Global Environmental Change 48 (2018) 168–181

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Multidimensional stress test for hydropower investments facing climate, geophysical and financial uncertainty

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ARTICLE INFO

Keywords:
Climate change adaptation
Resilience
Water resources
Hydropower
Nepal
Himalayas

ABSTRACT

Investors, developers, policy makers and engineers are rightly concerned about the potential effects of climate change on the future performance of hydropower investments. Hydroelectricity offers potentially low greenhouse-gas emission, renewable energy and reliable energy storage. However, hydroelectricity developments are large, complicated projects and possibly critically vulnerable to changes in climate and other assumptions related to future uncertainties. This paper presents a general assessment approach for evaluating the resilience of hydroelectricity projects to uncertainty in climate and other risk factors (e.g., financial, natural hazard). The process uses a decision analytic framework based on a decision scaling approach, which combines scenario neutral analysis and vulnerability-specific probability assessment. The technical evaluation process involves identification of project objectives, specification of uncertain factors, multi-dimensional sensitivity analysis, and data mining to identify vulnerability-specific scenarios and vulnerability-specific estimations of risk. The process is demonstrated with an application to a proposed hydropower facility on the Arun River in Nepal. The findings of the case study illustrate an example in which climate change is not the critical future uncertainty, and consequently highlight the importance of considering multiple uncertainties in combination.

1. Introduction

There is increasing interest in the development of hydropower as a source of renewable, clean energy able to increase the penetration of other renewables as a result of its ability to store energy and supply reliable baseload. The hydropower opportunities left undeveloped since the 1970s are being re-evaluated due to a combination of the increase in global energy demand (population growth coupled with increasing per capita electricity demand) and the urgent need to decrease greenhouse gas emissions (Zarfl et al., 2015). As a partial solution to the shortfall of renewable energy, hydropower holds great promise: existing hydropower generation capacity is sufficient to supply the electricity needs of one billion people, and only approximately a quarter of its global potential has so far been developed (World Energy Council, 2016).

Thirty-six gigawatts (GW) of new hydropower capacity were added worldwide in 2014, and 33 more were added in 2015, bringing the global installed capacity to over 1200 GW (IHA, 2016). Still, particularly vast hydropower resources remain untapped in the Indus, Ganges, and Brahmaputra river basins of south Asia (Rasul, 2014; Ray et al., 2015). In Africa, likewise, developed hydropower capacity is approximately 14 GW (Cervigni et al., 2015), or less than 8% of the 1900 GW of hydropower potential (World Bank, 2009). Six hundred and forty five million Africans have no access to electricity (IHA, 2016), but hydropower project development spending has fallen victim to a continent-wide infrastructure funding gap (Foster and Briceño-Garmendia, 2010). In some countries of Latin and South America, much of the economically exploitable hydropower has been developed (e.g., Uruguay, Venezuela), but in other countries the bulk of hydropower potential remains untapped (e.g., Brazil, Costa Rica, Chile, Colombia, Ecuador, Peru) (World Energy Council, 2013). Overall, there remains an estimated 430 GW of unexploited hydropower potential in the Latin American region (IHA, 2016).

Concerns slowing the adoption of hydropower worldwide (with the notable exception of China, which now produces approximately a quarter of the world's hydropower (OECD IEA, 2015)) are often linked

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https://doi.org/10.1016/j.gloenvcha.2017.11.013
Received 1 January 2017; Received in revised form 24 November 2017; Accepted 28 November 2017

to doubts about the long-term resilience of hydropower facilities in a changing climate (Mukheibir, 2013; van Vliet et al., 2016). Because of the large capital costs required, as well as up-front social costs (e.g., population displacement) and environmental costs (e.g., flooding of critical habitat), potential regrets associated with investments in hydropower, among all possible energy sector investments, are high. Confidence that hydropower facilities will operate long into the future with performance at or near design performance must be correspondingly high to justify investment. The 2016 Hydropower Status Report of the International Hydropower Association (IHA, 2016) dedicates a chapter to the subject and describes climate-specific resilience in three ways: 1) the ability to recover after an external stressor or extreme event; 2) the capability to succeed in an environment dominated by uncertainty; and 3) the capacity of a facility or system to withstand or adjust to the possible impacts of climate change.

A number of studies have explored the climate change resilience of hydropower by evaluating basin-wide changes in hydropower generation potential in the context of changes in hydrology and water resources (e.g., Beyene et al., 2010; Bharati et al., 2014; Christensen et al., 2004; Christensen and Lettenmaier, 2007; Finger et al., 2012; Giuliani et al., 2016; Grumbine et al., 2012; Hamlet et al., 2010; Ho et al., 2016; Lehner et al., 2005; Majone et al., 2016; Markoff and Cullen, 2008; Maurer et al., 2009; Mehta et al., 2011; Minville et al., 2009; Schaefli et al., 2007), the ability of diminishing glaciers to continue to sustain baseflows on which run-of-river hydropower facilities rely (Bolch et al., 2012; Shrestha and Aryal, 2011), the vulnerability of hydropower structures to glacier-lake outburst floods (Dussaillant et al., 2010), and the impact of seasonality shifts on hydropower timing (Laghari et al., 2012; Madani and Lund, 2010; Sharma and Shakya, 2006). Some have found substantial evidence of the effects of climate change on hydropower already: Destouni et al. (2013) in northern Europe; Hanshaw and Bookhagen (2014) in the Andes, Peru; and Sorg et al. (2012) in Central Asia.

There are important limitations in the ability of these previous studies to inform risk-management aspects of hydropower investment. All of the coupled hydrologic-hydropower models cited in the previous paragraph used as climate input the output from general circulation models (GCMs) from the Intergovernmental Panel on Climate Change (IPCC) Coupled Model Intercomparison Project (CMIP), with the exception of Mehta et al. (2011), which used a scenario of 2 ° warming in the Sierra Nevada, California. Some assessed only streamflow without investigating the facility itself (e.g., Ho et al., 2016; Minville et al., 2008), thereby not identifying the vulnerabilities of hydropower to climate change in a systematic way. Even where infrastructure models have been involved, the results have been contingent on the projections and downscaling method that happened to be used. In many cases, these studies based their conclusions regarding climate change vulnerability on model results forced with only one or two climate change scenarios. By not systematically exploring climate change vulnerabilities, each leaves unanswered the question of greatest concern to policy-makers grappling with the potential risks and rewards of hydropower investment.

Furthermore, risks to hydropower investment are not limited to climate change. Recent studies have found that capital cost overruns (Ansar et al., 2014) and electricity selling price (Gaudard et al., 2016) are key concerns for hydropower investors. Other non-climate-change risks are due to earthquakes, landslides, other natural disasters, or military action, with associated risks of dambreak and flood surge to inhabitants and structures downstream (Benn et al., 2012; Dai et al., 2005; Dussaillant et al., 2010; Peng and Zhang, 2012; Richardson and Reynolds, 2000), and storage loss from sediment accumulation (Annandale, 1987; Castillo et al., 2015; Wild et al., 2016). It is clear that hydropower investment would benefit from a comprehensive assessment of the uncertain factors that potentially impact the benefits and costs of hydropower investments.

Previous studies have presented tools for multidimensional sensitivity analysis (Lempert et al., 2006, 2003) and applied those tools to water systems planning (e.g., Groves and Lempert, 2007; Kasprzyk et al., 2013; Kwakkel et al., 2016); however, those studies are not targeted at hydropower, and none have demonstrated a multidimensional stress test framework that addresses the shortcomings of GCM-led climate change risk assessments. Groves et al. (2015) performed project-scale climate change vulnerability analysis on five hydropower projects planned for sub-saharan Africa, and noted that the sensitivity of the performance of two of the projects to hydropower selling price may be more significant than to climate change, but did not evaluate the relative vulnerabilities quantitatively. Kucukali (2011) presents a multidimensional risk assessment for hydropower projects that does not address climate change risks, while Kubiszewski et al. (2013) presents a process for multidimensional risk assessment of hydropower systems that gives only cursory attention to climate change through the inclusion of a narrow set of prescribed climate change scenarios. Yang et al. (2016) evaluated risks to the water-energy-food nexus of the Brahmaputra river basin, including a thorough treatment of climate change risks, but did not address risks to hydropower investments, in particular, or present a generalized methodology.

The process described in this paper assesses multidimensional risk to hydropower investments including cost, selling price, discount rate uncertainty, natural hazards (e.g., landslide, earthquake), sediment damage to turbines, and a bottom up approach to climate change risks. The process integrates simulated results from coupled climatic, glaciological and hydrological models, informed by data from in situ and remote-sensing based measurements, that are bottom-up and site-specific. To those elements is added an infrastructure model to evaluate the resilience of hydropower facilities that is responsive to changes in both climate- and non-climate factors. A stress-testing approach applied to the model chain, coupled with a data mining algorithm, allows for identification of the relative significance of risks of different types to the project. Once the project vulnerabilities are identified, adaptation options can be quantitatively evaluated.

The manuscript is organized as follows: Section 2 describes the process, Section 3 demonstrates the process through an evaluation of a proposed hydropower project in the Arun river basin of Nepal, and Section 4 presents areas for further research and concludes.

2. Methods

The risk management framework presented in this paper was developed in response to a recent mandate of the World Bank that all International Development Association (IDA) Country Partnership Frameworks must include climate- and disaster-risk considerations in the analysis of the country's development priorities, and, when agreed upon with the country, incorporated into the content of the development programs. This mandate did not specify the means by which climate change risks should be assessed, and no consensus existed on the appropriate process. Context was provided, however, by the Independent Evaluation Group of the World Bank, which found that "climate models have been more useful for setting context than for informing investment and policy choices," and concluded that the prominent applications of climate change projections to infrastructure performance analysis "often have relatively low value added for many of the applications described" (IEG, 2012).

In response, a clear process for demonstrating the resilience of a water system investment to climate, geophysical and economic uncertainty was presented in Ray and Brown (2015). The process adopts bottom up decision scaling techniques (Brown et al., 2012) for climate change risk assessment, and provides guidance on methods for risk management. The process presented in Ray and Brown (2015) is structured as a decision tree or decision flow that leads the analyst to a particular analytical method based on the characteristics of the project being investigated. The procedure consists of four successive phases: Phase 1 Project Screening; Phase 2 Initial Analysis; Phase 3 Stress Test;