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Simulated climate adaptation in storm-water systems: Evaluating the efficiency of within-system flexibility

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ABSTRACT

Changes in regional temperature and precipitation patterns resulting from global climate change may adversely affect the performance of long-lived infrastructure. Adaptation may be necessary to ensure that infrastructure offers consistent service and remains cost effective. But long service times and deep uncertainty associated with future climate projections make adaptation decisions especially challenging for managers. Incorporating flexibility into systems can increase their effectiveness across different climate futures but can also add significant costs. In this paper we review existing work on flexibility in climate change adaptation of infrastructure, such as robust decision-making and dynamic adaptive pathways, apply a basic typology of flexibility, and test alternative strategies for flexibility in distributed infrastructure systems comprised of multiple emplacements of a common, long-lived element: roadway culverts. Rather than treating a system of dispersed infrastructure elements as monolithic, we simulate "options flexibility" in which inherent differences in individual elements is incorporated into adaptation decisions. We use a virtual testbed of highway drainage crossing structures to examine the performance under different climate scenarios of policies that allow for multiple adaptation strategies with varying timing based on individual emplacement characteristics. Results indicate that a strategy with options flexibility informed by crossing characteristics offers a more efficient method of adaptation than do monolithic policies. In some cases this results in more cost-effective adaptation for agencies building long-lived, climate-sensitive infrastructure, even where detailed system data and analytical capacity is limited.

1. Introduction

If infrastructure managers accept that the hydro-climatology for which they must design, build, and maintain, is non-stationary, as much of the climate science literature now urges (Gibbs, 2012; Milly et al., 2008; Olsen, 2015; Donat et al., 2016), the question remains as to how and when they should adapt design specifications, and the systems themselves, to accommodate environmental change. The Intergovernmental Panel on Climate Change (IPCC) defined adaptation as "The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities" (Agard and Schipper, 2014, p. 1758). Adaptations are, thus, actions that reduce climate sensitivity, alter climate exposure, or increase system resilience (Adger et al., 2005). Given continued deep uncertainty about the unfolding climate (Hallegatte et al., 2012; Ranger et al., 2013), an emerging adaptive posture, especially for long-lived infrastructure, eschews narrowly matching capacity to future expected conditions and instead emphasizes mixtures of robust and flexible design (Walker et al., 2013; Kwakkel et al., 2015).

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Decision strategies seeking to optimize infrastructure performance through a "predict-then-act" approach may be less effective in a changing climate. Strategic approaches thus are starting to favor choices scaled to the climate risk as best that it can be assessed now (Brown et al., 2012; Olsen, 2015) and solutions that are adaptable over time as climate trends unfold, for example via "dynamic adaptive policy pathways" (Walker et al., 2013). Dynamic adaptation entails a variety of tactics that evolve over time, such as delaying some decisions until more information is available, and seeking interim solutions that interfere less with future options, either physically or financially (Hallegatte, 2009). Where this approach is not feasible, and large systems must be built now, then a strategy of robustness to a wider range of future conditions makes sense (Lempert et al., 2003). Robust strategies may be quite expensive, and have predominantly been applied to large-investment, high consequence decisions.

In this analysis of adaptation options, the system in question is the array of culverts commonly incorporated into road and highway drainage infrastructure. Culverts are covered water conveyances embedded in the roadbed whose main purpose is to transport surface runoff from one side of the road to the other; they are emplaced where drainage ways intersect with the roadbed and impounded water might damage or even destroy the road (Federal Highway Administration, 2012) or cause nearby property damage. In many parts of the world outside of deserts this intersection is quite common, and even roads providing lower service levels are constructed with frequent culvert crossings. Culverts are sized according to expected runoff volumes and are at risk to variation in the intensity, duration and frequency of precipitation events. Each emplacement has different characteristics and will respond to climate change in different ways. But, design, performance, and maintenance specifications for individual units are often codified by governing agencies via blanket standards. Culverts thus constitute a system of dispersed elements built to similar standards with limited adaptation options (they typically have design lives of 50–70 years and many remain in service for a century or longer) and high climate exposure. Culvert failure can destroy roads and present life-threatening conditions in response to localized, intense rainfall and runoff episodes or to regional events such as the Hurricane Irene floods, which destroyed thousands of culverts in Vermont during 2011 (Irene Recovery Office, 2013).

While climate theory and models projecting human-induced climate change suggest increasing temperatures almost universally, there is much less consensus regarding precipitation and other elements of the hydrologic cycle (IPCC, 2007), especially for regional-to-local changes and runoff (Kirtman et al., 2013). The hydrologic cycle is generally expected to intensify in a warming climate (Donat et al., 2016) but projections exhibit substantial geographic variation and large uncertainty (Tebaldi et al., 2006). Despite uncertainty, rainfall intensity has increased over much of the U.S. in recent decades and is projected to continue increasing (Walsh et al., 2014; Prein et al., 2017; Feng et al., 2016). In the southwestern U.S., our regional focus here, annual daily maximum precipitation is expected to increase between 11% and 21% under the IPCC Representative Concentration Pathway (RCP) 8.5 (Wuebbles et al., 2014). But precipitation projections are complicated by the myriad ways that shifts can be realized: changing means without changing extremes, changing intensities in given durations without changing means, and changes that exhibit strong seasonality. Additionally, precipitation is generated by a number of different phenomena, some of which are not well simulated in current climate models (O'Gorman, 2015), and some (e.g., convective) more likely than others (e.g., stratiform) to stress stormwater systems. Potential increases in rainfall intensity from convective and orographic effects are of particular concern in Colorado (Mahoney et al., 2012), where our virtual testbed is located. In the face of such uncertainties the current adaptation trend in the U.S. is to increase infrastructure capacity (Exec. Order No., 2015).

2. Infrastructure adaptation strategies

In previous work using this simulation testbed (McCurdy and Travis, 2017) and driven by interest of stormwater system managers asked to adopt forward-looking adaptation strategies as part of local and regional climate action plans, we investigated the effect of crossing characteristics on the most efficient system-wide adaptation strategy. That is, we posited and tested blanket adaptation policies, such as upgrading all culverts in anticipation of, vs. in reaction to, change. In the current study we ask: Do individual crossings respond to climate change in ways that warrant individual-level adaptation strategies linked to characteristic sets of culvert emplacements? And do these differentials suggest different sequences or pathways of adaptation? In the next section we situate such strategies within the emerging framework of adaptation pathways. Following that we establish a methodology and test the efficacy, and to evaluate the potential benefits, of crossing-specific adaptation strategies using exploratory modeling analysis (Bankes, 1993).

2.1. Strategic flexibility and outcome robustness

Researchers have identified the value of flexibility in climate adaptation across diverse applications, including agriculture, water supply, flood control, and other climate-sensitive sectors (Iglesias et al., 2011; Kwakkel et al., 2012; Lempert and Groves, 2010; Walthall et al., 2012; Woodward et al., 2014; Kwakkel et al., 2016). Most of this research focuses on what we refer to as strategic flexibility. In the dynamic adaptive pathways approach, strategic flexibility places value on maintaining a wider range of future options and creating a framework for decision-makers to engage in those options. These strategies draw from concepts of ecological adaptive management (Tompkins and Adger, 2004), and financial "real options" (Linquiti and Vonortas, 2012). They emphasize continual learning, explicitly valuing flexibility and avoiding path dependence.

A simple example of strategic flexibility, illustrated to resemble a transit system cartogram used in other decision research (see, for example, Haasnoot et al., 2012), is illustrated in Fig. 1a. As time progresses the decision-maker has several opportunities to switch strategy to either a new pathway or an existing one that they previously opted not to take. For example, coastal engineers might opt for beach and dune replenishment now but plan eventually for seawall installation if and when relative sea level rise and storm surge heights reach a certain threshold. Constant monitoring and analysis are required to specify the nature of the switch among pathways.