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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.

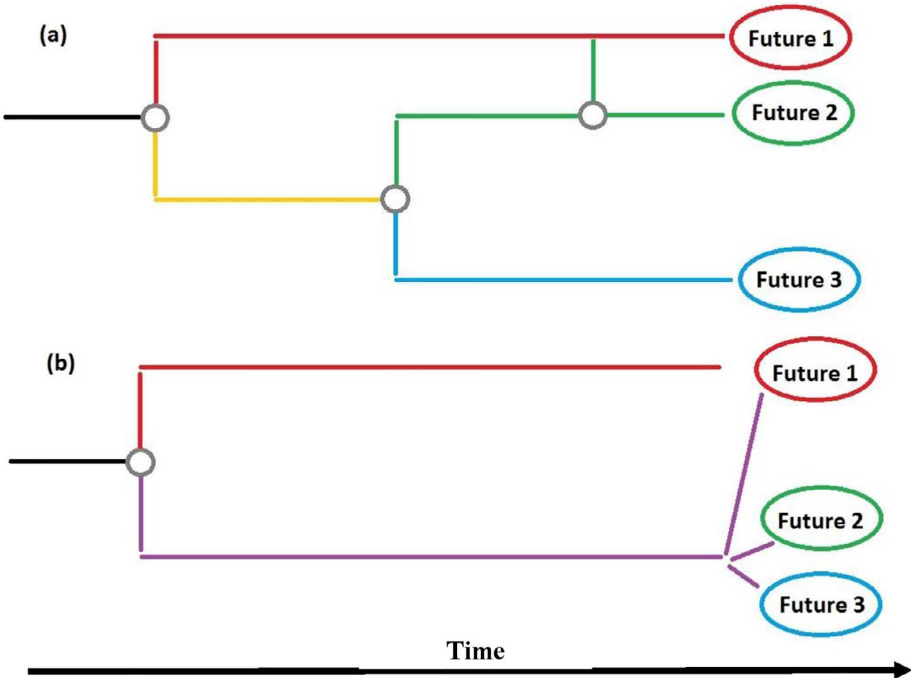

Fig. 1. A simple schematic styled after the diagrams of Adaptation Pathways (Haasnoot et al., 2012) to compare strategic flexibility and outcome robustness. (a) A policy with strategic flexibility: as time progresses a decision maker has multiple opportunities to change strategies based on recent information. (b) A policy with outcome robustness: choices are robust to variations in future climate and well adapted to a wider range of futures. While outcome robustness and strategic flexibility are shown separately they are frequently designed to make flexible strategies adapted to a wide range of futures. Options 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.

Strategic flexibility for adapting to climate change has been formalized in Dynamic Adaptive Policy Pathways (Haasnoot et al., 2011; 2012; 2013), Real-Options (Woodward et al., 2014), and Adaptive Policy Making (Walker et al., 2001). Each of these techniques incorporates flexibility in different project planning or implementation stages and by a variety of decision tools. Dynamic pathways focuses on the timing of adaptation, identifying for how long a decision will meet performance criteria, and when opportunities exist to shift adaptation strategies (Haasnoot et al., 2013). Kwakkel et al. (2015) accomplished this using exploratory models and simulating many possible futures. Dynamic pathways are typically calculated without discounting costs or losses to preserve comparability among simulations over a long time period (up to 100 years) (Kwakkel et al., 2016). Real Options is a financial decision analysis method which incorporates the value of future flexibility (options) into a net present value cost-benefit analysis (Woodward et al., 2011). Real Options thus stresses the financial outcome of a decision with options selected in the present. Finally, Adaptive Policy Making is a structured approach to designing and implementing 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. A strategically-flexible strategy can require significant analysis and continual monitoring. Investments in strategic flexibility may be logical for large, critical infrastructure like river dike systems or coastal defenses, which are indeed the focus of most pathways analyses in the current literature, but would be challenging for smaller budget, more distributed infrastructure operations.

Decision tools that emphasize outcome robustness attempt to identify strategies that are effective over a wide range of possible futures and thus are less likely to need modification over time, such as enlarging the free-board of a flood wall or the capacity of a reservoir. This draws on the engineering concept of robust design, emphasizing strategies that are insensitive to variation in uncontrollable or unpredictable factors (Park et al., 2006). Methods for identifying outcome robustness are extensively explored in Robust Decision Making (Lempert et al., 2003), and Decision Scaling (Brown et al., 2012). Robust Decision Making was developed as a method to simulate the performance of adaptation strategies over a wide range of futures and to identify the conditions under which strategies succeed or fail (Lempert and Groves, 2010). Decision Scaling accomplishes this by first using sensitivity analysis to determine where a system will fail due to climate change and then examining climate model output to assess the likelihood of that future (Brown et al., 2012). Both are bottom-up approaches, and like other forms of robustness analysis, depend on identifying trade-offs (Herman et al., 2015). Strategies that emphasize outcome robustness are often costlier, and appropriate for systems with a high consequence of failure.

Strategic flexibility and outcome robustness are not mutually exclusive and in some sense both accomplish the same task, but on different time frames. Outcome robustness is traditionally used as a tool to inform large, irreversible decisions or long-term planning,

Table 1
CDOT culvert design guidelines.

Road type	Urban/rural	design storm
Multilane Roads – including interstate highways		
	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

whereas strategic 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; strategic flexibility accomplishes this by providing opportunities and methods for adapting to changes as they emerge and outcome robustness by selecting an option that is robust to future changes.

2.2. Options flexibility

Many of the decision-making tools and techniques described above lend themselves to large decisions backed by significant institutional capacity and specialized expertise. Within the literature there is a noticeable gap in the exploration of methods that small and mid-sized governments can employ for a large number of smaller decisions. 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 et al., 2014). Here we explore the potential of options flexibility as an additional approach to crafting dynamic adaptation strategies especially for decision-makers with limited resources.

We define options 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 level. This type of flexibility is particularly relevant when choosing policies that govern a group of similar elements (i.e. culverts, bridges, road surfaces, buildings, etc.). Typically, these structures are ruled 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), which were used to parameterize our testbed.

Anticipated climate change 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 recurrence intervals could be changed to emphasize recent trends or to incorporate projections of climate change. These approaches were recently prescribed for federal projects in the U.S. by presidential executive order requiring projects to be built to a higher flood standard and with larger freeboard, based on the "best available" climate and hydrological science that integrates "current and future changes in flooding" (Exec. Order No 13690, 2014).

Climate change is typically characterized as a problem with 'deep uncertainty' (Hallegatte et al., 2012; Ranger et al., 2013). Deep uncertainty is "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 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 the local level (Donat et al., 2016; Milly et al., 2002).

Such monolithic policies assume climate is the main determinant of an adaptation strategy. The uncertainty associated with climate change creates challenges for monolithic adaptation policies, especially as the diversity of affected elements increase. If a decision maker were to use the 'best available climate science' for a project in Colorado, recent literature would show that the annual maximum daily precipitation may increase by as much as 20%, or even decrease slightly, over the life span of infrastructure projects. Finding little clarity in the best available climate science, they may opt for a robust solution, say building 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 widely distributed elements like culverts, where in some cases failure will have minimal impact.

A monolithic strategy, or one without options flexibility, can be viewed as either of the decision trees shown in Fig. 1. One decision is made and applied to every element in the system. A decision that incorporates options 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 options 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 strategic flexibility or outcome robustness, increasing options flexibility often incurs additional cost. Decision makers must spend additional time and resources to gather information and evaluate the cost and benefits of each decision for each element. Yet, managers can often incorporate options flexibility using existing analysis capabilities.

2.3. Options flexibility and culverts

Experience and the literature (Perrin and Dwivedi, 2006) suggests that managers lack data and analytical resources to evaluate how each emplacement would respond to changing climate parameters and to assign individualized adaptation plans; thus options flexibility, even if it were more efficient, is often out of reach of local transportation managers. Efforts to improve culvert asset management (Meegoda et al., 2009) including with condition-based assessment (Cahoon et al., 2002) are emerging in some transportation agencies. Our previous work (McCurdy and Travis, 2017) showed, however, that blanked adaptation may lead to costly over-adaptation. So, in this study we allow each simulation to randomly assign individual culvert characteristics that affect key variables, including the cost of upgrading each specific 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 increase of capacity in advance of failure). We then evaluate the additional data-gathering and analysis effort to implement this adaptation strategy for a rough efficiency analysis.

3. Methods

To examine the efficacy of options flexibility we use a testbed of eight realistic road crossings served by culverts conveying runoff. The eight original crossings are used as "seeds" of the analysis and their characteristics are perturbed to create tens of thousands of simulations with different crossing characteristics. The crossings are based on Colorado Department of Transportation (CDOT) bid tabulations for actual projects (Colorado Department of Transportation, 2016). Each crossing has fixed characteristics (based on the original project bids) which 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. We test the effect of options flexibility in the timing of adaptation strategy by simulating extreme events and adaptation over a 100 year period. Simulations without options flexibility use the same adaptation timing for all crossings, whereas simulations with options flexibility assign different strategies to each crossing based on the crossing's characteristics.

The use of a strategy with options flexibility necessities a method of assigning adaptation strategies to specific crossings. A frequently used method is to base adaptation decisions primarily on climate predictions. Here we examine a different approach in which adaptation strategies are applied based on known or knowable characteristics of the installed culverts (see Table 4). Additionally we examine the impacts of uncertainty in these characteristics on adaptation decisions, simulating a manager's imperfect knowledge of emplacements.

3.1. Model inputs

Here we offer a short description of model inputs and functions, and a more complete description of the testbed can be found in McCurdy and Travis (2017). The model code for this analysis of options flexibility has been archived at: http://wwa.colorado.edu/climate/extremes/stormwater_mgmt.html.

3.2. Adaptive strategies

We simulate adaptation timing based on the typology offered by Smit et al. (2000) which classifies adaptations as anticipatory, reactive, or concurrent with respect to a climate stimulus (Table 2). Additionally, we include a Nominal Strategy: one without adaptation. The Concurrent Strategy increases the capacity of crossings at the time of normal replacement or when damage from an extreme event warrants replacement. Simulations using the Anticipatory Strategy increase culvert capacity by replacing one crossing a year until the capacities of all crossings in the testbed have been increased. 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.

3.3. 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), cost, and build date (Table 3).

Table 2
Adaptation strategies.

strategy name	Description
Nominal	Replacement as necessary with same sized crossings. Typically at end of useful life but also on failure.
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
Options-Flexibility	Strategy is specific to each crossing depending on variable characteristics

Table 3
Fixed crossing characteristics.

County	Road	Design storm (yrs)	Material	Design life (yrs)	Replace delay (days)	Cost (USD)	Bid approval 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

3.4. Variable characteristics

Each crossing is randomly assigned variable characteristics that determine its adaptability and climate sensitivity (Table 4). Capacity Increase 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 for a 100 year recurrence interval, and the Capacity Increase is 2, the new design capacity is for a 200 year event. Increasing culvert capacity is one of the most expensive adaptations. Resilience Factor describes how much a crossing's design event can be exceeded before the crossing is destroyed; this includes an age factor that increases likelihood of an exceedance event destroying a crossing. Cost to Increase Capacity defines the cost per unit of increase in crossing capacity. Emergency Factor describes the additional cost to replace a crossing when it is destroyed by an extreme event. Emergency repairs and unplanned road closures are especially costly to agencies users and avoided whenever possible (Perrin and Dwivedi, 2006). Post Increase Discount applies a reduction in cost of capacity increase following an initial increase in capacity. This reflects additional cost of increasing capacity (i.e. additional excavation, environmental impact assessment, etc.) compared to replacing with the same sized crossing.

3.5. Simulated flood events

The model simulates extreme events using random draws from a Generalized Extreme Value (GEV) distribution fitted to precipitation records for Colorado (Eq. (1)) (Coles, 2001).

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

where z is the annual maximum precipitation over a given duration, μ is the location parameter, σ is the shape parameter, and ξ is the scale parameter. Using CDOT's methods for sizing infrastructure we assume that the size of runoff events is proportional to the size of precipitation events. That is, a 100 year precipitation event would produce a 100 year run off event. Following Mailhot and Duchesne (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 type altogether (Field et al., 2012; Read and Vogel, 2015); few studies address such changes and work is needed to assess infrastructural sensitivity to other statistical shifts. Shifts in the location parameter are accomplished by applying a climate factor which changes the magnitude of the design event to that of an event with a higher recurrence interval. For example, given a climate factor of two, the magnitude of the 100 year recurrence event will have shifted, by the end of the simulation, to be equivalent to the magnitude of the original 200 year

Table 4
Variable culvert characteristics.

System characteristic	Reference Value	Step	Range
Cost to Increase Capacity	2.0	0.5	1.0–4.0
Capacity Increase	2.0	0.25	1.5–2.5
Post Increase Discount	0.5	0.1	.03-.07
Emergency Cost	1.5	0.1	1.3–1.7
Resilience Factor	0.1	0.05	.05–0.25

System characteristic	Range	Model implementation
Cost to ↑ Capacity (CIC)	1.0–4.0	CIC * Original Design Size (DS) = New DS
Capacity Increase (CI)	1.5–2.5	(CI * Original Cost (OC) *% capacity ↑) + OC = New Cost (NC)
Post Increase Discount (ID)	0.3–0.7	(ID * 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

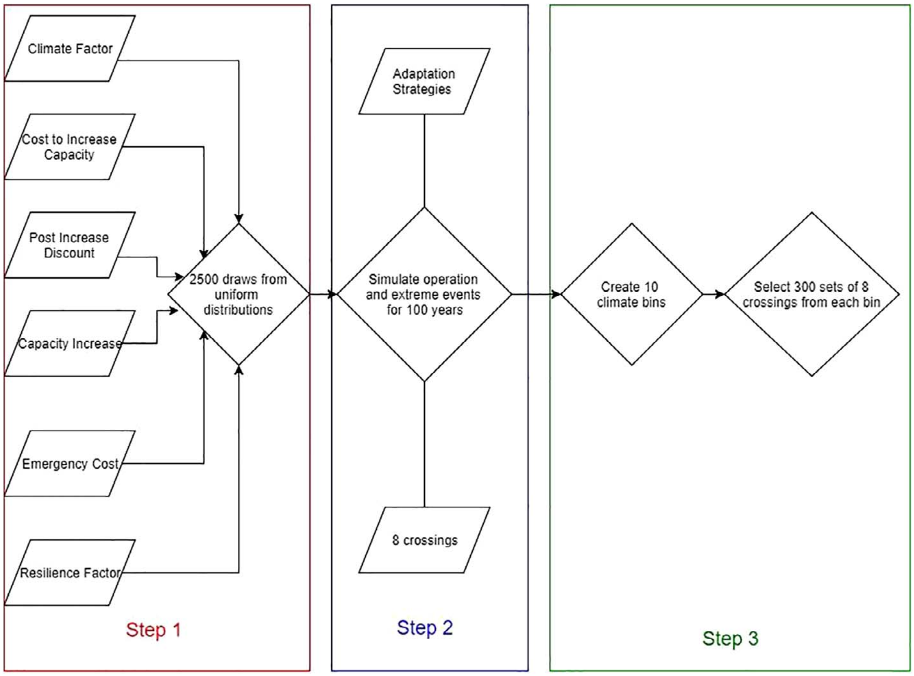

Fig. 2. Diagram showing the simulation process. Parallelograms are inputs, and diamonds are processes.

event. Each year the location parameter is linearly increased to simulate this non-stationary behavior.

3.6. Comparative outcomes

To compare outcomes with and without options flexibility we simulate the normal operation and replacement of eight crossings with fixed (Table 3) and variable (Table 4) characteristics under four adaptation strategies (Table 2). Fig. 2 depicts the basic procedure for generating scenarios divided into four steps described in detail here. In step one 2500 combinations of five variable culvert characteristics plus the climate factor are drawn from uniform distributions in the style of exploratory modeling analysis (Bankes, 1993). The climate factor determines how fast the magnitude and frequency of extreme events is increasing or decreasing; it ranges from .75 to 3. A climate factor of two, for example, implies that the 100-year event magnitude shifts, by the end of the simulation, to equivalent of the original 200 year event. This method shifts the location of the distribution but maintains the shape. In step two each of the 2500 parameter combinations is run 104 times through 100-years of operation to produce a total of 260,000 100-year simulations for the set of eight culverts or 2,080,000 100-year simulations of individual emplacements. Each set of 104 combinations is aggregated using the mean of each measure of success. Experiments with additional simulations for single crossings indicate that this number of simulations achieves convergence in the testbed configuration.

In step three the results of the simulation are divided by climate factor into 10 bins. We then randomly draw 300 sets of eight culverts from each bin (ensuring that each draw has eight crossings with unique fixed characteristics as described in Table 3). This creates 3000 sets of crossings with different variable characteristics experiencing similar amounts of climate change.

In simulations without options flexibility, each crossing is adapted using the same timing strategy. In strategies with options flexibility each crossing is assigned an adaptation strategy based on its variable characteristics. Strategies are assigned using the multinomial regression model developed in McCurdy and Travis (2017). 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 strategy with options flexibility 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. Costs and damages are not discounted, following the practice of other long time-period infrastructural simulation studies (e.g., Kwakkel et al., 2016), because discounting biases the results by time step and confuses the comparison of strategies for long-lived systems. Project planning and tactical choices to meet budget constraints will add discounting. This is a simplified view of culvert success and in the real world additional costs and benefits, such as user delay, might be incorporated. A test of the model including the cost of user delay found that results were extremely sensitive to small changes in the time length of delay and the value assigned to an hour of delay. This could easily be included by a decision maker who better knows the delay tolerance and willingness of their users to pay.

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 strategies with options flexibility by the difference between the best

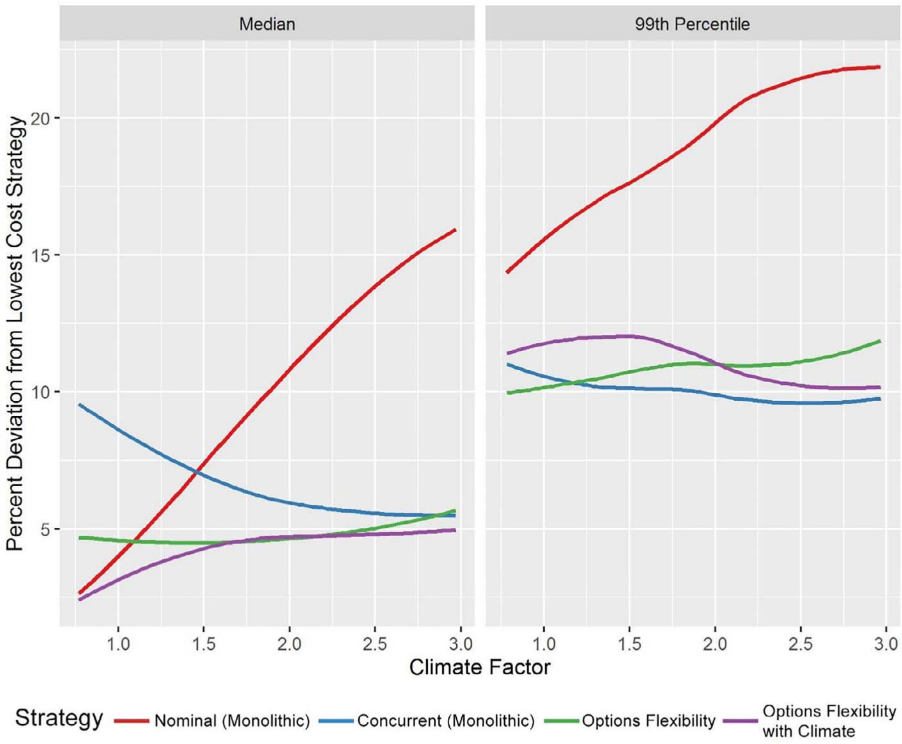

Fig. 3. Percent deviation from the most cost-effective strategy vs changes in climate factor. (a) Median percent deviation from the most cost effective strategy vs climate factor. (b) 99th percentile percent deviation from the most cost effective strategy vs climate factor. Only in the low ranges of 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 options 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.

strategy for each crossing and the strategies assigned. We contrast the distributions by examining means and the 90th percentile, and by plots comparing the deviations from the best strategy.

4. Results

The different adaptation strategies impose 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.

4.1. Monolithic vs. "best" strategy

To assess the efficacy of options 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. Fig. 3 shows the changes in mean and 90th percentile costs across a range of climate change, from an increase in recurrence 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).

If 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 strategy with options flexibility that accounts for individual crossing characteristics. The strategy with options flexibility 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 scenarioswith a decrease or a large increase in risk the Nominal or Concurrent strategies (respectively) became the preferred choice regardless of other crossing characteristics. A strategy with options flexibility informed by knowledge of the climate trend provides benefits (reduced costs) at the lower rates of climate change (Fig. 2a). 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. Further into the right tail of the distribution, as shown by the 99th percentile (Fig. 3b), 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

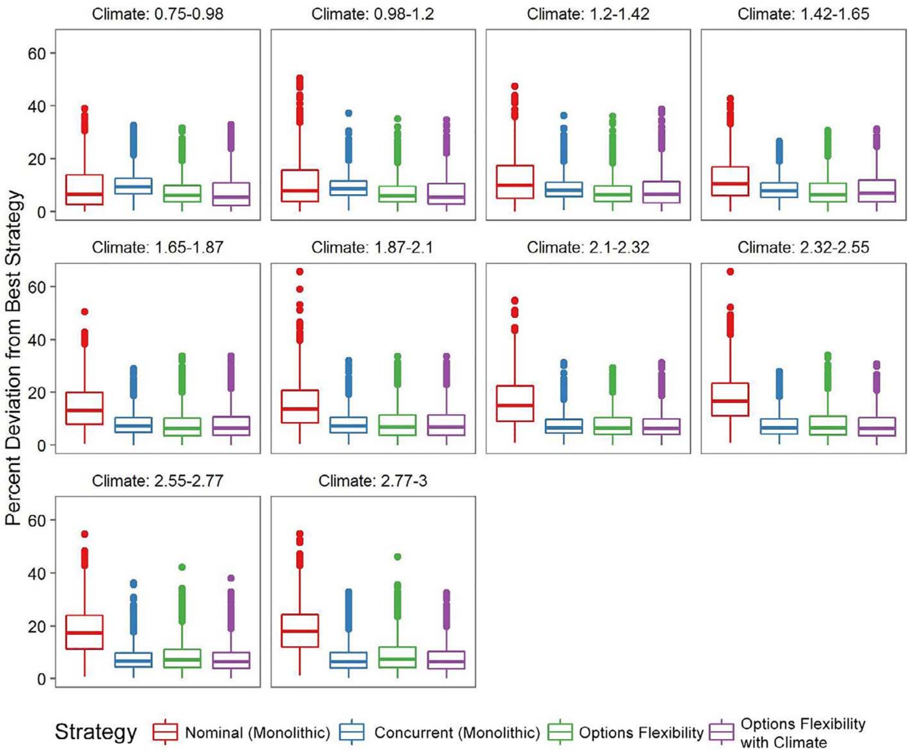

Fig. 4. Percent deviation from the most cost-effective strategy grouped by climate factor. Middle line represents the 50th percentile, boxes extend from the 25th and 75th percentiles, and whiskers extend to the 1.5 times the interquartile range with observations outside of that plotted as dots. Each 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.

and whisker plots (Fig. 4). Of particular note is the increase in variability of the Nominal Strategy as the magnitude of climate impact increases. The performance of the strategy with options flexibility is remarkably consistent relative to the baseline throughout the simulation. The strategy with options flexibility shows the most benefit over monolithic strategies under moderate levels of climate change. It achieves this consistency by identifying and proactively upgrading the most at-risk and climate-sensitive crossings, resulting in fewer high losses as compared to monolithic strategies. This may be of particular interest to transportation 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.

4.2. 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 only known with some degree of uncertainty. Many DOT's are grappling with culvert and other roadway element asset and data management plans (Perrin and Dwivedi, 2006). The cost of collecting and acting on this data varies widely by system structure, geography, and agency context, and standards for accuracy and uncertainty in culvert data are not yet widely adopted, though such parameters are needed to judge the value of information. To simulate a range of information about system characteristics, we treated the standard error for each parameter as a fraction of its original range shown in Table 4, and tested 10%, 30%, and 50% of the original range. This allows us to explore the wide range of uncertainty that will vary from agency to agency. 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.

Fig. 5 shows that the strategy with options flexibility 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. But 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 that responds differently to adaptation and change, diversification of adaptation strategies is an effective way to minimize the potential for large losses.

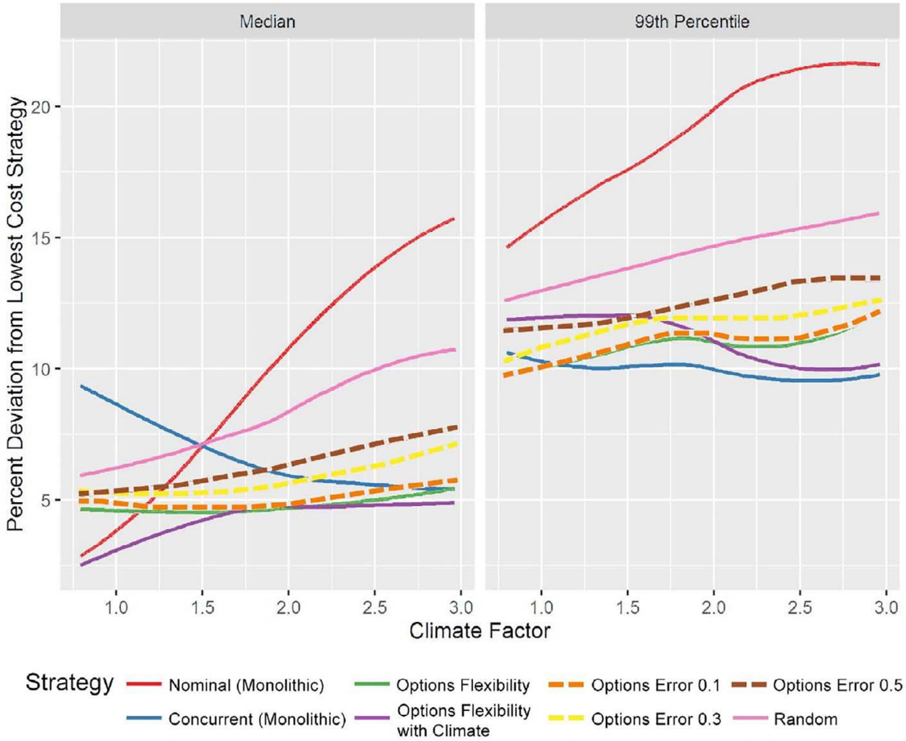

Fig. 5. Percent deviation from the most cost-effective strategy vs changes in climate factor. (a) Mean percent deviation from the most cost effective strategy vs climate factor. (b) 99th percentile percent deviation from the most cost effective strategy vs climate factor. Solid lines show the standard strategies. The dashed lines show the Strategy with options flexibility 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 "Options Error .5" follows a similar path to the Strategy with options flexibility but shifted further from the most cost effective strategy.

5. Conclusions

Sixty-five percent of interstates and 74% of other roads in the US are in rural areas, many of them managed by small towns and counties (Federal Highway Administration, 2011). The majority of climate sensitive infrastructure decisions over the next 100 years will be made at the local level for projects costing tens or hundreds of thousands of dollars rather than large projects costing millions 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. Current policies aimed at adaptation in such dispersed infrastructure systems favor broad monolithic standards. Many of the decision tools proposed for adapting to climate change reflect these policies. A more discerning approach based on characteristics of individual infrastructure units, matched with flexible standards, could make adaptation more efficient.

Using a testbed of simulated yet realistic crossings to evaluate effects of increasing runoff intensity on stormwater infrastructure, we show that incorporating options 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 does a monolithic policy strategy. Additionally, we found that randomly adapting infrastructure at the time of replacement, can, by balancing the risk of over- and under-adapting, offers improvements to the efficiency of adaptation in the face of deep uncertainty about future climate. Furthermore, applying different engineering standards based on known or learnable environmental and infrastructure characteristics offers a way to increase the efficiency of adaptation through simple policy changes. Cost-effective methods of decision-making will be especially important for smaller governments with limited resources.

Future work will determine how much a decision maker should be willing to pay for this information. This analysis was limited to the cost of implementing 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 options 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.

Declaration

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.crm.2017.12.002.

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