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Working Paper

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

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Abstract

Changes in temperature and precipitation patterns resulting from climate change may adversely affect the performance of long-lived infrastructure. Adaptation may be necessary to ensure that infrastructure continues offering consistent service and remains cost effective. Deep uncertainty associated with future climate projections makes adaptation decisions especially challenging for managers. Previous work shows that 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, offer a simple typology of flexibility, and present a new method of increasing flexibility, termed vertical flexibility. Rather than treating a system of dispersed infrastructure elements as monolithic, vertical flexibility acknowledges the inherent differences in individual elements and incorporates this information into adaptation decisions. We examine the performance of flexible policies that allow for multiple adaptation strategies with varying timing qualities based on individual characteristics for a virtual testbed of highway drainage crossings, or culverts. Our results show that a vertically-flexible strategy informed by crossing characteristics offers a more efficient method of adaptation than do monolithic policies. We explore the implications of vertical flexibility as a cost-effective adaptation strategy for agencies building long-lived climate sensitive infrastructure, especially where detailed system data and analytical capacity is limited.

Introduction

If infrastructure managers accept that the hydro-climatology for which they must design, build, and maintain, is non-stationary, as much of the literature now urges (Gibbs, 2012; Milly et al., 2008) (Olsen, 2015), the question remains as to how and when they should adapt policies and the systems themselves. 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 & Schipper, 2014, p. 1758). Adaptations are actions which reduce climate sensitivity, alter climate exposure, or increase system resilience (Adger et al., 2005). Given continued deep uncertainty about the unfolding climate (Hallegatte, Shah, Lempert, Brown, & Gill, 2012; Ranger et al., 2013), the emerging adaptive posture, especially for long-lived infrastructure, has tended to empathize mixtures of robust and flexible design (Walker et al., 2013).

Decision strategies seeking to optimize infrastructure performance through a “predict-then-act” strategy are, *ipso facto*, less effective in a changing climate. Strategic approaches thus are starting to favor choices that are scaled to the climate risk (Brown et al., 2012; Olsen, 2015) or dynamic solutions that are adaptable over time as climate trends become more manifest, for example “adaptation pathways” (Walker et al., 2013). Dynamic adaptation may entail delaying some decisions, 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 the strategy has been toward robustness to a wider range of future conditions (Lempert et al., 2003). Robust strategies may be quite expensive, and have predominantly been applied to high consequence decisions with a diverse options space.

Here we apply an exploratory modeling analysis (Bankes, 1993) to highway stormwater infrastructure, with a focus on culverts---covered water conveyances embedded in the roadbed whose main purpose is to transport surface runoff from one side of the roadbed to the other. Culverts are emplaced where drainage ways intersect with the roadbed and where impounded water might damage or even destroy the road (Federal Highway Administration, 2012), or cause local 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 culverts. Such systems are at risk to variation in the intensity, duration and frequency of extreme precipitation events. Their individual elements, expressing different characteristics, will respond to climate change in varying ways. 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 (once in place they may have design lives of 50-70 years and many end up in service for a century or longer) and relatively 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 in Vermont (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 especially for soil moisture and runoff (Kirkman et al., 2013). The hydrologic cycle is generally expected to intensify (Donat et al., 2016) but predictions exhibit geographic variability and high uncertainty (Tebaldi et al., 2006). Rainfall intensity has increased over much of the U.S. in recent decades and is projected to continue increasing (Walsh et al., 2014). In the southwestern U.S., where our testbed is located, annual daily maximum precipitation is expected to increase between 11% and 21% under the IPCC Representative Concentration Pathway (RCP) 8.5 (Wuebbles, Kunkel, Wehner, & Zobel, 2014). Precipitation predictions are complicated by the myriad ways that shifts in precipitation can be realized: changing means without changing extremes, changing intensities in given durations without changing means, or 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). Potential increases in rainfall intensity from convection and orographic effects are of particular concern in Colorado (Mahoney et al., 2012). Despite the uncertainty the current adaptation trend in the U.S. is to increase the design storm for infrastructure (Exec. Order No., 2015).

Infrastructure Adaptation Strategies

In other work (McCurdy and Travis, 2016) we investigated the effect of crossing characteristics on the most efficient system-wide adaptation. That is, we posited and tested blanket adaptation policies, such as upgrading all culverts on a nominal, or an anticipatory schedule. In the current study we ask: do individual crossings respond to climate change in ways that warrant individual-level adaptation strategies? In the next section we situate such strategies within the broader frame of flexible adaptation. Following that we establish a methodology to test the efficacy, and to evaluate the potential benefits, of such crossing-specific strategies.

Horizontal and Outcome Flexibility

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, Quiroga, Moneo, & Garrote, 2011; J. H. Kwakkel et al., 2012; Lempert & Groves, 2010; Walthall et al., 2012; Michelle Woodward et al., 2014). Most of this research focuses on what we refer to as horizontal or outcome flexibility. Horizontal flexibility places a high value on maintaining a wide 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 & Adger, 2004), and financial "real options" (Linquiti & Vonortas, 2012). They emphasize continual learning, explicitly valuing flexibility and avoiding path dependence.

The term “horizontal” is in reference to adaptation pathway illustrations that resemble a transit system map and in which time flows horizontally, left to right, while options stack vertically. A simple example of horizontal flexibility in illustrated in figure 1a. As time progresses the decision-maker has several opportunities to switch their strategy to either a new pathway or an existing one that they previously opted not to take. Horizontal flexibility for adapting to climate change has been formalized in Adaptation Pathways (AP) (M. Haasnoot, Middelkoop, van Beek, & van Deursen, 2011), Real-Options (RO) (Michelle Woodward et al., 2014), and Adaptive Policy Making (APM) (Walker, Rahman, & Cave, 2001). Each of these techniques incorporates flexibility in different stages or using different decision tools. AP focuses on the timing of adaptation, identifying when a decision-maker has the opportunity to shift adaptation strategies, and for how long a decision will meet predefined performance criteria (Marjolijn Haasnoot, Kwakkel, Walker, & ter Maat, 2013). Kwakkel (2014) accomplished this using exploratory models and simulating many possible futures. RO is a financial decision analysis method which enables a decision maker to incorporate the value of future flexibility (options) into a net present value cost-benefit analysis (M. Woodward, Gouldby, Kapelan, Khu, & Townend, 2011). Finally APM is a structured approach to design and implement flexible adaptation strategies (Walker et al., 2001). It provides a framework for decision makers to assess and review their decisions based on predetermined measures of success and specifies actions to take when conditions for success are not being met. Computational experiments using these strategies show they offer important, but different advantages over traditional predict-then-act approaches to decisions making; however there are reasons to be skeptical. Implementing horizontally-flexible strategies can require significant analysis and continual monitoring, perhaps especially challenging for limited budget, more routine infrastructure operations.

Decision making tools that emphasize outcome flexibility attempt to identify strategies that are effective over a wide range of possible futures; thus they are less likely to need adaptive modification over time. This draws on the engineering concept of robust design, emphasizing strategies that are insensitive to variation in uncontrollable or unpredictable factors (Park, Lee, Lee, & Hwang, 2006). Methods for identifying outcome flexibility are extensively explored in Robust Decision Making (RDM) (Lempert et al., 2003), and Decision Scaling (DS) (Brown et al., 2012). The Rand Corporation developed RDM as a method to simulate the performance of adaptation strategies over an extremely wide range of futures and to identify the conditions under which strategies succeed or fail (Lempert & Groves, 2010). DS works in the opposite direction, first using a sensitivity analysis to determine where a system will fail due to climate change and then examining available climate model output to assess how likely that future is (Brown et al., 2012). Strategies that emphasize outcome flexibility are often more costly, and appropriate for systems with a high consequence of failure. Increased cost often means they are not economical for lower-consequence decisions where failure is more acceptable.

Horizontal and outcome flexibility are not mutually exclusive and in some sense both accomplish the same task, but on different time frames. Outcome flexibility is traditionally used as a tool for making large, irreversible decisions or forming long term plans, whereas horizontal flexibility is more explicitly a continuous process. At the time of decision both strive to identify strategies which will be successful in a range of unpredictable futures; Horizontal flexibility accomplishes this by adapting to future changes and outcome flexibility by selecting an option that is robust to future changes.

Vertical Flexibility

In this paper we explore the potential of vertical flexibility as an additional dimension to crafting dynamic adaptation strategies. We define vertical flexibility as increasing the number of available options at the time of a decision, specifically allowing decisions to be made on a more granular rather than monolithic scale. This type of flexibility is particularly relevant when making policy decisions that govern a group of similar elements (i.e. culverts, bridges, road surfaces, buildings, etc.). Typically, these structures are governed by blanket policies enacted at the agency level. In the United States many such standards are promulgated at the state level, for example the Colorado Department of Transportation's culvert guidelines in table 1 (Colorado Department of Transportation, 2004).

Table 1-CDOT Culvert Design Guidelines

Road Type	**Urban/Rural**	**Design Storm**
Multilane Roads - including interstate		
	Urban	100-year
	Rural	50-year
Two-Lane Roads		
	Urban	100-year
	Rural (Q_{50} > 4000 cfs)	50-year
	Rural (Q_{50} < 4000 cfs)	25-year

These guidelines have not been altered to reflect anticipated changes in climate, nor have any of CDOT's methods for calculating the return period been adjusted to the notion of non-stationarity. Adaptation could be implemented within CDOT's current framework in one of two ways. The required design storm for all infrastructure could be increased to a larger event, or the methods to calculate return intervals could be changed to incorporate projections of climate change. Both of these approaches were recently implemented for federal projects in the U.S. by presidential executive order requiring projects to be built to the 500-yr flood, with 2 feet of freeboard over the 100-yr flood, or using the best available climate science ("Exec. Order No 13690," 2014). These methods of adaptation are monolithic policies that assume climate is the main, or only variable which should be included when deciding on an adaptation strategy.

Climate change is typically characterized as a problem with 'deep uncertainty' (Hallegatte et al., 2012; Ranger et al., 2013). The term 'deep' uncertainty refers to "a situation in which analysts do not know or cannot agree on: (1) models that relate key forces that shape the future; (2) probability distributions of key variables and parameters in these models, and/or (3) the value of alternative outcomes" (Hallegatte et al., 2012, p. 2). The deep uncertainty with regards to climate change is created from the uncertainty in future greenhouse gas emissions, uncertainty in model accuracy and parameterization especially at small scales, and uncertainty in how natural systems will react to increases in radiative forcing (Hallegatte, 2009; Milly et al., 2008; Walker et al., 2013). While there is agreement that climate change will likely result in a general intensification of the hydrologic cycle there is less certainty about how changes will be manifest at local level (Donat et al., 2016; Milly, Wetherald, Dunne, & Delworth, 2002).

The uncertainty associated with climate change creates challenges for monolithic policies, especially as the spatial scale and diversity of affected elements increases. If a decision maker were to use the 'best available climate science' for a project in Colorado they would find that the annual maximum daily precipitation may decrease, or increase, by as much as 20% and possibly more when model uncertainty is included. Finding little clarity in the best available climate science, they may opt to build to the 500 year flood, at a significant increase in expense.

This might make sense for projects with high potential for damage but not for widespread, distributed elements like culverts, where in some cases flooding will have minimal impact.

A monolithic strategy or one without vertical flexibility can be viewed as either of the decision trees shown in figure 1. One decision is made and applied to every element in the system. A decision which incorporates vertical flexibility allows for decisions to be made on an element level taking into account individual characteristics of each unit within the system. The culvert guidelines in table 1 already incorporate some vertical flexibility; they treat rural and urban areas differently and specifications vary depending on the size of the road. Additional flexibility for climate-sensitive decisions could be incorporated by evaluating the ease of increasing capacity, site characteristics that change the probability of failure, the type of traffic served by the road, and other factors. As with increasing horizontal or outcome flexibility, increasing vertical flexibility comes with additional cost. Decision makers must spend additional time and resources to gather information and evaluate the cost and benefits of each decision. Vertical flexibility can generally be based on a decisions maker’s current knowledge.

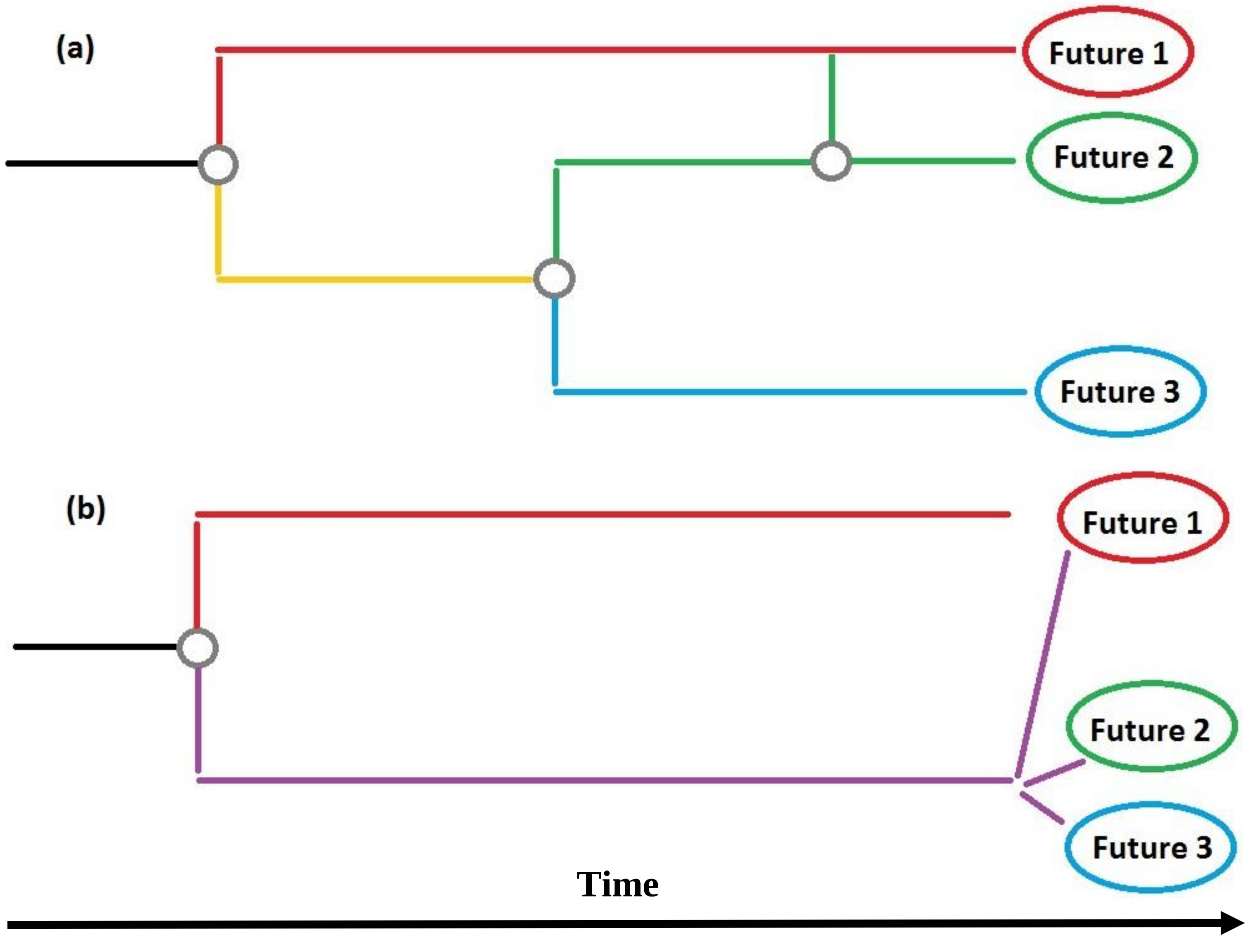

Figure 1-A simple schematic styled after the diagrams of Adaptation Pathways (Haasnoot et al., 2012) to compare Horizontal and Outcome flexibility. (a) A policy with Horizontal Flexibility: as time progresses a decision maker has multiple opportunities to change strategies based on recent information. (b) A policy with Outcome Flexibility: choices are robust to variations in future climate and well adapted to a wider range of futures. While Outcome and Horizontal flexibility are shown separately they are frequently designed to make flexible strategies adapted to a wide range of futures. Vertical flexibility (not pictured) can be viewed as increasing the number of decisions available i.e. expanding one decision map for a monolithic policy into many decisions for individual elements.

Vertical Flexibility and Culverts

In McCurdy and Travis (2016) we investigate how crossings with different properties respond to changes in adaptation timing. We found that some crossing characteristics can significantly increase the likelihood of benefiting from earlier adaptation regardless of the rate of climate change. In that study we assumed that all of the crossings in our testbed were subject to the same management policy and received the same climate treatment. In this study we use the same testbed of culverts but allow each simulation to randomly assign individual characteristics that affect key variables, including the cost of upgrading that culvert, its resilience to exceedance (how much the flow can exceed design before damage occurs), and the additional costs associated with upgrading on failure (as opposed to a planned upgrade).

Methods

To examine the efficacy of vertical flexibility we use a testbed of eight realistic road crossings served by culverts conveying runoff. The crossings are based on recent Colorado Department of Transportation (CDOT) bid tabulations for actual projects (Colorado Department of Transportation, 2016a). Each crossing has fixed characteristics (based on the original project bids) that remain static in the simulations, and variable characteristics which affect the crossing's climate sensitivity and adaptability. Variable characteristics are randomly assigned at the start of each iteration. Here we test the effect of vertical flexibility in the timing of adaptation strategy by simulating extreme events and adaptation over a 100 year period. Simulations without vertical flexibility use the same adaptation timing for all crossings, whereas simulations with vertical flexibility assign different strategies to each crossing based on the crossing's characteristics.

Model Inputs

Here we offer a short description of model inputs and functions, a more complete explanation can be found in McCudy and Travis (2016).

Adaptive Strategies

We simulate adaptation timing based on the typology offered by Smit et al. (2000) which classifies adaptations as being anticipatory, reactive, or concurrent with respect to a climate stimulus (table 2). Additionally we include a Nominal Strategy: one without adaptation. Simulations using the Anticipatory Strategy increase culvert capacity by replacing one crossing a year until all crossings in the testbed have been upgraded. The Concurrent Strategy increases the capacity of crossings at the end of their useful life or when damage from an extreme event warrants a replacement. The Reactive Strategy initially follows the rules of the Nominal Strategy and switches to the Concurrent Strategy if a crossing needs to be replaced after damage by an extreme event.

Table 2- Adaptation Strategies

Strategy Name	Description
Nominal	Replacement as necessary with same sized crossings. Typically at end of useful life.
Concurrent	Crossing capacity is increased at replacement, assuming climate is changing and damaging events are indicators of that change
Anticipatory	Crossing capacity is increased prior to normal replacement in anticipation of future increase in flood events
Reactive	Switch from the Nominal Strategy to the Concurrent Strategy when a crossing is destroyed by an extreme event, used as a pacemaker for adaptation
Vertically-Flexible	Strategy is specific to each crossing depending on variable characteristics

Fixed Characteristics

Each crossing has the following fixed characteristics: county name, road designation, design storm, design life, replacement delay (number of days with reduced traffic capacity or speed due to replacement), and cost (table 3).

Table 3-Fixed Culvert Characteristics

County	Road	Design Storm	Material	Design Life	Replace Delay	Cost	Date
Dolores	SH145	100	Concrete	80	25	$ 497,747	7/18/2013
Routt	US40	100	Concrete	80	50	$ 1,385,135	2/5/2015
Ouray	US550	100	Concrete	80	30	$ 1,281,625	10/29/2015
Huerfano	SH12	100	Concrete	80	45	$ 995,000	1/15/2015
Jackson	SH125	100	Concrete	80	40	$ 453,761	5/8/2014
Montezuma	US491	50	Steel	50	25	$ 270,105	7/18/2013
Mesa	SH139	50	Steel	50	25	$ 189,363	10/6/2014
Lake	SH82	100	Concrete	80	43	$ 709,426	6/5/2014

Variable Characteristics

Each crossing is randomly assigned variable characteristics that determine its adaptability and climate sensitivity (table 4). Upgrade Amount describes how much the capacity of a crossing is increased at the time of replacement. For example if a crossing's original design capacity was 100 years and the upgrade factor is 2 the new design capacity is for a 200 year event. Resilience Factor describes how much the design event of a crossing can be exceeded before the crossing is damaged. Upgrade Cost defines how much upgrading the crossing costs per unit of increase. Emergency Factor describes the additional cost to replace a crossing when it is destroyed by an extreme event. Post Upgrade Factor applies a reduction in cost to upgrades following an initial upgrade.

Table 4-Variable Culvert Characteristics

System Characteristic	Range	Model Implementation
Upgrade Amount (UA)	1.5-2.5	UA * Original DS = New Design Size (DS)
Upgrade Cost (UC)	1.0-4.0	(UC * Original Cost (OC) * % capacity ↑) + OC = New Cost (NC)
Post Upgrade Factor (PF)	0.3-0.7	(PF * OC * UC * % capacity ↑) + OC = NC
Emergency Cost (EC)	1.3-1.7	(EC * OC * UC * % capacity ↑) + OC = NC
Resilience Factor (RF)	0.1-0.5	(% DS Exceeded / RF) * OC * EC = Damage Cost

Simulated Flood Events

The model simulates extreme events using random draws from a Generalized Extreme Value (GEV) distribution fitted to precipitation records for Colorado (equation 5) (Coles, 2001).

$$F(x) = \exp\left\{-\left[1+\xi\frac{(z-\mu)}{\sigma}\right]^{-\frac{1}{\xi}}\right\} \tag{5}$$

where z is the annual maximum precipitation over the a given duration, μ is the location parameter, σ is the shape parameter, and ξ is the scale parameter. Following Mailhot et al. (2009)

we implement climate change as a shift in the location parameter keeping the shape and scale parameters constant. There is evidence that climate change may affect other moments of the distribution or potentially change the distribution altogether (Field et al., 2012; Read & Vogel, 2015); few studies address such changes and work is needed to assess infrastructural sensitivity to other statistical shifts. Shifts in the distribution are accomplished by applying a climate factor which changes the magnitude of a design event to that of an event with a higher return interval. For example, given a climate factor of two, the magnitude of the 100 year event will have shifted, by the end of the simulation, to be equivalent to the magnitude of the original 200 year event. Each year the location parameter is linearly increased to simulate this non-stationary behavior.

Comparative Outcomes

To compare outcomes with and without vertical flexibility we run simulations with the same crossing characteristics (Upgrade Amount, Emergency Cost, Resilience Factor, Post Upgrade Factor, and Upgrade Cost) under all four strategies. Each of these are run 104 (for parallelization across eight processor cores) times to simulate a variety of event realizations. The 104 runs are then aggregated using the mean of all measures of success. This provides a total of 2500 one-hundred year simulations each with different model parameters and eight crossings. The 2500 simulations are then divided into 10 bins by climate change factor, ranging from .75 to 3 (the .75 factor implies a lessening of intensity for a given return period event). To create a set of simulations where each crossing has different characteristics but a similar climate we draw one of the eight culverts from each of the bins 300 times. From this we produce 3000 simulations, each run for 100 years with the same eight crossings experiencing a similar climate but otherwise having different characteristics.

In simulations without vertical flexibility, each crossing is adapted using the same timing strategy. In strategies with vertical flexibility each crossing is assigned a strategy based on its variable crossing characteristics. Strategies are assigned using the multinomial regression model developed in McCurdy and Travis (2016). In that study we found that the Anticipate Strategy was never selected as having the best outcome, and that there was little difference between the Reactive and Concurrent strategies. In light of these results we did not compare a vertically-flexible strategy based on model predictions to either of these strategies.

We evaluate the efficacy of strategies based on installation and flood damage costs compared to the lowest cost strategy given the crossing characteristics and climate factor. This is a simple and compartmentalized view of culvert success and in the real world additional costs and benefits, such as user delay, might be incorporated. Some original simulations included the cost of user delay but we found the model was very sensitive to small changes in the time length of delay and the value assigned to an hour of delay. It could easily be included by a decision maker who better understands the delay tolerance and willingness to pay of their users.

We examine three simulation groups, in which: (1) each crossing is treated with the same strategy; (2) each crossing is treated with the strategy predicted as the best by the multinomial model; and (3) each crossing is treated with the lowest cost strategy; henceforth this is the 'best' strategy. We compare monolithic and vertically flexible strategies by the difference between the best strategy for each crossing and the strategies assigned. We contrast the distributions by examining means and the 90th percentile, and plots comparing the deviations from the best strategy.

Results

The different adaptation strategies pose two flavors of inefficiency: under-adapting or over-adapting. The Concurrent Strategy reduces the risk of under-adapting and the Nominal Strategy reduces the risk of over-adapting. At varying levels of climate change we see each of these outperforming the other.

Monolithic vs. "Best" Strategy

To assess the efficacy of vertical flexibility we compare use of a single strategy for all crossings (either Nominal or Concurrent), assigning a strategy to each crossing based on results from a multinomial model that uses the characteristics of individual crossings to predict which adaptation strategy has an outcome with the least cost. To assess the performance of each strategy we compared it to the "best" strategy, that is, the one that resulted in the least cost. Figure 2 shows the changes in mean and 90^{th} percentile costs across a range of climate change, from an increase in return interval of 25% to a decrease by a factor of 3 (i.e., the original 100 year event ranges from a 125 year event to a 33 year event).

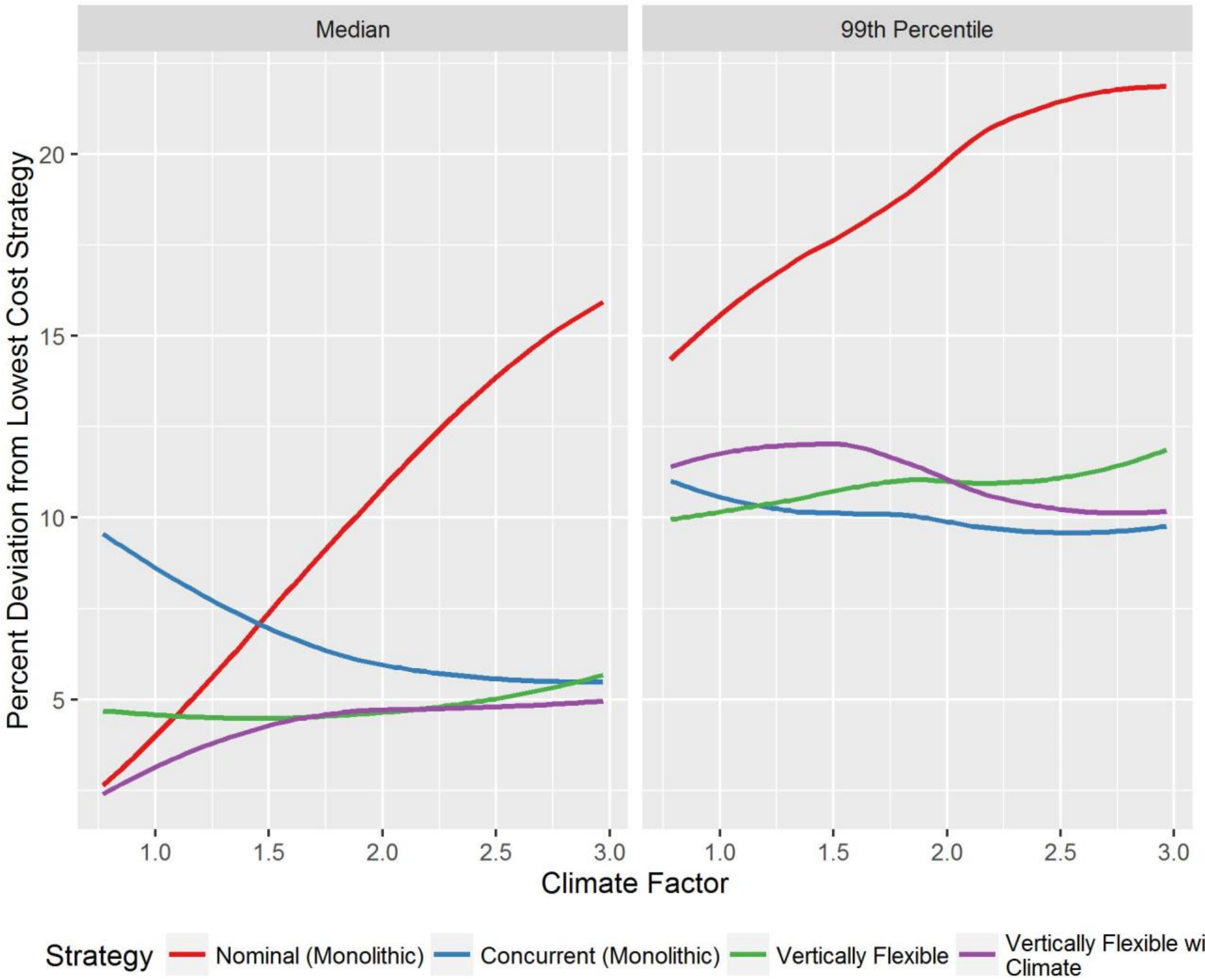

Figure 2- Percent deviation from the most cost-effective strategy vs changes in climate factor. (a) Median percent deviation from the most cost effective strategy vs climate factor. (b) 99th percentile percent deviation from the most cost effective strategy vs climate factor. Only in the low ranges of climate change is the nominal strategy the most cost-effective approach simulated. At the upper tail of events, where culvert damage and replacements are the most likely, the nominal strategy underperforms the others at all ranges of climate change. The special case of vertical flexibility in which the climate is "known" (that is, included in the multinomial model predictions, the purple line) provides a wedge of value at low (1 to 1.5) climate change.

Assuming that a decision maker has additional information about the climate sensitivity and adaptability of each infrastructure element, we show that they can frequently do better than the single strategy approach by using a vertically-flexible strategy that accounts for individual crossing characteristics. The vertically-flexible strategy performed best under moderate increases in flood risk with its efficacy diminishing in situations with no change or a decrease in risk, and with higher levels of climate change (the left and right ranges in fig 2). Under climate scenarios with a decrease or a large increase in risk the Nominal or Concurrent strategies (respectively) became the preferred choice regardless of other crossing characteristics. A vertically-flexible strategy informed by knowledge of the climate trend provides benefits (reduced costs) at the lower rates climate change (fig 2 a). Knowing that flow intensity will increase only slightly (climate factor 1-1.5) over a century allows the decision maker to forego unnecessary up-grades. As we move more into the right tail of the distribution as shown by the 99th percentile (figure 2b), the nominal strategy exhibits a greater relative cost increase over the other strategies, and the value of knowing the rate of climate change is much reduced.

To visualize the full range of results from each strategy we plotted the relative increases over the least cost adaptation using box and whisker plots (figure 3).

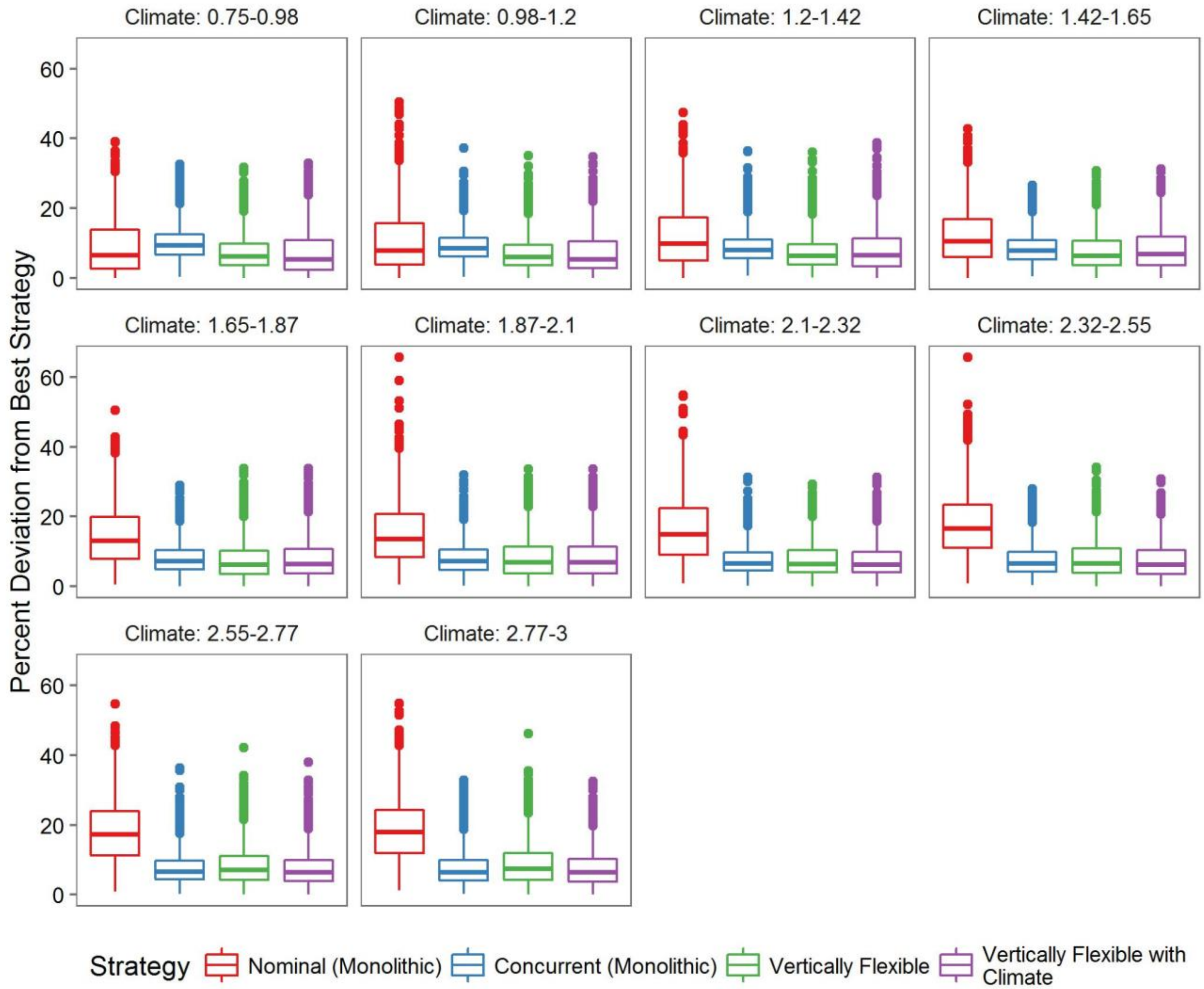

Figure 3-Percent deviation from the most cost-effective strategy grouped by climate factor. Middle line represents the 50th percentile, boxes extend from the 25th and 75th percentiles, and whiskers extend to the 1.5 times the interquartile range with observations outside of that plotted as dots. Each plot is labeled by the range of climate factor represented. For example as climate factor increased the Nominal Strategy shifted further from the optimal and became more variable.

Of particular note in figure 3 is the increase in variability of the Nominal Strategy as the magnitude of climate impact increases. Throughout the simulation the performance of the vertically-flexible strategy is remarkably consistent relative to the baseline. The vertically-flexible strategy shows the most benefit over monolithic strategies under moderate levels of climate change. The vertically-flexible strategy achieves this consistency by identifying and proactively upgrading the most at-risk and climate-sensitive crossings. This results in fewer high losses as compared to monolithic strategies. This result may be of particular interest to managers aiming to keep upfront cost low in order to meet a budget. It emulates a minimax approach to risk management, as described by (Kunreuther et al., 2013), while controlling for upfront cost.

Uncertainty in System Characteristics

In the above analysis we assumed that all of the non-climate system characteristics were known exactly, though in reality these values may not be known or known with some degree of uncertainty. Since we have no specific knowledge on the difficulty of measuring crossing characteristics, we treated the standard error for each parameter as a fraction of its original range shown in table 4. To explore different levels of uncertainties we tested 10%, 30%, and 50% of the original ranges. We used these values as standard deviations of a normal distribution with a mean of 0. Random draws from these distributions were added to the original crossing characteristics used in the model prior to employing the multinomial model for strategy prediction. Additionally we created a random strategy in which each crossing was assigned either the Nominal or Concurrent strategy.

Figure 4 shows that the Vertically-Flexible strategy is robust to uncertainty in the values of crossing characteristics, with uncertainty having a greater impact at higher levels of climate change. Comparing the results to the random assignment shows model skill even under large uncertainty in the values of crossing characteristics. Random strategy assignment, while almost never the ‘best’ strategy in the simulation, is also rarely the ‘worst’. This leads us to suggest that for a system of similar elements in which each responds differently to adaptation and change, but with no additional information about how elements will respond, an effective minimax strategy is diversification. We explore this concept further in the conclusions section.

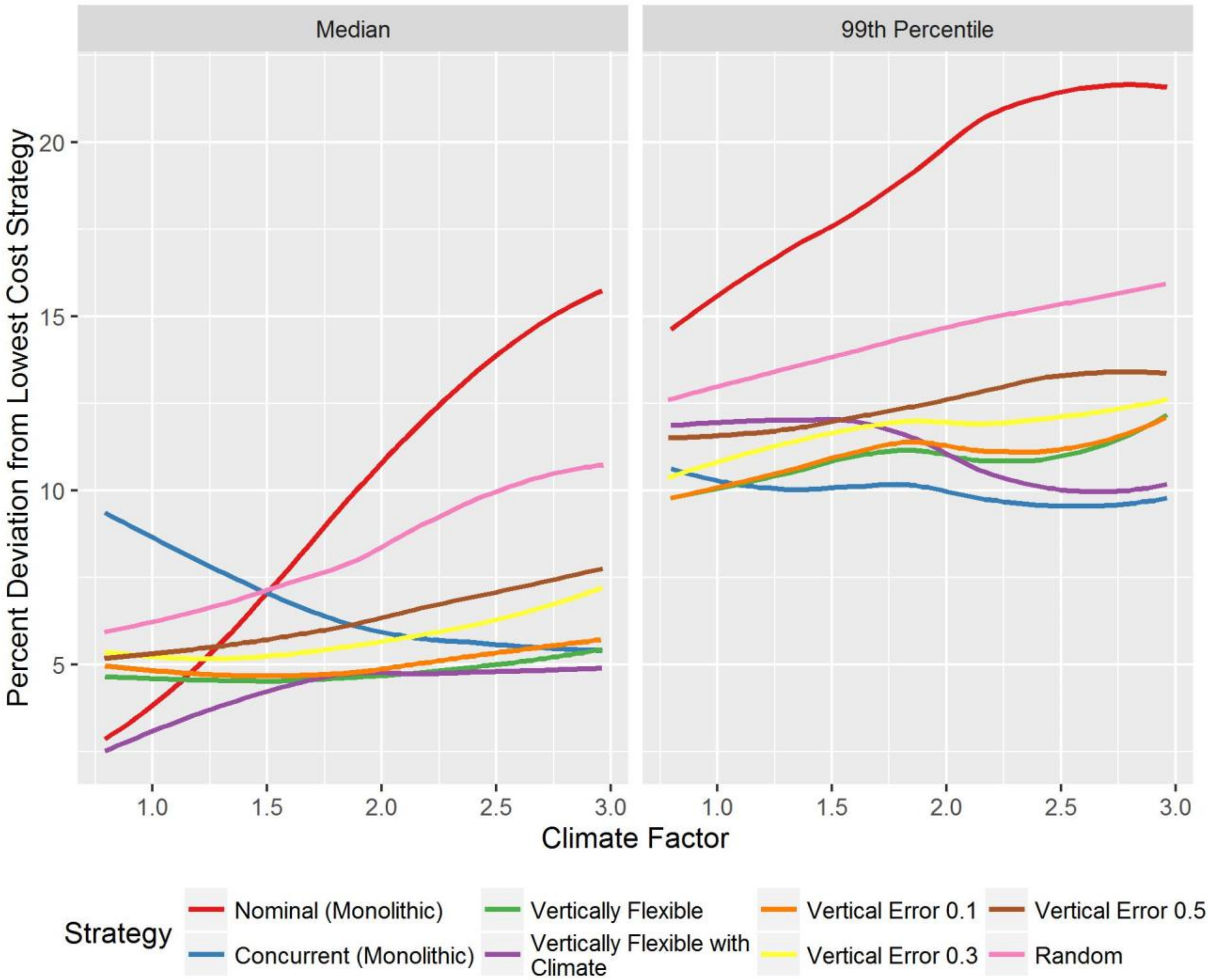

Figure 4- Percent deviation from the most cost-effective strategy vs changes in climate factor. (a) Mean percent deviation from the most cost effective strategy vs climate factor. (b) 90th percentile (results from the top decile) percent deviation from the most cost effective strategy vs climate factor. Solid lines show the standard strategies. The dashed lines show the Vertically-Flexible Strategy determined using variable crossing characteristics with error added from a normal distribution with mean zero and standard deviation of .1, .3, and .5 times their modeled range. The dotted line shows a simulation in which each crossing was randomly assigned either the Nominal or Concurrent strategy. For example the "Vertical Error .05" follows a similar path to the Vertically-Flexible strategy but shifted further from the most cost effective strategy.

Conclusions

Using a testbed of realistic crossings to simulate effects of increasing runoff intensity on stormwater infrastructure, we found that incorporating vertical flexibility in adaptation, that is adapting each culvert according to its performance characteristics and climate sensitivities, thus increasing the options available to a decision-maker, can lead to more efficient adaptation than a monolithic policy strategy. These results indicate that efficiency gains can be found in dimensions of adaptation decisions that are mediated by existing system characteristics. For example, managers might focus on infrastructure with a high potential to be adversely impacted by moderate levels of climate change. Our model assumes that the manager knows individual culvert characteristics (with some level of uncertainty) and does not incur additional cost to learn them; the validity of this assumption will vary by agency (Maher, 2015; Jay Meegoda et al., 2009). Future work could determine how much a decision maker should be willing to pay for this information. This analysis was also limited to the cost of implementing the strategies and not the benefits gained by increased crossing reliability. A full economic analysis should include those benefits and also a realistically-limited budget for crossing improvements. Despite these simplifications, our work suggests that vertical flexibility could act as a bridge between a predict-then-act approach governed by broad policies covering a diverse system, and more nuanced decision strategies based on characteristics of individual elements, even in the face of deep uncertainty associated with climate change.

The majority of climate sensitive infrastructure decisions made over the next 100 years will not be for large projects costing hundreds of millions of dollars. The majority will be made at the local level for projects costing tens or hundreds of thousands of dollars. While the cost of failure for any one installation will be minor, the collective costs, of either under- or over-adaptation, are potentially quite large. Our results show that even a naïve, random strategy choice is an improvement over a monolithic policy approach, suggesting that simple diversification may be an efficient strategy in the face of climate change. This conclusion motivates the comparison of a group of dispersed infrastructure to a portfolio of investments. It is common knowledge that diversification can be an effective method for reducing investment risk. By designing the infrastructure portfolio to various levels of climate change, a decision maker can insure that a larger portion of their investment will perform well under varying levels of change. Modern Portfolio Theory (Markowitz, 1952) suggests that each investment is evaluated by how it contributes to the overall portfolio. It also evaluates the correlation of individual investments. In the case of infrastructure, a manager can evaluate the correlation of risk based on possible future conditions and on geographic correlation. Recent advances in decision-making strategies for climate adaptation under deep uncertainty provide a diverse set of options for managers. For large infrastructure installation and maintenance, such as water supply and coastal or urban flood protection, these techniques can help managers improve the efficiency of costly and complex decisions. Optimal and robust techniques may be time- and cost-intensive, requiring additional expertise and computational resources. As climate change alters the hydrologic cycle decisions about long-lived infrastructure such as culverts will be made at all levels of government, many of them with limited capacity and resources to support decision making strategies that incorporate horizontal and outcome flexibility. Indeed, the United States National Climate Assessment identifies rural communities as a unique adaptation challenge due to their limited institutional capacity and a lack of economic diversity (Melillo, Richmond, & Yohe, 2014). Approximately 70% of US road miles are in rural areas, many of them managed by small towns and counties. Vertically-flexible adaptation policies and guidelines can help those decision-makers work in a familiar framework and evaluate adaptation choices based on expertise and experience they already have.

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