation of the actions. In light of the final Adaptation Pathways Map, a plan for action can be made, which specifies the actions to be taken immediately, the developments to monitor, and when next actions of a pathway should be taken to stay on track of the preferred pathway.

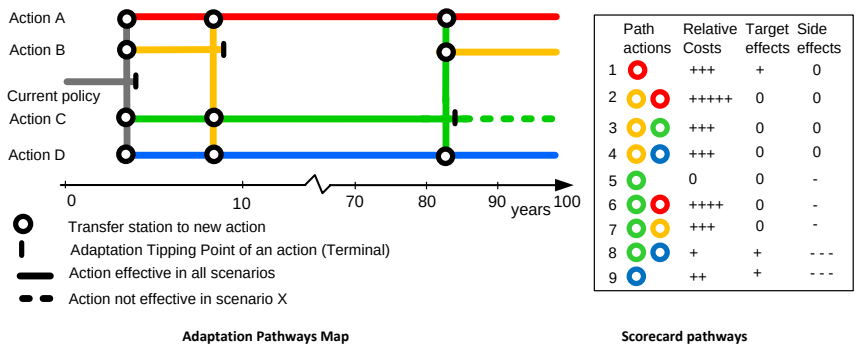

Figure 1 An example of an Adaptation Pathways Map and a scorecard presenting the costs and benefits of the 9 alternative pathways presented in the map (adapted from Haasnoot et al. 2013)

Figure 1 shows a stylized example of an Adaptation Pathways Map. In the map, starting from the current situation, targets begin to be missed after four years. Following the line of the current policy, one can see that, after four years, there

are four options. Actions A and D should be able to achieve the targets for the next 100 years in all climate scenarios. If Action B is chosen after the first four years, a tipping point is reached within about five years; a shift to one of the other three actions will then be needed to achieve the targets (follow the lines of action B). If Action C is chosen after the first four years, a shift to Action A, B, or D will be needed in the case of Scenario X (follow the solid line of action C). In all other scenarios, the targets will be achieved for the next 100 years (the dashed line of action C).

Adaptation pathways can be developed in a variety of ways. Haasnoot et al. (2012) systematically assess adaptation tipping points and explore options after an adaptation tipping point across a range of transient climate scenarios through simulations; Haasnoot et al. (2013) derive the pathways from expert judgment on adaptation tipping points; Haasnoot (2013) derives pathways from expert written storylines and game simulations, and Kwakkel et al. (2014) use a multi-objective robust optimization approach.

The adaptation pathway approach has been applied to a variety of cases. Most notably, it forms the underpinning of the Dutch Delta Programme (Delta Programme 2014) and it has been used in the Thames Estuary 2100 project (Reeder and Ranger online). Haasnoot et al. (2013) demonstrate the adaptation pathway approach with an example drawn from the Dutch Delta Programme focused on the Lake IJselmeer area in the Netherlands. Rosenzweig and Solecki (2014) adopt the notion of adaptation pathways to discuss climate adaptation in

New York after hurricane Sandy. Other applications are ongoing. For example, the approach is currently being used in Bangladesh and Indonesia.

RDM and DAPP in wicked problem situations

We have presented RDM and DAPP as two distinct approaches to supporting decision-making under deep uncertainty. There are, however, commonalities between the approaches. For example, both DAPP and RDM rely on a participatory scoping of the problem and the use of sets of scenarios to identify vulnerabilities. A vulnerability in the context of RDM is the set of uncertain developments under which a policy fails. This is closely related to the idea of an adaptation tipping point in DAPP. There are also complementarities between the approaches. RDM has a strong emphasis on the iterative process of scenario discovery and policy refinement. RDM is less well developed with respect to the architecture of policies that can be adapted over time. In contrast, DAPP focuses on the adaptive policy architecture, but is more open ended on how to design policies that fit this adaptive architecture. Hence, researchers are increasingly working on combining elements from both approaches (Groves et al. 2014).

Both RDM and DAPP emerged as planning approaches in the presence of deep uncertainty. Looking at these approaches in light of the characteristics of wicked problems, how well do they hold up?

Looking at the literature on RDM and MORDM, we observe that there is a strong focus on supporting deliberation through analysis. In an evaluative study of scenario discovery, Parker et al. (2014) found that scenario discovery is able to

summarize the information contained in a large ensemble of simulation runs in an easily understandable way. Users appreciated the ability to analyze tradeoffs, and found the results to be quite unambiguous. This ability to analyze tradeoffs is particularly apparent in the multi-objective extension to RDM, where the set of solutions found through optimization is not handled as the final set of possible solutions. Instead it offers a starting point for learning about the problem, about possible solutions, and about tradeoffs (Kasprzyk et al. 2013; Singh et al. 2015). If no clearly preferred solution is found, at least it is learned that the problem framing needs to be adapted. Moreover, the iterative process of policy refinement through modeling supports learning and computer-assisted reasoning (Bankes et al. 2001).

There are, however, several facets of wicked problems to which RDM does not offer a clear answer. RDM starts from the idea of scoping a problem by defining a system boundary and agreeing on outcomes of interest. Once these are set and models are developed or tuned to fit with this scoping, it will be hard and often expensive, although not impossible, to revise this in light of what is being learned. That is, RDM assumes substantial consensus among decision-makers and stakeholders on the system under study. It is therefore not surprising that RDM practitioners often stress the importance of using existing models that are accepted by the various decision-makers and stakeholders (Lempert et al. 2013). Another issue that is not extensively addressed in the RDM literature at present is the fact that, in many complex wicked problem situations, decisions are largely irreversible, there is no right to be wrong, and there is path dependency. RDM helps in reducing the scenarios under which an action fails with its iterative

improvement of the robustness of candidate actions, but does not provide detailed guidance on how to design plans that can be adapted over time, nor does it offer support for analyzing path dependency and lock-ins. It is exactly here that there exist complementarities with the DAPP approach, which focuses more strongly on making the path dependency between actions, and the presence or absence of lock-ins, more transparent.

Examining DAPP as an approach for supporting decision-making on wicked problems, there are several aspects that stand out. First, DAPP strongly emphasizes the importance of keeping multiple pathway options open to the future, which helps alleviate the irreversibility of decisions and reduces the risk of being wrong. Pathways make lock-ins transparent and help foster understanding of which options are left open given a certain choice now. Moreover, pathways specify future actions that can be taken if the initial actions prove to be insufficient. Second, some of the work on model-based support for the design of adaptation pathways has explicitly approached it as a multi-objective problem (Kwakkel et al. 2014), where support is focused on creating clarity with respect to tradeoffs among competing decision alternatives. Third, DAPP does not dictate a single solution; instead, it helps produce a map of possible routes into the future; and can, for example in combination with the Perspectives method (Offermans 2012; Offermans et al. 2011), present the consequences of different values and perspectives of stakeholders. In light of this, decision-makers and stakeholders can have an informed debate on which actions they would like to take in the future, with an awareness of how these actions might affect their solution space in the future.

There are several facets of wicked problems to which adaptation pathways are less well suited. Similar to RDM, DAPP assumes that the outcomes and system boundaries are largely uncontested. The process envisioned by DAPP also limits possibilities to change the system conceptualization over the course of the analysis. This is not impossible, but might be costly. Another less well-developed aspect is the computer-assisted learning about a problem that is one of the strengths of RDM. DAPP is substantially more open ended in the methods, tools, and techniques one can employ for supporting adaptation pathway design.

In conclusion, both RDM and DAPP address somewhat different aspects of what makes wicked problems wicked. RDM facilitates the analysis of tradeoffs and the iterative learning about a policy problem. DAPP helps in studying the reversibility of decisions and offers insight into future actions that can be taken if the initial actions prove to be insufficient. This suggests that research on combining RDM with DAPP is a fruitful direction for future work.

Both RDM and DAPP still struggle with the fact that, in many wicked problems, the problem definition itself is open to change and co-evolves with solutions that are suggested, and that rival system boundaries and conceptualizations may be present. In the context of model-based support for decision-making, a relatively precise and unambiguous system conceptualization is required, which can be at odds with the wicked nature of the problem under study. The exploratory modeling approach advocated for supporting decision-making under deep uncertainty (McInerney et al. 2012) can be used to at least partly alleviate this

concern. Kwakkel et al. (2013), for example apply scenario discovery using two models that represent substantially different conceptualizations of the system under study. Similarly, Auping et al. (2015) explore the consequences of alternative strategies for coping with societal aging using three distinct conceptualizations of how public support for societal aging policies develop. Pruyt and Kwakkel (2014) apply a similar multi-model approach to identify effective policies for reducing homegrown terrorism, where the three models are inspired by rival explanations for the emergence of homegrown terrorists. These examples demonstrate that it is at least technically feasible to handle multiple partially incommensurable system conceptualizations in a single exploratory modeling approach.

References

Auping, W., Pruyt, E., and Kwakkel, J. H. (2015). "Societal Ageing in the Netherlands: A Robust System Dynamics Approach." *Systems Research and Behavioral Science*, 32(4), 485-501.

Bankes, S. C., Lempert, R. J., and Popper, S. (2001). "Computer-Assisted Reasoning." *Computing in Science and Engineering*, 3(2), 71-76.

Bankes, S. C., Walker, W. E., and Kwakkel, J. H. (2013). "Exploratory Modeling and Analysis." *Encyclopedia of Operations Research and Management Science*, S. Gass, and M. C. Fu, eds., Springer, Berlin, Germany.

Ben Haim, Y. (2001). *Information-Gap Decision Theory: Decision Under Severe Uncertainty*, Academic Press, London, UK.

Brown, C., Ghile, Y., Laverty, M., and Li, K. (2012). "Decision Scaling: Linking Bottom-Up Vulnerability Analysis with Climate Projections in the Water Sector." *Water Resources Research*, 48(9).

Bryant, B. P., and Lempert, R. J. (2010). "Thinking Inside the Box: a participatory computer-assisted approach to scenario discovery." *Technological Forecasting and Social Change*, 77(1), 34-49.

Churchman, C. W. (1967). "Wicked problems. Guest editorial." *Management Science*, 14(4).

Delta Programme (2014). "Delta Programme 2015: Working on the delta."

Dessai, S., Hulme, M., Lempert, R. J., and Pielke jr, R. (2009). "Do We Need Better Predictions to Adapt to a Changing Climate?" *EOS*, 90(13), 111-112.

Dewulf, A., Craps, M., Bouwen, R., Taillieu, T., and Pahl-Wostl, C. (2005). "Integrated Management of Natural Resources: Dealing with Ambiguous Issues, Multiple Actors and Diverging Frames." *Water Science & Technology*, 52(6), 115-124.

Fischbach, J. R. (2010). "Managing New Orleans Flood Risk in an Uncertain Future using Non-Structural Risk Mitigation." Ph.D. Ph.D. dissertation, Pardee RAND Graduate School Santa Monica, CA.

Groves, D. G. (2005). "New Methods for Identifying Robust Long-Term Water Resources Management Strategies for California." Ph.D. Ph.D. dissertation, Pardee RAND Graduate School, Santa Monica, CA.

Groves, D. G., Bloom, E., Lempert, R. J., Fischbach, J. R., Nevills, J., and Goshi, B. (2014). "Developing Key Indicators for Adaptive Water Planning." *Journal of Water Resources Planning and Management*, 141(7).

Groves, D. G., and Lempert, R. J. (2007). "A New Analytic Method for Finding Policy-Relevant Scenarios." *Global Environmental Change*, 17, 73-85.

Haasnoot, M. (2013). "Anticipating Change - Sustainable Water Policy Pathways for an Uncertain Future." Ph.D. Ph.D. dissertation, Twente University, Enschede, the Netherlands.

Haasnoot, M., Kwakkel, J. H., Walker, W. E., and ter Maat, J. (2013). "Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world." *Global Environmental Change*, 23(2), 485-498.

Haasnoot, M., Kwakkel, J. H., Walker, W. E., and Ter Maat, J. (2013). "Dynamic Adaptive Policy Pathways: A New Method for Crafting Robust Decisions for a Deeply Uncertain World." *Global Environmental Change*, 23(2), 485-498.

Haasnoot, M., Middelkoop, H., Offermans, A., van Beek, E., and van Deursen, W. P. A. (2012). "Exploring pathways for sustainable water management in river deltas in a changing environment." *Climatic Change*, 115(3-4), 795-819.

Hallegatte, S., Shah, A., Lempert, R., Brown, C., and Gill, S. (2012). "Investment Decision Making Under Deep Uncertainty: Application to Climate Change." The World Bank.

Hamarat, C., Kwakkel, J. H., and Pruyt, E. (2013). "Adaptive Robust Design under Deep Uncertainty." *Technological Forecasting and Social Change*, 80(3), 408-418.

Herman, J. D., Reed, P. M., Zeff, H. B., and Characklis, G. W. (2015). "How should robustness be defined for water systems planning under change." *Journal of Water Resources Planning and Management*, 141(10).

Herman, J. D., Zeff, H. B., Reed, P. M., and Characklis, G. (2014). "Beyond optimality: multistakeholder robustness tradeoffs for regional water portfolio planning under deep uncertainty." *Water Resources Research*, 50(10), 7692–7713.

Kasprzyk, J. R., Nataraj, S., Reed, P. M., and Lempert, R. J. (2013). "Many objective robust decision making for complex environmental systems undergoing change." *Environmental Modelling & Software*, 42, 55-71.

Kwadijk, J. C. J., Haasnoot, M., Mulder, J. P. M., Hoogvliet, M. M. C., Jeuken, A. B. M., van der Krogt, R. A. A., van Oostrom, N. G. C., Schelfhout, H. A., van Velzen, E. H., van Waveren, H., and de Wit, M. J. M. (2010). "Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands." *Wiley Interdisciplinary Reviews: Climate Change*, 1(5), 729-740.

Kwakkel, J. H., Auping, W. L., and Pruyt, E. (2013). "Dynamic scenario discovery under deep uncertainty: the future of copper." *Technological Forecasting and Social Change*, 80(4), 789-800.

Kwakkel, J. H., Haasnoot, M., and Walker, W. E. (2014). "Developing Dynamic Adaptive Policy Pathways: A computer-assisted approach for developing adaptive strategies for a deeply uncertain world." *Climatic Change*.

Kwakkel, J. H., Walker, W. E., and Marchau, V. A. W. J. (2010). "Adaptive Airport Strategic Planning." *European Journal of Transportation and Infrastructure Research*, 10(3), 227-250.

Kwakkel, J. H., Walker, W. E., and Marchau, V. A. W. J. (2010). "Classifying and communicating uncertainties in model-based policy analysis." *International Journal of Technology, Policy and Management*, 10(4), 299-315.

Lempert, R. J., and Groves, D. G. (2010). "Identifying and Evaluating Robust Adaptive Policy Responses to Climate Change for Water Management Agencies in the American West." *Technological Forecasting and Social Change*, 77(6), 960-974.

Lempert, R. J., Groves, D. G., Popper, S. W., and Bankes, S. C. (2006). "A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios." *Management Science*, 52(4), 514-528.

Lempert, R. J., Kalra, N., Peyraud, S., Mao, Z., Tan, S. B., Cira, D., and Lotsch, A. (2013). "Ensuring robust flood risk management in Ho Chi Minh City." *Policy Research Working Paper*, 6465.

Lempert, R. J., Popper, S., and Bankes, S. (2003). "Shaping the Next One Hundred Years: New Methods for Quantitative, Long Term Policy Analysis." RAND, Santa Monica, CA, USA.

Lempert, R. J., Schlesinger, M. E., and Bankes, S. C. (1996). "When We Don't Know the Cost or the Benefits: Adaptive Strategies for Abating Climate Change." *Climatic Change*, 33(2), 235-274.

Lempert, R. J., Sriver, R. L., and Keller, K. (2012). "Characterizing Uncertain Sea Level Rise Projections to Support Investment Decisions." California Energy Commission, Sacramento, CA.

Liebman, J. C. (1976). "Some simple-minded observations on the role of optimization in public systems decision-making." *Interfaces*, 6(4), 102-108.

Lund, J. R. (2012). "Provoking More Productive Discussion of Wicked Problems." *Journal of Water Resources Planning and Management*, 138(3), 193-195.

Matrosov, E. S., Padula, S., and Harou, J. J. (2013). "Selecting portfolios of water supply and demand management strategies under uncertainty - contrasting economic optimisation and 'robust decision making' approaches." *Water Resource Management*, 27, 1123-1148.

Matrosov, E. S., Woords, A. M., and Harou, J. J. (2013). "Robust Decision Making and Info-Gap Decision Theory for water resource system planning." *Journal of Hydrology*, 494, 43-58.

McInerney, D., Lempert, R., and Keller, K. (2012). "What are robust strategies in the face of uncertain climate threshold responses." *Climate Change*, 112, 547-568.

Offermans, A. (2012). "Perspectives Method: towards socially robust river management." PhD., University of Maastricht, Maastricht, the Netherlands.

Offermans, A., Haasnoot, M., and Valkering, P. (2011). "A method to explore social response for sustainable water management strategies under changing conditions." *Sustainable Development*, 19(5), 312-324.

Parker, A. M., Srinivasan, S. V., Lempert, R. J., and Berry, S. H. (2014). "Evaluating simulation-derived scenarios for effective decision support." *Technological Forecasting and Social Change*.

Popper, S., Griffin, J., Berrebi, C., Light, T., and Min, E. Y. (2009). "Natural Gas and Israel's Energy Future: A Strategic Analysis Under Conditions of Deep Uncertainty." RAND, Santa Monica, California.

Pruyt, E., and Kwakkel, J. H. (2014). "Radicalization under deep uncertainty: a multi-model exploration of activism, extremism and terrorism." *System Dynamics Review*, 30(1-2), 1-28.

Reed, P. M., and Kasprzyk, J. R. (2009). "Water resources management: the myth, the wicked and the future." *Journal of Water Resources Planning and Management*, 135(6), 411-413.

Reeder, T., and Ranger, N. (online). "How do you adapt in an uncertain world? Lessons from the Thames Estuary 2100 project." *World Resources Report*Washington DC.

Rittel, H. W. J., and Webber, M. W. (1973). "Dilemmas in a General Theory of Planning." *Policy Sciences*, 4, 155-169.

Rosenzweig, C., and Solecki, W. D. (2014). "Hurricane Sandy and adaptation pathways in New York: Lessons from a first-responder city." *Global Environmental Change*.

Seong, S., Popper, S., and Zheng, K. (2005). "Strategic Choices in Science and Technology: Korea in the Era of a Rsing China." RAND, Santa Monica, CA.

Singh, R., Reed, P. M., and Keller, K. (2015). "Many-objective robust decision making for managing an ecosystem with a deeply uncertain threshold response." *Ecology and Society*, 20(3).

Walker, W. E., Lempert, R., and Kwakkel, J. H. (2013). "Deep Uncertainty." *Encyclopedia of Operations Research and Management Science*, S. Gass, and M. Fu, eds., Springer, Berlin, Germany.

Walker, W. E., Rahman, S. A., and Cave, J. (2001). "Adaptive Policies, Policy Analysis, and Policymaking." *European Journal of Operational Research*, 128(2), 282-289.