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Robustness-based evaluation of hydropower infrastructure design under climate change

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ABSTRACT

The conventional tools of decision-making in water resources infrastructure planning have been developed for problems with well-characterized uncertainties and are ill-suited for problems involving climate nonstationarity. In the past 20 years, a predict-then-act-based approach to the incorporation of climate nonstationarity has been widely adopted in which the outputs of bias-corrected climate model projections are used to evaluate planning options. However, the ambiguous nature of results has often proved unsatisfying to decision makers. This paper presents the use of a bottom-up, decision scaling framework for the evaluation of water resources infrastructure design alternatives regarding their robustness to climate change and expected value of performance. The analysis begins with an assessment of the vulnerability of the alternative designs under a wide domain of systematically-generated plausible future climates and utilizes downscaled climate projections *ex post* to inform likelihoods within a risk-based evaluation. The outcomes under different project designs are compared by way of a set of decision criteria, including the performance under the most likely future, expected value of performance across all evaluated futures and robustness. The method is demonstrated for the design of a hydropower system in sub-Saharan Africa and is compared to the results that would be found using a GCM-based, scenario-led analysis. The results indicate that recommendations from the decision scaling analysis can be substantially different from the scenario-led approach, alleviate common shortcomings related to the use of climate projections in water resources planning, and produce recommendations that are more robust to future climate uncertainty.

1. Introduction

Investments in water infrastructure typically involve tradeoffs between large capital costs and difficult-to-quantify delayed benefits ranked by current societal values, all subject to large uncertainties regarding future climatic, demographic, technological, and socio-economic conditions (Fankhauser et al., 1999; Pahl-Wostl, 2007; Jeuland, 2010; Furlong, et al. 2016). The design process for new water projects can be lengthy and highly complex, as such projects may often cause societal and environmental impacts, both positive and negative, that go well beyond the lifetime of the investment (Bednarek, 2001; Hallegatte, 2009; Hall et al., 2015). And though the complexities and uncertainties inherent in the design of new water infrastructure often warrant lengthy cautious discussion that delays investment, the world's poor living in conditions of high climate variability (e.g., in sub-Saharan Africa) suffer

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through the delays (Brown and Lall, 2006; Hall and Murphy, 2012; Strzepek et al., 2013; Groves et al., 2015). The primary purpose of this work is to improve the process of water infrastructure planning such that cost-effective, sustainable design alternatives can be more confidently identified and implemented considering climate variability and change.

The conventional modeling paradigms in water systems planning have assumed stationarity in long-term natural processes and estimated decision-relevant climate or hydrological statistics, for example, annual mean flow or 100-year flood from historical data (Hirsch, 2011; Jeuland and Whittington, 2014). This statistical information allowed planners to define generally few number of possible future states with known occurrence probabilities, and subsequently identify optimal or near-optimal project designs through expected utility maximization (Maas et al., 1962; Loucks et al., 1981; Wurbs, 1993; McInerney et al., 2012). However, recent evidence of climate change, including unprecedented changes in the precipitation patterns, and the frequency and intensity of storms, the timing and magnitude of surface runoffs has raised questions regarding whether water system planners shall continue to use stationarity-based methods, when making long-term, costly investment decisions (Milly et al., 2008, 2015; IPCC, 2013; Arnell and Lloyd-Hughes, 2014; Koutsoyiannis, 2014). There is now a general agreement that climate-related uncertainties in water planning are deep due to unknowable trajectories of future greenhouse gas emissions (O'Neill et al., 2014), natural variability dominating at decision-relevant time scales (Deser et al., 2012; Enserink et al., 2013), and our understanding of the how the biophysical systems would respond to climate change, particularly at finer scales needed for decision-making (Hawkins and Sutton, 2011; Forster et al., 2013; Hall, 2014).

Over the past few decades, growing concerns on the use of conventional planning methods have resulted in interest in new, risk-based planning approaches for better consideration of climate uncertainty in decision-making (Lempert et al., 2004; Brekke et al., 2009; Hall and Borgomeo, 2013; Kwakkel et al., 2016). As an initial response, many water system planners have focused on climate information from the coupled Atmosphere-Ocean General Circulation Models (AOGCMs, hereafter GCMs) to understand and assess the possible range of outcomes under climate change. This predict-then-act approach typically begins with selecting a subset of scenarios describing the state of future global development and demographic conditions, such as the Intergovernmental Panel on Climate Change (IPCC)'s "representative concentration pathways" (RCPs) (Moss et al., 2010). The selected set of scenarios is then evaluated through a subset of GCMs to assess the global climate response to greenhouse gas concentrations and then downscaled to a finer temporal and spatial resolution needed by the decision-makers. The downscaled climate projections are then evaluated through linked simulation models, e.g., hydrology, water quality, and reservoir operations to assess the outcomes of climate change. As a result, the findings of the predict-then-act analyses rely heavily on the probability distribution of climate or hydrologic variables that are affected by the subjective assumptions and the source of information defining the scenarios and modeling procedures (Dessai and Sluijs, 2007; Dessai and Hulme, 2009).

Decision-centric frameworks attempt to address the shortcomings of predict-then-act approach by shifting the emphasis from climate science modeling to climate vulnerability at the local level (Walker et al., 2013; Singh et al., 2014; Wise et al., 2014; Herman et al., 2015). These approaches use exploratory modeling to examine a broad range of outcomes under future climate uncertainty, then identify decision alternatives or management actions to reduce vulnerability to climate change. Vulnerability reduction can be expressed in various ways, for example by increasing the system's ability to perform adequately or acceptability under uncertainty (robustness), to adapt to changing conditions (flexibility), or to recover quickly from undesired states or failures (resiliency). Decision-centric frameworks typically apply structured sensitivity analyses to identify critical outcomes across a broad range possible futures, and commonly aim to cover extreme or surprise futures often described as 'black swans' (Taleb 2007). The decision rules employed in decision-centric frameworks are typically non-probabilistic and show a departure from the conventional, expected utility based decision rules to accommodate for greater risk-aversion. For example, they rank choices based on the worst possible outcome, *maximin* (Wald, 1950), a weighted score from the worst and best possible outcomes, *optimism-pessimism* (Hurwicz, 1951), or based on acceptable performance on a specified performance benchmark, *satisficing* (Simon, 1955).The most prominent decision-centric frameworks are Robust Decision Making (Groves and Lempert, 2007; Lempert and Collins, 2007; Bryant and Lempert, 2010), vulnerability-based or scenario-neutral planning (Prudhomme et al., 2010; Nazemi et al., 2013; Nazemi and Wheater, 2014), Info-Gap Decision Theory (Ben-Haim, 2006; Korteling et al., 2013), and decision scaling (Brown et al., 2011; Whateley et al., 2014).

It is common in both decision-centric frameworks and predict-then-act analyses that the scenarios defining the domain of plausible future climates are derived from GCM-based climate change projections. However, this *ex ante* use of climate projections presents potentially biased inputs, which potentially bias the evaluation of design or planning alternatives. The use of an ensemble of projections reveals the performance of designs for the futures those models happen to produce, which is not an unbiased representation of possible climate change (Stainforth et al., 2007; Weigel et al., 2010; Knutti et al., 2013), notwithstanding bias correction techniques, which map projections to historical conditions but do not address biases in projections of the future or sampling bias in the selection of GCMs used. The emission or concentration scenarios used in climate models incorporate numerous assumptions and subjective choices about how the future would unfold that cannot be verified. For example, all RCP scenarios from the IPCC's 5th Assessment Report assume a large reduction in the atmospheric aerosol emissions by the end of the 21st Century, which is argued to be too narrow (Stouffer et al., 2017). Also, many GCMs share basic structural assumptions, numerical schemes, and data sources, and consequently respond quite similarly to related models (Weigel et al., 2010; Knutti et al., 2013) leading to biases when viewed as independent realizations of possible future climate (Steinschneider et al., 2015a). They perform poorly in simulating interannual variability in precipitation (Brown and Wilby, 2012; Rocheta et al., 2014), the frequency and intensity of extreme events (Sillmann et al., 2013; Crétat et al., 2014), especially at fine scales relevant for the water system planners (Schiermeier, 2007). The choice of downscaling method (Pielke et al., 2012) and methodological challenges related to model calibration, e.g., model overfitting (Rougier and Goldstein, 2014) introduces additional concerns in the use of GCM projections in decision-making. Consequently, careful consideration is warranted in the sampling of future climate conditions in scenarios used for infrastructure design, whether