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Assessing strategies for protecting transportation infrastructure from an uncertain climate future

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ABSTRACT

This paper investigates the importance of explicitly considering the stochastic nature of future climate impact predictions and predictive accuracy for optimal investment planning in the protection of coastal and inland transportation infrastructure against climate impacts. Such impacts include sea level rise, coastal and riverine flooding resulting from more frequent and intense precipitation events, storms, storm surges and other extreme events. For this purpose, numerical experiments utilizing stochastic optimization based methodologies were conducted on a case study of the Washington, D.C. Greater Metropolitan area proximate to the Potomac River under varying climatic predictions. Results from the numerical experiments suggest a 54% reduction in added costs due to the implementation of chosen protective infrastructure investments. They also indicate a reduction in added costs (capital investment and added delays) on the order of 19% when the investments are chosen to hedge against probable future flooding events as compared with planning for the 50th percentile SLR prediction with associated weather events. A potential gain of nearly 27% in reduced costs through improved predictive accuracy in climatic forecasts is also noted, suggesting significant value in more accurate forecasts.

1. Motivation

Sea level rise (SLR) along with more frequent, intense hydrometeorological events resulting from changes in climate, e.g. increase in urban stormwater runoff volume (Alamdari et al., 2017), can affect the performance of critical infrastructure systems, including vehicular roadway and intermodal freight networks. These changes especially affect those infrastructure elements located in close proximity to a shoreline or river, where they are more frequently impacted by coastal or inland flooding. Such flooding events affect not only daily performance as a result of temporary inundation of links, but long-term structural stability as a consequence of, for example, erosion of their foundations.

Protective measures can be taken to reduce the potentially devastating consequences of climate change on this infrastructure. In the context of the transportation system, building seawalls, raising transportation elements, and improving the drainage of roadways are among mitigative actions considered in many communities (National Research Council, 2010). More recently, innovations in the implementation of green infrastructure have provided alternative, sustainable options (Gill et al., 2007). However, protecting all transportation infrastructure elements from any flood would be cost prohibitive as actions taken on even one element can require significant capital investment. As the underlying phenomena from which future flooding events are derived are complex and not perfectly understood, rather than providing exact projections, predictions are given in the form of continuous probability distributions or as potential scenarios with frequencies. Parris et al. (2012) encourage the use of multiple scenarios for taking future coastal

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management decisions. They argue that considering only the most probable outcome may result in the loss of vulnerable assets. Thus, there is a need for investments to be targeted and to hedge against probable future SLR and flooding event scenarios.

Ebinger and Vandycke (2015), as well as many others (CCSP, 2008; Chambwera et al., 2014; Dewar and Wachs, 2008; Schwartz, 2010), argue that in developing future programs for the transport sector, climate change should be explicitly considered. They further recognize the importance of accounting for uncertainty in future climate conditions in prioritizing investments and developing policies. They assert that investments should be made to reduce potential future damages, prevent disruptions and lessen costs associated with recovery. CCSP (2008) points out the need for new investment planning methodologies that enable the incorporation of uncertainty in magnitude, timing and impact of climate change effects in optimal decision making. They argue that the current, standard deterministic methods are inadequate and ill-informed in providing decision makers with suggested actions. The permanent impact of SLR on the infrastructure is contrasted with the more temporary impacts of other hazards of anthropogenic or natural cause in Dewar and Wachs (2008). Dewar and Wachs (2008) also suggest that methodologies are needed to help decision making under uncertainty for this application.

Few works quantify impacts of uncertain flooding or SLR on society. Eijgenraam et al. (2014) analyzed the effectiveness of protective actions in reducing societal costs. Specifically, their paper presents a normative model to optimize flood-protection standards for building shoreline levees and seawalls. Lu et al. (2012) show the effectiveness of protective actions in reducing total capital and effected land-use costs. They emphasize the importance of considering extreme values in long-term planning. Among these quantitative works, only a few considered the impacts on transportation system performance. Specifically, Suarez et al. (2005) studied the impact of SLR and related flooding events on transportation network performance. By accounting for the changes in demographics and land use due to SLR, they showed a doubling in delays and lost trips over the 21st century. Lu et al. (2012) take the stochasticity of climate change predictions into account in their cost-benefit analysis of a set of proposed, high-level mitigative actions (total shoreline protection, protection plus accommodation, accommodation plus transportation infrastructure protection) for the city of Tampa Bay, while Lu and Peng (2011) consider multiple future climate projections in a vulnerability assessment of roadway infrastructure. Finally, a bi-level, multi-stage stochastic optimization formulation and developed solution methodology were proposed in previous work by the authors (Asadabadi and Miller-Hooks, 2017). These mathematical-based tools consider both direct and indirect impacts for different combinations of timing, location, type and extent of protective investments whose implementations seek to hedge against future flooding uncertainty. This solution approach integrates multi-temporal decisions and explicitly considers multiple future SLR trends and probabilistic precipitation scenarios. This tool is employed in the analyses herein.

While numerous works purport the importance of considering uncertainty in adaptation planning for climate change impacts on transportation networks, and even some works give methodologies for this purpose, no prior work has quantified the importance of considering uncertainty in this context. Moreover, no work in the literature has analyzed the effect of prediction accuracy on investment planning outcomes nor has any work quantified the importance of more accurate predictions for these applications. This paper seeks to fill this gap.

This paper investigates the importance of explicitly considering the stochastic nature of future climate impact predictions and predictive accuracy in transportation and shoreline infrastructure investment planning to mitigate the negative effects of climate change on roadway system performance. It considers both direct and indirect impacts for different combinations of timing, location, type and extent of protective investments whose implementations seek to hedge against future uncertainty. To this end, the paper seeks answers to several questions: (1) What are the long-term costs of a no-investment strategy? (2) How might the system perform if investments are made for one future scenario, but a different scenario is realized, e.g. plans are devised for the most likely scenario, but more devastating sea levels arise? (3) What is the value of making investment decisions such that they hedge against multiple possible futures? (4) How much improvement in investment effectiveness can be gained through accurate prediction? (5) How does investment in only a subset of optimally selected projects impact performance? To answer these and other related questions, optimal or near-optimal investment strategies are studied and compared under high, low and average predictions of future SLR estimates and related flooding events for a real-world based case study involving the Washington, D.C. Greater Metropolitan area proximate to the Potomac River.

By quantifying losses or gains incurred from *no planning* (i.e. no investments but a range of future scenarios), planning for the minimum threat or 5th percentile of SLR and associated flood predictions (*minimal planning*), planning for the most likely future or 50th percentile of predictions (*conventional planning*), planning for the worst-case scenario or 95th percentile predictions (*robust planning*), and *planning for uncertainty* (i.e. hedging against a range of future scenarios), government agents concerned with maximizing societal benefits can consider the risks and consequences of their decisions. Their decisions can range from inaction to overspending. The results can also help governmental agencies that fund scientific research to assess the necessity for more accurate future climatic forecasts. Before proceeding to the case study, an overview of the mathematical tools employed in this investigation is given.

2. Solution framework

The problem of choosing the type, timing and extent of roadway and coastal infrastructure investment over a long-time horizon (e.g. 40–60 years) is modeled as a bi-level, multi-stage, stochastic, mixed-integer program. This bi-level conceptualization enables the modeling of system user response (drivers in the lower-level) to government investment decisions taken in the upper level. Drivers are assumed to choose their routes such that a user equilibrium (UE) will be reached given a network configuration determined by both the scenario (realization of uncertain parameters) and decisions taken at the upper level. The time horizon is divided into shorter time periods or stages. Protective and remedial investments at midpoints within any stage along this time horizon are modeled through

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