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Exploring scientific information for policy making under deep uncertainty

Laura G. Forni [a], [*], S.E. Galaitsi [b], Vishal K. Mehta [a], Marisa I. Escobar [a], David R. Purkey [a], Nicholas J. Depsky [a], Nilo A. Lima [c]

[a] *Stockholm Environment Institute, Davis, CA, USA*
[b] *Stockholm Environment Institute, Somerville, MA, USA*
[c] *Ministry of Environment and Water (MMAyA), Bolivia*

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ABSTRACT

Each actor evaluating potential management strategies brings her/his own distinct set of objectives to a complex decision space of system uncertainties. The diversity of these objectives and uncertainties requires detailed and rigorous analyses that respond to multifaceted challenges. The utility of this information depends on the accessibility of scientific information to decision makers. This paper demonstrates data visualization tools for presenting scientific results to decision makers in two case studies, La Paz/El Alto, Bolivia, and Yuba County, California. Visualization output from the case studies combines spatiotemporal, multivariate and multirun/multiscenario information to produce information corresponding to the objectives and uncertainties described by key actors. These tools can manage complex data and distill scientific information into accessible formats. Using the visualizations, scientists and decision makers can navigate the decision space and potential objective trade-offs to facilitate discussion and consensus building. These efforts can help identify stable negotiated agreements between different stakeholders.

1. Introduction

This paper describes a decision support tool that combines a scenario elicitation framework, simulation modeling, and decision space visualization within a participatory and interactive process for long-term water resources planning. Such long-term planning must account for uncertainties and imperfect knowledge about the future. Decision-making under uncertainty is a difficult process for several political, social and technical reasons (Lempert, 2003) and can overwhelm and even paralyze decision-makers without sufficient information (Pfaff et al., 2013). Stakeholders and water managers are facing new challenges within complex systems from shifting environmental conditions under climate change, water scarcity, drought, flooding, increased urban water demand, intensification of irrigated agriculture and groundwater use, to name a few (Arnell, 2004; Hunt and Watkiss, 2011; Joyce et al., 2011; Mehta et al., 2013; Vogel et al., 2015). Addressing these challenges requires a multi-criteria analysis framework that can represent the complexity of physical systems. Decision-making that incorporates diverse stakeholder objectives within computer modeling and innovative visualization as part of an iterative participatory process can facilitate tackling complex systems problems under uncertainty.

Representing changing system dynamics is especially important in cases of deep uncertainty regarding future conditions. Lempert (2003) defines cases of deep uncertainty as situations "where analysts do not know, or the parties to a decision cannot agree on, (1) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future, (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (3) how to value the desirability of alternative outcomes." This paper uses model output visualizations within participatory processes to address the deep uncertainty about the future state of the world defined by Lempert to support decision-making in complex systems.

It should be noted that, while the importance of model uncertainty on model-based decision-making is well established in the literature — e.g. Uusitalo et al. (2015) — the literature contains very few quantitative examples of its application, especially where

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[*] Corresponding author.
E-mail address: Laura.Forni@sei-us.org (L.G. Forni).

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deterministic models have been used in a decision-making context. Model uncertainty was not included in the modeling framework for the case studies described here.

To evaluate the potential adaptation options under deep uncertainty and within a complex system, one approach involves deploying multi-objective optimization models to find possible Pareto optimal decisions. Optimal strategies assume that sufficient future conditions are known, but for situations under deep uncertainty, even multi-objective optimization is not sufficient, because optimum solutions based on assumptions of uncertain futures may produce poor or unacceptable outcomes for other plausible trajectories (Mortazavi-Naeini et al., 2015). McInerney et al. (2012) liken this to “dancing on the top of a needle,” wherein optimal strategies lose their prescriptive value if they are sensitive to these uncertainties.

Simulation modeling can better represent human-induced changes such as climate change on environmental systems, and it can capture interacting subsystems such as agriculture, the urban sector, and politically-imposed environmental constraints — instream flow requirements and hydrological implications of conservation areas (Harou et al., 2009; Kasprzyk et al., 2013). Multi-component simulation models can represent the non-linearity of key variable changes in a system and the non-separable spatial and temporal dependencies (Dale et al., 2015; Girard et al., 2015; Kasprzyk et al., 2013; Reed and Kollat, 2012; Yates et al., 2005a).

According to Chandrasekaran (2005), handling deep uncertainties requires a shift in point of view from optimality to robustness to make the desired outcomes less sensitive to uncertainty. Robust adaptations “perform reasonably well compared to other strategies across a wide range of plausible scenarios” under an interactive exploration of those futures (Lempert, 2003). Even in cases of deep uncertainty, having results for a large set of plausible future scenarios within a systems model allows stakeholders to explore and assess the system risks (Calizaya et al., 2010; Groves et al., 2015; Groves and Lempert, 2007; Mahmoud et al., 2009; Pahl-Wostl and Hare, 2004). The Robust Decision-making framework, requires stakeholders to consider an ensemble of scenarios and identify adaptation strategies that are robust rather than optimal (Lempert, 2002; Lempert et al., 2006; Lempert and Collins, 2007).

By varying the factors that decision-makers can and cannot control, and combining these factors' possible trajectories, ensemble model runs produce a range of plausible futures. Within this range, decision-makers can explore model outcomes and identify actions they can implement to promote system robustness. Bossert (1998) called this “range of options available to decision-makers according to specific functional dimensions” the *decision space*. Hall et al. (2007) draw a distinction between the *situation space*, composed of facts about the situation, and the *decision space*, which presents information to compare options for influencing future outcomes. Pfaff et al. (2013) define the decision space as the range of options that includes the underlying mechanics of the interconnected factors influencing the options' relative desirability as well as the landscape of plausible futures to account for the inherent uncertainties of future conditions that could accompany any given course of action. Decision space exploration is used in many fields operating under uncertainty, such as military strategizing, (Chandrasekaran, 2005; Chandrasekaran and Goldman, 2007), urban planning for emergencies (Klein et al., 2009; Pfaff et al., 2013), organizational operations (Nyland et al., 2015), disease treatment selection (Pfaff et al., 2014) and natural resources management (Albert et al., 2015; Celino and Concilio, 2011; Mortazavi-Naeini et al., 2015).

Due to the increasing complexity and heterogeneity of scientific data, communication of key insights can benefit from new sophisticated visualization techniques (Booshehrian et al., 2012; Ji Soo Yi et al., 2007; Johnson and Rhyne, 2004; Keim et al., 2008; Rhyne et al., 2006; Tory and Moller, 2004). Scenario analysis using simulation models often produces multifaceted outputs through different means: 1) spatiotemporal (represents spatial structures and dynamic processes); 2) multivariate (consisting of multiple variables such as streamflows, reservoir storage, water demand satisfaction, and glacial area); 3) multimodal (from different data sources depending on the domain); and 4) multi-run (ensemble data from multiple simulation runs computed from varying parameters) (Kehrer and Hauser, 2013). To facilitate stakeholder participation in exploring the decision space for uncertain futures, visual analytics uses interactive, visual, and logical methods for the representation and communication of multifaceted data (Fu et al., 2015; Hauser, 2006; Kehrer and Hauser, 2013; Thomas and Cook, 2006).

This paper contributes to the literature by developing a visualization tool for decision support that aids knowledge exchange and participation within complex water management decision spaces in two case studies facing different water resources challenges. A Bolivian case study examined urban water management for the burgeoning metropolitan region of La Paz/El Alto, where water supply services cannot meet current demands. The second case study, in California's Yuba River basin, followed efforts to update the Integrated Water Resources Management (IWRM) plan through incorporating different water management actions and their impact on water supply, ecological conditions, and hydropower production objectives. In the case studies, stakeholders used Decision Space Visualizations (DSV) for interactive exploration of plausible futures and evaluation of robust adaptation options for long-term integrated water resources planning.

2. Methods

To effectively provide scientific information to policy makers, the information needs to respond to key actors' questions and be aligned to their existing conceptual model (Pahl-Wostl and Hare, 2004; Jakeman and Letcher, 2003; Liu et al., 2008; McNie, 2007; Vogel et al., 2015). The utility of complex scientific information depends on humans' ability to process that information effectively (Liu et al., 2008; McNie, 2007).

DSVs combine outcomes of a range of underlying factors into a single evaluative dimension (Pfaff et al., 2013). They integrate model outputs from multiple time steps into a single data form to provide a clearer representation of the overall effects of the underlying changes (Aigner et al., 2008, 2007; Andrienko et al., 2010; Kehrer et al., 2011; Kehrer and Hauser, 2013; Love et al., 2005; Matkovic et al., 2009). Under an established common analytical framework, a DSV process allows for the investigation of similarities and differences between scenario results for comparison and evaluation (Berger et al., 2011; Gleicher et al., 2011; Verma and Pang, 2004). DSVs provide an overview of relative robustness of options to empower stakeholders to better understand their choices, facilitating an open participation process that adds transparency to water management negotiations and decision-making.

The methodology employed in the case studies can be summarized in three steps. First, we solicited stakeholder participation to characterize their system's decision space using a problem framework called “XLRM” (Lempert et al., 2003), described in detail in Section 2.1. Second, the water system simulation model, WEAP (Section 2.2), was deployed to represent the futures of system performance using different inputs established in the first step. Third, a visualization tool was developed to represent, communicate, and interactively explore potential impacts of choices within the stakeholder-defined decision space to support the evaluation of