SIMULATED CLIMATE ADAPTATION IN STORMWATER CONVEYANCE STRUCTURES

by

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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Abstract

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Simulated climate adaptation in stormwater conveyance structures

Thesis directed by Associate Professor William R. Travis

Adaptations in infrastructure may be necessitated by changes in temperature and precipitation patterns to ensure that investments offer a consistent service level and remain cost effective. The timing of individual adaptations will vary and can be described in relation to the climate stimulus as being anticipatory, concurrent, or reactive. Furthermore, climate change adaptation can be implemented as flexible policies that acknowledge the inherent differences in individual elements or as monolithic policies applied uniformly to all elements of an infrastructure system. Significant progress has been made in studying climate change adaptation decision making that incorporates climate uncertainty, but less work has examined how adaptation strategies interact with existing infrastructure characteristics to influence adaptability. Here we examine the interaction of culvert characteristics and the timing of adaptation strategies under varying amounts of climate change using a virtual testbed of realistic drainage crossings or roadbeds in Colorado. Additionally we examine the performance of flexible policies that allow for different timing strategies based on individual crossing characteristics.

We use one-at-a-time sensitivity analysis and Monte Carlo simulations to compare the impact of varying amounts of climate change and crossing characteristics on the cost efficiency and service level of crossings. Based on the results of these analyses we use a metamodel approach with multinomial regression to create what we refer to as a vertically flexible strategy, i.e. allowing for unique adaptation timing based on the characteristics of individual crossings.

We find that existing characteristics can have a greater impact on the success of strategies than the amount of climate change. Furthermore we find that crossing characteristics can be used as a decision criterion to effectively choose the timing of strategies even if the future climate is unknown. Our results show that a vertically-flexible strategy informed by crossing characteristics offers a more efficient method of adaptation than monolithic policies. We explore the implications of this as a cost-effective adaptation strategy for agencies building long-lived climate sensitive infrastructure, especially where detailed system data and analytical capacity is limited.

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Table of Contents

List of Figures

List of Tables

Chapter 1-Introduction and Overview

This research had three goals. First, it sought to analyze and model the problem of stormwater infrastructure planning and management in a changing climate. It did this by developing a flexible decision modeling testbed, using it to simulate the impacts of increasing rainfall intensity on culverts (infrastructure elements that convey runoff across a road alignment), and analyzing the outcomes of alternative management decisions. Second, it placed this particular infrastructural case into the broader framework of adaptation strategies, for other types of infrastructure but also for adaptation decision-making overall. This was done by deriving propositions from the literature, and forming them into strategies to be tested in the virtual testbed, and then reflecting back on the more universal question of how and when to adapt in a non-stationary environment. Finally, the work included development of the necessary tools and code for exploratory modeling analysis.

Given the current concentrations of greenhouse gasses and projections of future emissions, levels of climate change that necessitate adaptation are considered inevitable (Smith, Horrocks, Harvey, & Hamilton, 2011). Accepting the need for adaptation prompts several fundamental questions for managers of climate-sensitive systems: what degree of climate change should be expected, how will global climate change manifest locally, when should adaptation efforts start, and how much adaptation is necessary, amongst others. Many of these questions cannot be answered due to the deep uncertainty associated with future climate conditions (Hallegatte, 2009). This motivates calls for a risk and decision approach to climate change adaptation (Hultman, Hassenzahl, & Rayner, 2010; Jones & Preston, 2011). Much of this effort has focused on large and high-consequence infrastructure such as coastal and urban flood protection (Ranger, Reeder, & Lowe, 2013; Michelle Woodward, Kapelan, & Gouldby, 2014), and water supply (Lempert & Groves, 2010), with less focus on distributed systems like stormwater management.

This research aims to address this gap by analyzing a representative set of drainage crossings served by culverts. A culverts is defined by the Federal Highway Administration as

> …a conduit which conveys stream flow through a roadway embankment or past some other type of flow obstruction. Culverts are constructed from a variety of materials and are available in many different shapes and configurations. Culvert selection factors include roadway profiles, channel characteristics, flood damage evaluations, construction and maintenance costs, and estimates of service life (Federal Highway Administration, 2012, p. 15).

They are a ubiquitous part of the global road infrastructure and are sensitive to predicted increases in extreme precipitation patterns as a consequence of climate change (Tebaldi, Hayhoe, Arblaster, & Meehl, 2006). Additionally they are long lived, with potential design lives of 100 years (Maher, 2015), and even longer actual service lives (J. N. Meegoda, Juliano, & Wadhawan, 2007). Culverts installed today will need to function over a variety of unknowable futures climates. While dynamic and robust decision tools are well suited to decision making strategies for problems with deep uncertainty, the sheer number of culvert decisions made by numerous agencies renders these more costly and complex approaches less practical.

The effects of climate change at a decision scale are largely considered to be an irreducible uncertainty with no indication of improvement in the foreseeable future (Hulme, Pielke, & Dessai, 2009; Walker, Haasnoot, & Kwakkel, 2013). Despite these challenges, climate projections currently play an outsized role in climate adaptation decisions to the point that other uncertainties are ignored (Dessai, Hulme, Lempert, & Pielke, 2009). In this research we focus on the advantages of learning more about the climate sensitivity and adaptability of current infrastructure, thus turning to problems with reducible uncertainty. In the first part of this study, we investigate how changes in crossing qualities can influence the success of adaptation strategies both in conjunction with and without knowledge of future climate conditions. In the second part we use the results from part one to ask whether explicitly considering the climate sensitivity and adaptability of individual infrastructure elements can lead to more cost-effective adaptation than monolithic policies that ignore individual differences.

To address these questions we use a simple exploratory model for policy analysis (Bankes, 1993) and simulate a virtual testbed of culverts over a 100-year time span. The model operates at a yearly time step with culverts replaced at the end of their useful life and the potential for extreme events to damage or destroy culverts at each time step. We simulate climate change by increasing the probability of an exceedance event as the simulation progresses. We focus on the difference in the timing of adaptation strategies with the potential for adaptation to occur in anticipation of climate change, in conjunction with, or in reaction to change.

Our results show that differences in the climate sensitivity and adaptability of infrastructure can be as important as knowing the future climate, especially in cases of moderate climate change. We also find that policies which allow for individualized adaptation strategies are more effective than monolithic policies that specify a strategy for all elements. In all simulations we found anticipatory adaptation, replacing infrastructure prior to the end of its useful life, to be more costly than other options. Finally we show that given no additional knowledge of climate, or of the adaptability and climate sensitivity of infrastructure, diversification of adaptation strategies minimizes the risk of both over- and under-adaptation.

This motivates the comparison of infrastructure systems to investment portfolios, with the possibility that diversification strategies, and a focus on correlated risks common in financial planning, could be usefully applied to infrastructure decision making.

These results about incremental adaptation of low consequence, dispersed infrastructure imply conclusions relevant to several universal adaptation questions. Insufficient knowledge of future climate, and specifically climate on a local decision scale, is frequently cited as a barrier to engaging in climate change adaptation (Biesbroek, Klostermann, Termeer, & Kabat, 2013). Our results show that this may be more a perceived rather than a realistic barrier. The existing characteristics of infrastructure can be used to inform adaptation decisions regardless of climate change. With the knowledge that precipitation will likely intensify, a manager can begin upgrading a subset of their most vulnerable and easily adaptable infrastructure at the time of replacement. Furthermore a decision maker could take a risk management approach, aiming to reduce correlated negative outcomes.

Flexibility in various aspects of adaptation decisions and strategies is often proposed as a method to address deep uncertainty associated with future climate conditions. Many of these strategies seek to avoid unacceptable failures with high cost or fatalities, and as a consequence err toward over-adaptation. Seldom discussed in research are the consequences of over-adaptation which might be a very real risk for rural and developing communities with limited institutional resources. Adaptation almost always implies additional cost over a business-as-usual approach. Communities with limited resources will need to decide which systems to adapt, and often whether adaptation is important enough to warrant cutting budgets for other government services. Over-adaptation in one sector can limit a community's adaptive capacity by restricting adaptation in other areas, or by reducing community investment in services that increase their long-term adaptive capacity.

Our results also encourage skepticism of adaptive actions that sacrifice the current value of infrastructure in attempts to become better prepared for infrequent extreme events or uncertain future conditions. We simulated an anticipatory strategy in which all crossings were replaced at the beginning of the simulation and while these runs generally saw a decrease in flood damage they resulted in large additional construction cost from the early replacement events. Despite these results we can imagine situations in which anticipatory adaptation can be beneficial, namely in circumstances where the cost of failure is much higher (the infrastructure protects significant property) or when the probability of future loss is more certain (such as persistent nuisance flooding from sea level rise).

Next Steps and Limitations

This work is limited by several simplifications made to effectively model the system: treating damage as linearly increasing with the exceedance of design storm, simulating climate change as a simple shift in the location parameter of the distribution, using a single distribution for extreme event generation, treating culvert deterioration as a linear process, and assuming that adaptability and climate sensitivity varies between infrastructure elements.

Flood damage is notoriously hard to predict based on precipitation or inundation. Additionally it frequently exhibits non-linear behavior with a step function somewhere between minor damage and complete loss. In this research we ignore these complications and treat flood loss as a linear increase based on the degree to which the event exceeds the design flow, and we identify a discrete point at which the degree of damage will always necessitate replacement. We chose to make this simplification for two reasons. First, culvert failure and damage is extremely site-dependent and mediated by myriad environmental factors and construction choices. Lacking a large database of crossings and information about damages it is not possible to make generalizations to use in a statistical model. This limitation is partially addressed by varying the amount of flow needed to damage a culvert through what we refer to as a Resilience Factor, allowing us explore a large variety of damage curves.

In simulating extreme events we are limited by both the uncertainty of climate change and the diversity of distributions used. We chose to use a single generalized extreme value (GEV) distribution to generate events. Future work could examine how different distribution shapes respond to climate change and whether the shape and scale of a distribution affect the climate sensitivity or the adaptability of a crossing. We also chose to implement climate change as a simple shift in the location of the GEV distribution. While some research and modeling efforts indicate that climate change may potentially impact other moments of the distribution, these conclusions are much less certain and there is more disagreement in predictions. Exploring how changes in additional moments will impact adaptation decision making could be an important use of exploratory modeling.

Similar to flood damage, culvert deterioration is a non-linear process mediated by site-specific variables. Moreover, lacking a large database of site conditions, culvert installations, inspections, and replacements, it is impossible to determine relationships that are useful in a statistical model. This a broader problem that infrastructure managers are grappling with as many start to suspect that assumed design lives exhibit more variation that originally specified (Maher, 2015). Future work in this area has the potential to determine important interactions between culvert deterioration and climate change adaptation.

The final limitation is the most relevant to our conclusions. Our model assumes variation in the climate sensitivity and adaptability of infrastructure elements. We assume that this variability is knowable and can be used to inform infrastructure planning. Lacking real world data about culvert failure, installation cost, and flood damage it is impossible to determine the distribution of these differences. A system with no variation in adaptability and climate sensitivity likely does not exist but there are certainly systems where the variability is minimal. In these systems our conclusions regarding the use of crossing characteristics to select adaptation strategies are not generalizable, but our conclusions about diversifying strategies remain.

Accepting these limitations allowed us to efficiently model a system of dispersed elements and the implications of different adaptation strategies based on the climate sensitivity and adaptability of a crossing, and to address broader issues in the adaptation of dispersed infrastructure with limited intuitional resources, as well as the more universal questions of when and what to do in adaptation.

Chapter 2- Evaluating the efficiency of adaptation pathways

Introduction

A range of strategies is available to infrastructure managers attempting to adapt to climate change. As more system managers have become convinced, by current trends or projected future change, of the need for some explicit adaptive posture, studies of alternative adaptation actions have blossomed and provided initial foundations for evaluating their relative efficiency and efficacy. The climate change adaptation literature, back to at least the early 1980s (Kates, 1985), first offered simple classifications of the type and timing of adaptation: reactive, concurrent, or anticipatory (Smit et al., 2000). Other distinctions included incremental adaptations that adjust systems but leave their overall structure in place, and transformative adaptations that fundamentally alter system organization, scale, location or goals (Kates et al., 2014).

Growing attention to current extremes, in concert with continuing uncertainty about future climate change, yields a notion that some adaptations could be counted as "no regret." No regret options pay off by better adapting systems to current risks while also providing adaptive benefit as the future climate unfolds (Dilling, Daly, Travis, Wilhelmi, & Klein, 2015; Field et al., 2012; Thomalla, Downing, Spanger-Siegfried, Han, & Rockström, 2006). A more subtle framing replaces traditional adaptation with resilience, traditionally defined as a system's ability to recover after a shock without transforming. More recently, resilience has been elaborated into a more inclusive property of systems characterized by measures of preparation, absorption, recovery, and adaptation (Linkov, et al., 2013), especially in the face of unpredictable stresses (Sikula et al., 2015). Other approaches explore elaborated adaptation "pathways", recognizing the dynamic, time-transgressive nature of adaptation to trends that affect system performance, and allow learning and revision, over the long term (Marjolijn Haasnoot, Middelkoop, Offermans, Beek, & Deursen, 2012; Wise et al., 2014). Thus adaptation is increasingly evaluated with the tools of risk and decision analysis that search for the points at which systems fail (Brown, Ghile, Laverty, & Li, 2012), seek dynamic optimization (Kasprzyk, Nataraj, Reed, & Lempert, 2013; Jan H. Kwakkel, Haasnoot, & Walker, 2014), maintain future options (Hallegatte, 2009; Hultman et al., 2010; Jones & Preston, 2011; Moss et al., 2014), provide robustness (Lempert, Popper, & Bankes, 2003), or explicitly value future options (Michelle Woodward et al., 2014).

One common component of the contemporary adaptation literature is a grappling with the persistence, despite progress in climate science, of deep uncertainty associated with climate change projections. This weighs against a "predict-and-act" approach, and supports proposals for dynamic decision strategies that emphasize continual learning and revision (Walker et al., 2003, 2013). In the climate change context, these techniques have mostly been applied to planning large, integrated systems characterized by a diverse option space and a low tolerance for failure. The two most common applications have been in water supply systems and coastal flood protection. However, managers of more dispersed systems also need to adopt climate adaptation strategies. Given a commitment to adapting to climate change, the universal questions abide: what to do and when to do it? We test answers with exploratory modeling analysis (Bankes, 1993) applied to climate sensitive infrastructure via a virtual testbed of simulated stormwater conveyance elements.

Evaluating Adaptation in Dispersed Stormwater Infrastructure

Runoff must be conveyed across or through road alignments in some fashion or it will impound, and perhaps wash out, the roadbed. The most common device, referred to in this paper as a crossing or culvert:

> ….is a conduit which conveys stream flow through a roadway embankment or past some other type of flow obstruction. Culverts are constructed from a variety of materials and are available in many different shapes and configurations. Culvert selection factors include roadway profiles, channel characteristics, flood damage evaluations, construction and maintenance costs, and estimates of service life (Federal Highway Administration, 2012, p. 15).

Some pass permanent streams under roads, while others are emplaced to convey stormwater or peak flows caused by short-term, intense rainfall or snowmelt. All are designed, more or less formally, with a peak discharge in mind, and sized accordingly. With design lives of up to 100 years (Maher, 2015) and actual service lives sometimes greater than 120 years (J. Meegoda & Zou, 2015), crossing capacity is sensitive to climate change. Deep-fill culverts, with 10-20 or more feet of cover, are extremely expensive and disruptive to replace and thus counted on to perform for decades.

A variety of adaptive strategies remain available for such systems. One soft strategy is to relax expectations, reckoning that performance marginally outside nominal limits, perhaps routine incursion into what were originally defined as safety buffers, is acceptable during some period after climate change has moved the system out of specification and before it can be upgraded. Furthermore, accepting more “graceful failures,” like temporary impoundment or over-topping across road surfaces, may be less costly and disruptive than active adaptation.

Shortening the lifespan of infrastructure to reduce the decision horizon, another generic strategy for adapting to uncertain climate change (Hallegatte, 2009), may be poorly suited to the case of road beds and culverts due to the fixed cost associated with each replacement, though it might apply to the smallest devices and lowest service levels (as with driveways or backcountry roads). Such strategies are problematized, but perhaps also incentivized, by the difficulty of discerning the effect of climate change from natural variability in something as noisy as extreme precipitation (National Academies of Sciences, Engineering, and Medicine, 2016).

With dynamic options limited, robust strategies often mean installing a larger crossing with greater capacity than traditional minimum specifications. This strategy can be inefficient, and invokes the potential, rarely analyzed in climate change literature, for over-adaptation (De Bruin & Ansink, 2011). Over-adaptation in one area reduces resources available for other adaptations or future unforeseen consequences, hence reducing overall adaptive capacity (Smit & Wandel, 2006).

We explore options for when to adapt using a realistic testbed of road crossings, and test an adaptation typology common in the literature (Smit et al. 2000), including anticipatory, concurrent, and reactive, along with the nominal (no adaptation) case in which culvert capacity is not increased even when destroyed by extreme runoff. Rather than focus on the climate change forcing, we examine the efficacy of basing decisions on reducible uncertainty associated with characteristics of the crossings themselves, such as cost of damage or difficulty of upgrading a culvert, “which influence their propensity to adapt and/or their priority for adaptation measures” (Smit, Burton, Klein, & Wandel, 2000, p. 14). We then compare the influence of these characteristics to changes in flood frequency and total cost. We address these with two main research questions:

1. How do adaptation strategies with different timing qualities perform with varying crossing characteristics and climate change trends?
2. Can system characteristics be used to predict the preferred strategy based on cost, and if so, how much better are predictions when climate change is known?

Methods

We created a virtual testbed of culverts whose performance and costs can be simulated over specified timespans, henceforth referred to as the "culvert model" or simply the testbed. Our model follows the tradition of an exploratory tool for policy analysis, focusing on computational experiments to explore possible futures rather than a consolidative model acting as a surrogate for actual systems (Bankes, 1993; Jan H. Kwakkel, Walker, & Marchau, 2012). In other words, the culvert model is a 'what-if' tool rather than an attempt to predict future conditions, though it simulates actual culverts. The testbed structure is meant to provide for changing and enlarging the assemblage of simulated culverts, their crossing characteristics, and the external stresses applied (Francis, Falconi, Nateghi, & Guikema, 2011). Simulation results include individual and aggregate cost of flood damage, cost of normal and emergency construction, cost of delay hours, and the number of replacement events over a simulated life span. The model was written in the R programming language (see: R Project for Statistical Computing (Venables & Ripley, 2002)).

Climate Scenarios

We intersect crossing characteristics and climate change using a scenario approach (Schwartz, 1996) for climate trend. Changes especially in precipitation intensity, if not overall amounts, have the potential to stress stormwater infrastructure and result in premature failure and increased operating cost (Neumann et al., 2014). While climate change projections for impact and adaptation studies can be derived from global climate model output, we follow the approach of several infrastructure researchers and apply a feasible, though simple, climate trend guided by model output and climatological logic. Climate model output come with deep uncertainty and a mismatched scale; each simulation is only one realization of a possible future equally as unlikely as any un-modeled future (J. H. Kwakkel, Haasnoot, & Walker, 2012). Large multi-thousand-member ensembles (e.g. those available from http://www.climateprediction.net/) which explicitly resolve regional details have shown climate sensitivity (mean temperature response to a doubling of CO_2) ranging from 2° K to 11° K (Stainforth et al., 2005). There is additional concern that changes in the many initial parameters can have large and unknowable effects on long term simulations (Bradley, Frigg, Du, & Smith, 2014), and that ensemble and heavily-parameterized outputs may downplay extreme predictions (Jones & Preston, 2011). In light of these concerns we followed other decision researchers and used a scenario based approach to climate change aimed at capturing broad uncertainty (Hulme et al., 2009; Hultman et al., 2010; Kunreuther et al., 2013; Kwadijk et al., 2010; Jan H. Kwakkel et al., 2014; J. H. Kwakkel et al., 2012).

Our climate scenarios do reflect meteorological logic and climate modeling. Climate models show increases in precipitation totals and intensification of individual events on the global scale, especially in higher-latitudes, over the coming century of anthropogenic warming (Tebaldi et al., 2006). Significant precipitation intensification has already been observed in the latter half of the 20th century (Donat, Lowry, Alexander, O'Gorman, & Maher, 2016; Groisman et al., 2005), including in the north-central and northeastern sectors of the U.S. (Romero-Lanko et al., 2014). But, reflecting the tendency of model outputs to vary with scale, down-scaling to Colorado yields results that point both to intensification of heavy precipitation events (Mahoney, Alexander, Thompson, Barsugli, & Scott, 2012; Tebaldi et al., 2006) and no significant change (Alexander, Scott, Mahoney, & Barsugli, 2013; Mahoney, Alexander, Scott, & Barsugli, 2013).

Crossing Test Bed

Data on culverts is more difficult to find than for bridges. Other stormwater researchers confirm this, finding that most transportation infrastructure agencies do not have a centralized system for tracking culvert installations and condition (Jay Meegoda, Juliano, & Tang, 2009), except as they are specified in construction bids and plans. A recent survey found that 60% of road infrastructure management agencies in the U.S. did not keep systematic data on culverts (Maher, 2015). Analysts thus turn to hypothetical examples (Mailhot & Duchesne, 2009), or to specific crossing cases, often ones brought to the fore by recent failure (Gillespie et al., 2014). We used construction bid and project records for actual crossings in Colorado to choose a set of crossing characteristics to populate our testbed. By including a range of system characteristics, we varied the ease of adapting crossings, the consequences of crossing failure, and crossing sensitivity to increased flows.

Fixed Crossing Characteristics

To assign realistic characteristics to the crossings in our testbed, we selected eight recent culvert replacements bid by contractors for the Colorado Department of Transportation (CDOT) (Colorado Department of Transportation, 2016a). The cases include all of the costs associated with replacement, such as removal of previous structures, excavation and fill, mobilization, and paving. We characterize each crossing using the following variables: crossing road, design flood, material, service life, replacement delay (days with reduced traffic capacity or speed due to replacement), and cost. We review these variables in detail below and list their values in table 1, along with the actual install dates for the culverts we based our testbed on.

Table 1-Fixed Crossing 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

The crossing road, cost, replacement delay, and material characteristics are based on the CDOT bid tabulations. We estimated culvert service life based on material and previous research (Maher, 2015; Perrin Jr & Jhaveri, 2004). These values are static in the model, a limitation discussed in the introduction. The bid tabulations do no list the design flood so we assume all construction follows the specifications in CDOT's Drainage Design Manual (Colorado Department of Transportation, 2004). The manual provides individual specifications for rural and urban areas; based on the location of crossing we assumed that all of the culverts in our testbed are considered rural. The manual specifies that multi lane roads in rural areas should have culverts designed to the 50-year return interval (RI) and two lane roads should be designed to the 25-year RI if the 50-year flow is less than 4,000 cfs and 50-year flow is greater than 4,000 cfs. The manual also suggest increasing capacity where "associated damaged is judged to be severe". Of the culverts in the testbed we assumed that all but the Mesa and Montezuma culverts are designed to the 100-year flow due to the lack of alternative routes and severe consequences should they fail.

Each crossing road is characterized by four variables: average annual daily traffic (AADT), proportion of traffic from freight (trucks), delay in hours during a planned replacement, and delay in hours due to failure and emergency replacement (table 2).

Table 2-Road Characteristics

Road Name	**AADT**	**Percent Truck**	**Delay (planned)**	**Delay (unplanned)**
SH145	2000	12.3	0.2	1
US40	4600	11.7	0.1	0.3333
US550	5900	4.2	0.1	2
SH12	2200	5.5	0.1	3
SH125	1800	12.3	0.2	0.5
US491	7100	9.2	0.1	0.1
SH139	2000	8.5	0.1	0.1
SH82	960	1.9	0.1	1

We used CDOT's Traffic Data Explorer to determine the AADT and percent truck traffic (Colorado Department of Transportation, 2016b). We assumed that delays from planned failures would be minor due to the relatively low volume of traffic handled by each road. We calculated delay due to failure using Google Maps driving times and finding the shortest alternate route (Google Maps, 2016).

Variable Crossing Characteristics

Many culvert characteristics affect adaptability, and a crossing's sensitivity to climate. The characteristics we explore are shown in table 3 and elaborated on below. Over thousands of simulations, we test a range of values for each characteristic. To explore the possible impacts of these variables we conduct extensive sensitivity analysis on each of the variables.

Table 3-Variable Crossing Characteristics

System Characteristic	Starting Value	Step	Range
Upgrade Cost	2.0	0.5	1.0-4.0
Upgrade Amount	2.0	0.25	1.5-2.5
Post Upgrade Factor	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

We use three variables to represent the adaptability of a crossing: Upgrade Cost, Upgrade Amount, and Post Upgrade Factor. Upgrade Cost determines the cost of increasing the capacity of a crossing. The cost is proportional to the capacity increment and to the crossing's original cost multiplied by the Upgrade Cost. This cost is dependent on the individual circumstances of the crossing. In some cases upgrades may only entail a small increase proportional to the original cost, i.e. the upgrade can be accomplished by a larger pipe with minimal extra labor and excavation. In other cases the upgrade could invoke a significant cost increase, for example moving from a precast concrete box to a reinforced concrete box that is cast in place. Using a range of Upgrade Cost multipliers based on the original install cost allows us to explore a realistic range of these possibilities. The Upgrade Amount is the degree to which a crossing's capacity is increased under the different adaptation strategies. All upgrades are proportional to the original design storm. The Post Upgrade Factor allows replacements after the initial upgrade to be less expensive in line with cost estimates based on life cycle.

Emergency Cost and Resilience Factor are used to represent a crossing's sensitivity to changes in climate. Emergency Cost reflects the increased cost of replacement and repair after an unexpected failure. To find the cost of replacement after failure, the original cost is multiplied by the Emergency Cost Factor. The Resilience Factor describes the degree to which a flow can exceed design capacity before a crossing is damaged. Starting values for variable characteristics were calibrated such that the current infrastructure is more cost effective than an upgrade under scenarios with no climate change. The validity of this assumption will vary depending on specific infrastructure. Some researchers argue that current infrastructure is underspecified for the present climate, implying that increasing capacity may be beneficial regardless of climate change, a form of no regret action (Burton, 2004).

Simulating Climate Change and Extreme Events

Climate change is incorporated into the simulations using a linear change in the location parameter of a generalized extreme value (GEV) distribution following the methods used in (Mailhot & Duchesne, 2009). The cumulative distribution function for the GEV distribution is shown below in Equation 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 the a given duration, μ is the location parameter, σ is the shape parameter, and ξ is the scale parameter. We fit the original GEV distribution to a block maxima of yearly precipitation events to approximate shape and scale of yearly maximum stream flow, a technique used by CDOT when making infrastructure decisions (Colorado Department of Transportation, 2004). For distribution fitting we used extRemes package in R (Gilleland & Katz, 2011). Fitting was done using maximum likelihood estimation assuming stationarity and model selection was based on AIC. We fit models based on the GEV and Gumbel distributions. The effect of climate change is only realized in the location parameter of the GEV distribution. There is evidence that climate change could possibly cause changes to the shape parameters and other moments of distributions (Field et al., 2012; Read & Vogel, 2015). This possibility is important to explore and should be addressed in future work.

In one-at-a-time sensitivity, we apply three climate change scenarios: no change, low and high impact from climate change on the frequency of extreme events. Following Mailhot and Duschesne (2009), we apply all changes to climate by altering the return interval of the storm. The low and high scenarios reduce the return interval of the design storm by 33% and 50% respectively, which comports with a 6 to 15% increase in stream flow. 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 original 200 year event. Each year the location parameter is linearly increased to simulate this non-stationary risk.

Adaptation Strategies

We test four adaptation strategies: Nominal, Anticipatory, Reactive, and Concurrent. The Nominal strategy assumes no change in culvert replacement strategy over the entire simulation; in the event that a crossing's lifespan is reached, or the crossing is destroyed by a runoff event, it is replaced with a crossing of the same capacity. Under the Anticipatory strategy, all crossings are replaced with higher capacity crossings prior to the end of their lifespans. This would be the case if a manager decided that climate change is a significant enough threat that it requires increasing the capacity of culverts in anticipation, but where budgets restrict the rate of upgrade. The testbed simulations reported here allowed one crossing to be replaced each year until all crossings had been upgraded. Under the Concurrent Strategy the capacity of each crossing is increased at the time of normal replacement. The Reactive Strategy begins with the Nominal Strategy and switches to the Concurrent Strategy when a crossing is replaced following damage by an extreme event. We do not specify the method for increasing capacity as this will vary by site, but the most obvious action is to increase the size of the pipe or to re-engineer the inlet and outlet controls. Because the model is agnostic to the method of increasing capacity, upgrade costs are calculated as a percent of the original cost per unit of incremented capacity. We explore the implications of changing upgrade cost in the sensitivity analysis.

Simulating Crossing Failure

Anytime a crossing's capacity is exceeded by a runoff event, damage is incurred. Damage is calculated based on the original cost of the crossing and the Resilience Factor. The Resilience Factor specifies how much the crossing's design capacity can be exceeded before it is damaged to the point of replacement. Damage less than that required to destroy the crossing is assumed to linearly increase to the point at which the crossing is destroyed. Damage is calculated via equation 2:

$$d = \frac{E}{R} * C_{cost} \tag{2}$$

where E is the how much the event exceeded the crossings capacity, R is how much the crossing can be exceed and not be replaced (Resilience Factor), and C_{cost} is the cost of replacing the crossing. A crossing is replaced any time the damage exceeds the current value calculated using equation 3:

$$C_{value} = C_{cost} * \frac{t_c - C_{install}}{C_{life}} \tag{3}$$

where t_c is the current year, $C_{install}$ is the install year, and C_{life} is the service life of the crossing. If the damage exceeds the current value of the crossing, it is replaced.

If the crossing is damaged the number of delay days are estimated from a triangular distribution with a minimum of .1, a max of 3 and a mean of .6 days. If the culvert is destroyed the road is considered impassible for a number of days determined using a triangle distribution with a minimum of 1, a maximum of 4 and a mean of 2 days. These parameters are based on cases examined in Perrin et al. (2004) and could be improved by increasing the number of cases investigated. The model calculates delays according to the formula described in the Measures of Success section. In the case of failure, the cost of delay is added to the cost of delay incurred during normal replacement.

Replacing Culverts

Full replacement occurs if either the culvert reaches the end of its service life or it is destroyed during an extreme event. We assume that replacement will always occur at the end of the culvert's specified service life. Previous research has shown that replacement is often delayed due to budget constraints (J. Meegoda & Zou, 2015). We also assume that all crossings have a static service life based on the shape of the culvert and the materials used for construction. In reality crossing service lives are affected by many factors, including chemical composition of water, velocity of flow, scouring, and direction of flow, amongst others (J. N. Meegoda et al., 2007).

Figure 1 shows three examples of actual model runs, selected from the hundreds of thousands of simulations to show how the model operates and illustrate a few key differences between strategies. Figure 1a shows the Nominal Strategy with a no climate change. In this run the crossing experienced two small flood events that damaged the crossing but did not require replacement, and then at approximately year 70 the crossing is replaced at the end of its useful life. Figure 1b shows the Nominal Strategy with high climate change (climate factor of 2). In this run the crossing is replaced three times, once at the end of its useful life and twice after being damaged by extreme events. Damage from the events is higher due to the increased cost of failure-induced replacement. A Concurrent Strategy sample run with high climate change (figure 1c) experienced no flood events but the cost of normal replacement is more costly than the Nominal Strategy because the crossing's capacity is increased.

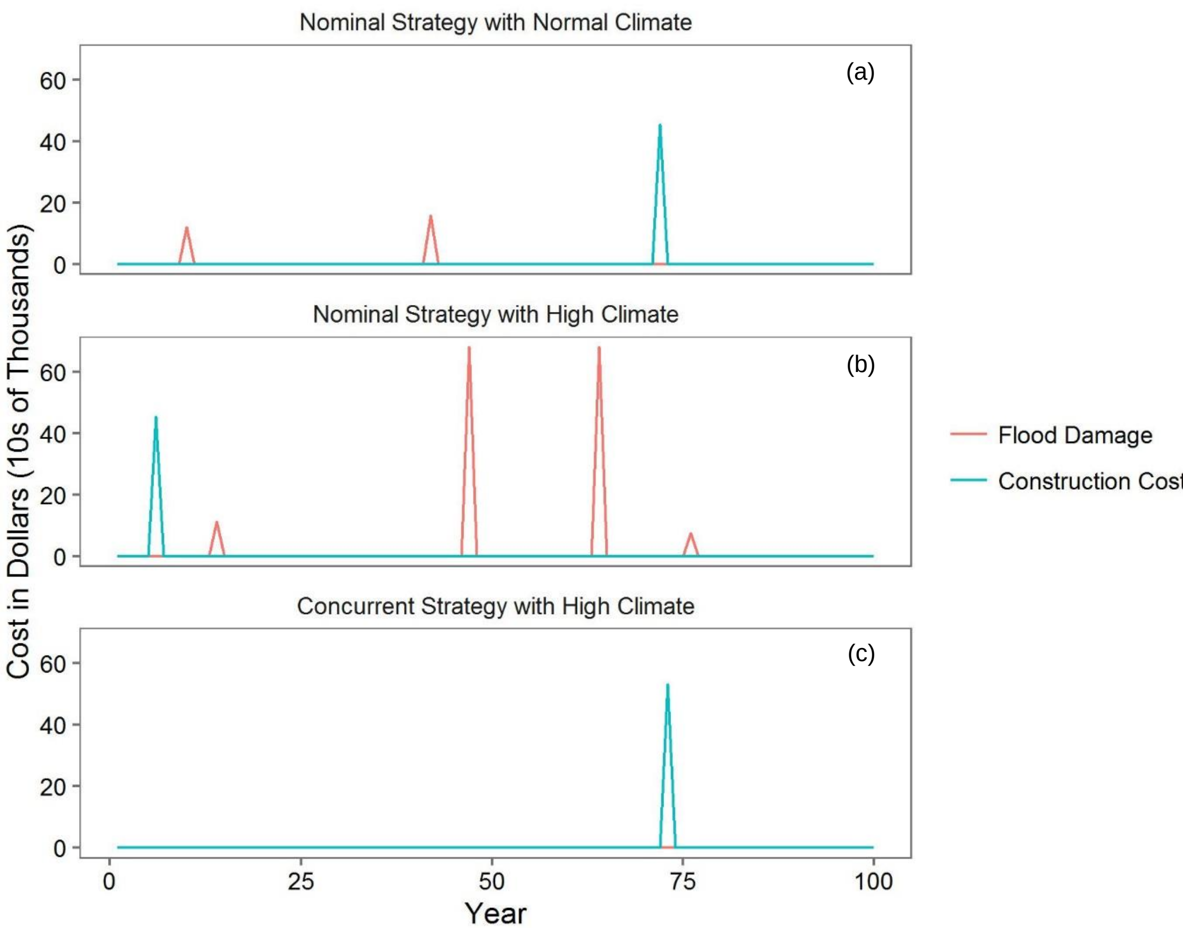


Figure 1-Flood damage and construction cost from sample model runs. (a) A sample run with no climate change and the Nominal Strategy. The sample run has two small flood events that damage the crossing but do not necessitate replacement and one normal replacement event. (b) A sample run with high climate change (climate factor of 2) and the Nominal Strategy. The run has an early replacement event followed by a damaging flood and then two floods within 20 years that both result in enough damage to require replacement. The cost for failure-induced replacement is noticeably higher than normal replacement. (c) A sample run with high climate change and the Concurrent Strategy. This run experienced a normal replacement at about year 74 and no flood events. The normal replacement event is more expensive than replacements in (a) or (b) because the capacity of the crossing is increased.

Measures of Success

Measuring the success of climate change adaptation is a challenging and multifaceted problem, including multiple temporal and spatial scales (Adger, Arnell, & Tompkins, 2005). In many business and engineering applications, measures of success can be conflicting, with no optimal solution, requiring satisficing by the decision maker (Clemen & Reilly, 2014). We use service level and cost of maintaining the system to evaluate the performance of adaptation strategies. Crossings have the potential to be part of an interconnected system where adapting one crossing can increase impacts on others. This problem is described by Adger et al. (2005) as a spillover effect. We assume that each of the crossings in our testbed is independent, and network effects are beyond the scope of this study. Even for our relatively simply testbed, the two criteria for success can be conflicting, with increased service level causing larger maintenance costs. To avoid making assumptions about manager decision preference we examine these measures independently.

To assess cost we simulate normal construction events, and repairs or replacement after flood events. Periodic maintenance and inspections could also be included but since these are unlikely to appreciably change under different climate scenarios or adaptation strategies, we do not explicitly model them. To determine success on the metric of cost we compare adaptation strategies to the Nominal Strategy under the same climate scenario. We refer to these costs as physical costs as they are the only costs directly incurred by operators. While the cost of impacts to users are real there is some evidence that decision makers do not always incorporate them into cost benefit analysis (Chang & Shinozuka, 1996; Perrin Jr & Jhaveri, 2004).

Service level is assessed by two metrics: number of replacements and the cost of delay. The number of replacements affects service on a variety of levels. First and foremost, replacement events create delays by reducing traffic speed and capacity of a road or by requiring an alternate route. Replacement events have potential for adverse environmental impacts, additional noise and disturbance in the area, and externalized impacts on local business. Delay hours have a clear economic impact by increasing the amount of travel time by users and slowing freight delivery. The impact of delay hours is calculated in dollars using equation 4 as specified by Perrin et al. (2004):

$$D = AADT * t * d * (c_v * v_v * v_{of} + c_f * v_f) \tag{4}$$

where AADT is the average annual daily traffic of the road, t is delay experienced by each vehicle, d is the number of days delays are experienced, c_v is the cost per hour of person delay ($17.18), c_f is the cost per hour of freight delay ($50), v_v percent of AADT that are passenger cars, and v_f is the percent of AADT composed of truck traffic.

Sensitivity Analysis

To investigate the impacts of adaptation timing on the efficiency of adaptation, we compare the measures of success described above over a number of different simulations. We address Question One using visualizations from a one-at-a-time local sensitivity analysis and a global sensitivity analysis. We address Question Two using a multinomial regression on the results from the global sensitivity analysis.

One-at-a-time Sensitivity Analysis

During this stage, we vary the Crossing Characteristics described above under no change, low and high climate scenarios. In each model run we alter one Crossing Characteristic according to a specified step; starting values and steps are detailed in table 3. The simulation is then run for 2,500 iterations for each strategy and climate scenario combination. To understand the impacts of variable crossing characteristics we use one-at-a-time sensitivity analysis (Hamby, 1994), varying each of the model parameters over the ranges in table 3. In this method each variable is altered over a specified range while all other variables are held constant. All of the ranges were selected as plausible values reflected in engineering guidelines for such crossings.

Global Sensitivity Analysis

We used Monte Carlo sampling to vary all variable crossing characteristics simultaneously. Because crossing characteristics are dependent on the specifics of each site and we are unable to determine a distribution we drew all values from a uniform distributions over the ranges specified in table 3. During this exercise we switched from using discrete climate scenarios to varying the climate factor continuously between 1 and 3. The global sensitivity analysis consisted of 2,000 realizations of crossing characteristics. Each set of crossing characteristics was simulated 104 times for 832,000 total simulations each containing 100 time steps, and using 2,000 model parameter combinations.

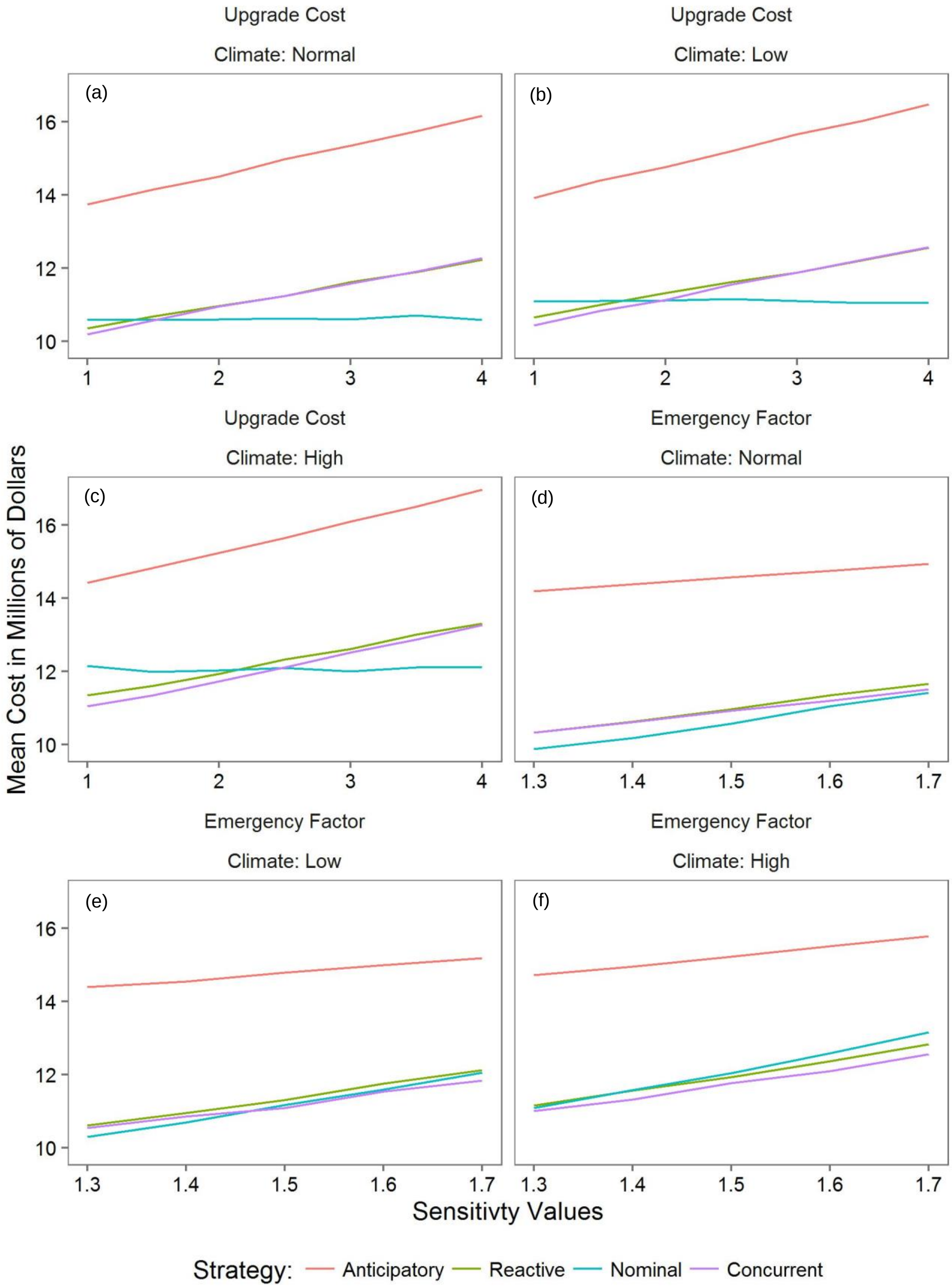
Multinomial Regression

We use a multinomial regression to assess the predictability of the preferred strategy (Hosmer Jr, Lemeshow, & Sturdivant, 2013). Since the Concurrent Strategy will almost always result in an increased service level, we judged the preferred strategy as the one that minimizes cost. As a training set we use the model simulations described above in the global sensitivity analysis, and for a test set we use the same procedure described above but repeated 100 instead of 2,000 times. We fit the multinomial models using the “mnnet” package in the R Project for Statistical Computing (Venables & Ripley, 2002). Initially we use all model parameters including climate as covariates and a bidirectional stepwise AIC to select the best combination. We include all predictors with $p<.05$ in the final model. Prediction skill was assessed by comparing results to random assignment of strategies, and the climatology of the training was set with a ranked probability skill score (RPSS).

Results

How do adaptation strategies with different timing qualities perform under different climate realizations and model parameterizations?

To address this question we used one-at-a-time sensitivity analysis as described above, altering one variable at a time while holding all others constant. Total cost and the total value of delay hours represent measures for cost and service level, respectively. Our analysis found that the Post Upgrade Factor and the Upgrade Amount had little impact on the resulting cost; as such, we do not depict them here. Key results are plotted in figure 2, physical cost against crossing characteristic values, and in figure 3, the value of delay costs against changes in crossing characteristics. In this plot we only include the Climate and Resilience Factors as the others only impact cost and not performance of crossings.


Upgrade Cost
Climate: Normal
Upgrade Cost
Climate: Low
Upgrade Cost
Climate: High
Emergency Factor
Climate: Normal
Emergency Factor
Climate: Low
Emergency Factor
Climate: High
(a)
(b)
(c)
(d)
(e)
(f)
Mean Cost in Millions of Dollars
Sensitivty Values
Strategy: Anticipatory Reactive Nominal Concurrent

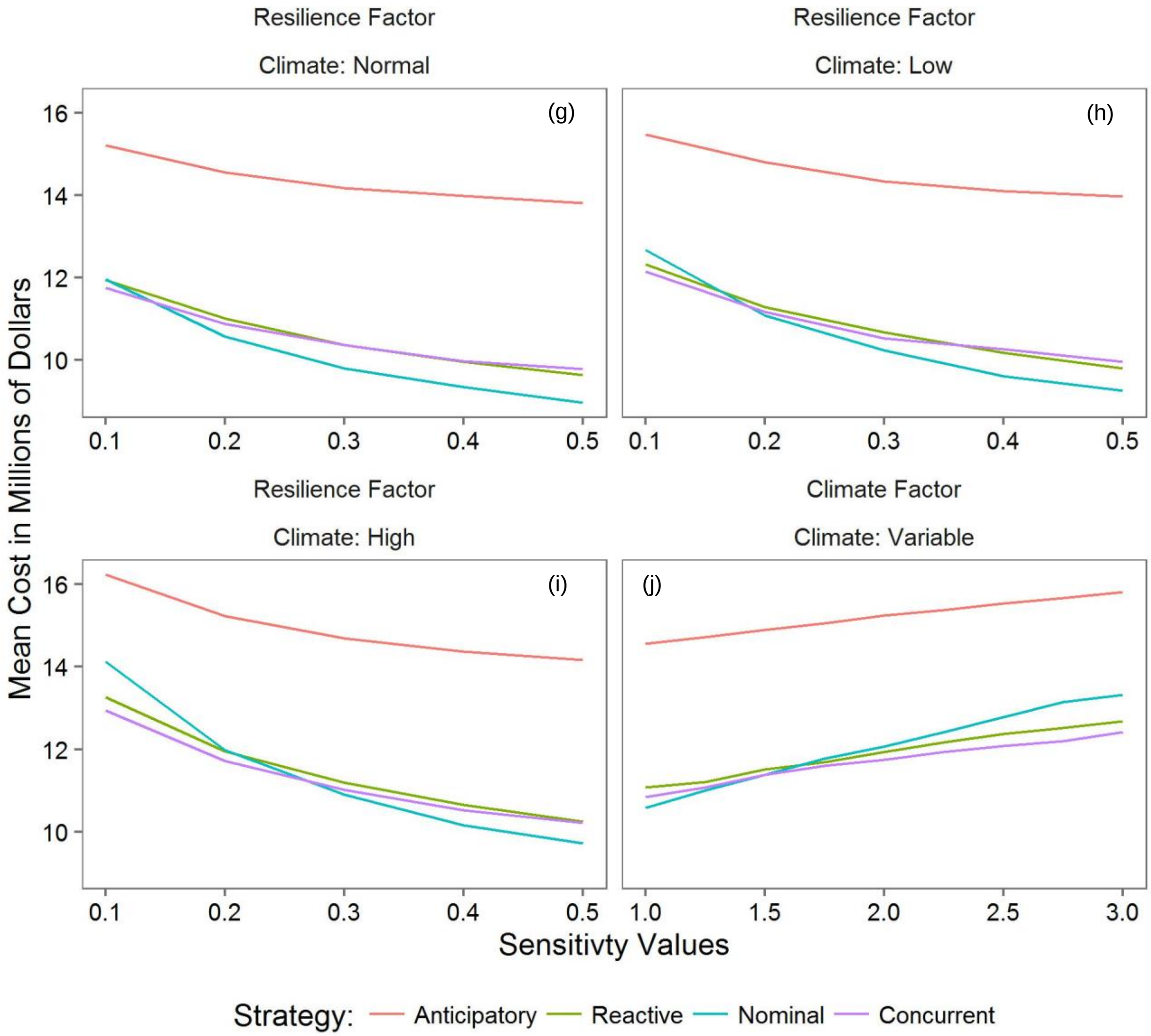


Figure 2-One-at-a-time local sensitivity analysis showing changes in mean physical cost vs changes in variable crossing characteristics for adaptation strategies with different timing. (a-c) Changes in mean physical cost vs changes in the upgrade cost under high, low, and no change climate scenarios. (d-f) Changes in mean physical cost vs changes in in the emergency factor under high, low and no change climate scenarios. (g-i) Changes in mean physical cost vs changes in the resilience factor under high, low, and no change climate scenarios. (j) Changes in mean physical cost vs changes in the climate factor. For example in the emergency factor plots (d-f) the cost of the Nominal Strategy vs. emergency factor goes from almost always being the lowest cost under normal climate (d) to almost always being the highest cost under the high climate (f)

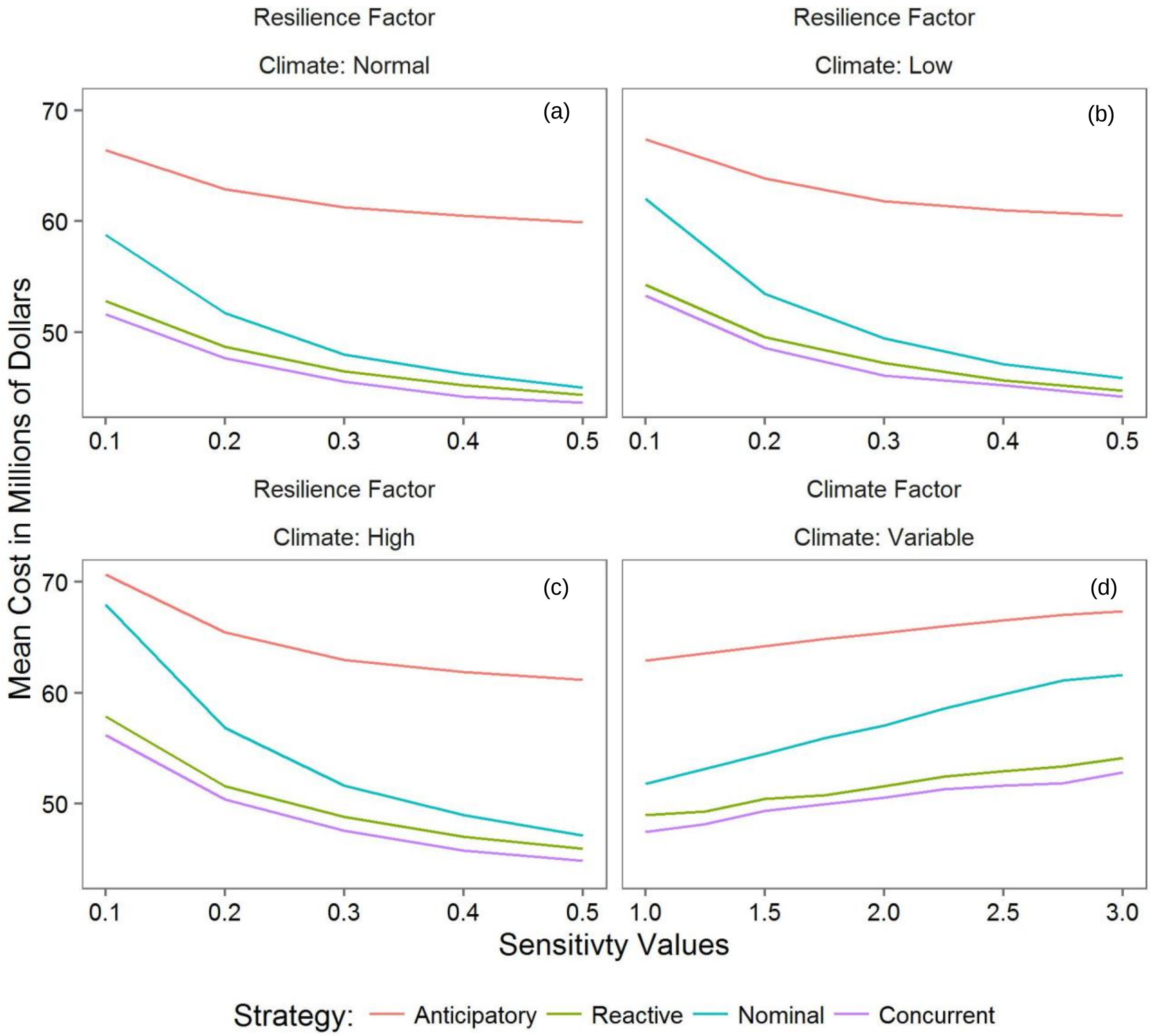


Figure 3 One-at-a-time local sensitivity analysis showing changes in user cost based on delay vs changes in variable crossing characteristics for adaptation strategies with different timing. (a-c) Changes in mean user cost vs changes in in the resilience factor under high, low and no change climate scenarios. (d) Changes in mean user cost vs changes in the climate factor. Here the Concurrent Strategy is always preferred as the increased cost are not included. Despite the earlier increase in capacity the Anticipatory strategy has higher delay cost from a premature replacement event.

It works out that the Anticipatory Strategy is inferior in level of service and cost; that is, it is outperformed by the other strategies under all parameters. One reason for this result is that each simulation inherits some value of previously installed infrastructure. Under the Anticipatory Strategy this value is sacrificed in the near term (the first eight years in these simulations) as crossings are replaced. In addition to increasing cost, these “premature” replacements actually yield a decrease service level due to delays occasioned by the replacements additional to what would occur under normal replacement cycles. It is conceivable that scenarios exist where this is the preferred strategy, but either the risk of damaging events would need to increase dramatically or the potential damage would need to be very large. In our simulation the crossings do not protect property other than themselves and the road, thus limiting the potential for very large losses. In situations where infrastructure protects additional investments, impoundment might cause additional damage, or where failure has a high risk of fatalities, an Anticipatory Strategy may be preferable.

Below we analyze in more detail the results for the Nominal, Concurrent, and Reactive strategies for both cost and service measures of success.

Upgrade Cost

We varied the Upgrade Cost between 1 and 4 with a .5 step. Under all climate scenarios the Nominal Strategy is flat (a slope of about 1), because none of the crossings are upgraded. Under the Concurrent Strategy total costs increase linearly as the upgrade costs increase. There is a slight modifying effect of the climate scenario, such that the slope increases with increased rate of climate change. We also find a modifying effect on the y-intercept under the Nominal Strategy, with an increase in cost from No Change to High Change climate scenarios because of the increased flooding. These effects result in the cost curve for the Upgrade Strategy crossing the Nominal Strategy curve at different points depending on climate the change scenario (figure 2 a-c). These results imply that as rate of climate change increases the cost-effective upgrade price increases, and the manager should be willing to pay more per unit upgrade because it helps reduce overall costs.

Rate of climate change

Climate change was simulated in the model as a linear increase in the probability of exceedance events. For example, a climate change factor of 2 represents a doubling of the probability, or halving of the return period. We vary the climate change factor from 1 to 3, while holding all other variables constant. As expected, the total costs increase as the climate change factor increases under all strategies (figure 2j & 3d). Anticipatory and Concurrent strategies reduce the rate of increase, with the Concurrent Strategy becoming preferable to the Nominal Strategy under higher rates of climate change. Under all three strategies, the cost of delay hours increased as the probability of extreme events increased. Similarly, to cost the slope of increase is greater for the Nominal strategy.

Emergency Factor

The Emergency Factor represents the increased cost of replacement after a flood event has damaged the crossing. The Emergency Factor's sensitivity is notable for the pronounced moderating effect of the climate scenario. Under No Climate Change the Nominal Strategy remains preferable to both the Concurrent and Reactive strategies (figure 2 d-f). Under the high rate of climate change this is reversed and the Concurrent Strategy is preferred under all Emergency Factor values. This shows the increased importance of the Emergency Factor as exceedance events become more common. Presumably this is what managers convinced that climate change is worsening or will worsen stormwater performance are trying to avoid by adopting more anticipatory strategies.

Resilience Factor

The Resilience Factor determines how much a crossing's capacity can be exceeded before it is destroyed. The initial value is 10% and we vary it between 5 and 25%, in 5% steps. This is the only sensitivity plot that does not exhibit a clear linear relationship between the change in y with respect to x. We believe this is caused by the shape of the underlying GEV distribution (figure 2 g-i & figure 3 a-d). As the capacity of the crossing is increased linearly it is able to handle an increasingly large number of rare storms. The results indicate that maintaining a crossing with a high resilience factor would be more advantageous than upgrading it. In many cases this would be a crossing already built in excess of its specified design flood or with engineered graceful failure. It is conceivable for this to be intentionally done in some cases or based on the available precast culvert sizes.

Summary

All of the model parameters behave in a predictable manner which comports with our understanding of how stormwater systems function. Several parameter values have the potential to change the preferred strategy under different climate scenarios. Additionally we see clear interactions between climate and several of the parameters, with climate altering both the y-intercepts and slopes. The interactions and potential changes motivate a global sensitivity analysis to better understand the nature of the decision space, including which combinations of variables make one strategy preferable over another and whether we can use our understanding of specific crossings to inform the strategy choice.

Can system characteristics be used to predict the preferred strategy based on cost, and if so, how much better are predictions when climate change is known?

To determine the predictability of strategy choice using System Characteristics, we constructed two multinomial models, one using the climate change factor as a covariate and the second not including the climate factor. We evaluated both models using Rank Probability Skill Score (RPSS) calculated with data not included in the training set (Weigel, Liniger, & Appenzeller, 2007). RPSS measures the skill of a prediction by comparing it to a baseline forecast, typically climatology. An RPSS of 1 indicates perfect prediction, 0 shows equivalent skill to the baseline, and negative numbers indicate less skill than the baseline. When assessing the efficiency of adaptation strategies there is no known climatology for how often a strategy will be preferred. For this reason we compare the results to always selecting the Nominal Strategy, selecting Nominal 50% of the time and Concurrent 50% of the time, selecting only the Concurrent strategy, and finally to climatology. All initial models were created with using Equation 4 with interaction decisions guided by the results from local sensitivity analysis.

$$\begin{aligned} Optimal\ Strategy \sim\ & Emergency\ Factor + Upgrade\ Cost + Climate\ Factor \\ & + Resilience\ Factor + Upgrade\ Factor + Upgrade\ Factor \\ & * Climate\ Factor + Upgrade\ Cost * Climate\ Factor + Emergency\ Factor \\ & * Climate\ Factor \end{aligned} \tag{4}$$

Selection based on bidirectional stepwise AIC removed all the interaction effects for the first model which included climate factor as a predictor, and retained all linear predictors. A Wald-Significance test showed all remaining covariates for both models to be significant at p > 0.01 level. Both models show skill compared to all the reference probabilities, including the climatology. RPSS results for both models are in table 4.

Table 4-RPSS Results for Multinomial Models

Model	**RPSS vs Nominal**	**RPSS vs Nominal and Upgrade**	**RPSS vs Climatology**
Aggregate	0.72	0.41	0.42
Aggregate w/o CF	0.71	0.38	0.39

In our test data the model was able to accurately predict 68% of the strategies, and exclusion of the Climate Factor did not change the number of accurate predictions.

Conclusions

In this study we simulated a realistic testbed of culverts varying, their characteristics and the frequency of extreme runoff events affecting them, and tested different adaption strategies that might be adopted by a manager convinced that climate change required some change in their design and maintenance. We found that the choice of when to implement adaptation strategies is affected by both the degree of climate change and crossing characteristics. Even for rather large climate change that halved the return interval of damaging runoff events, Anticipatory adaptation performed poorly as evaluated by both cost and level of service. This was caused by the increased number of replacements that sacrificed the value of the system prior to the end of its useful life. This finding emphasizes the need for continued and improved decision support for climate adaptation decisions. In addition to being ineffective we find that Anticipatory adaptation, at least in the case of rural crossings, may even be maladaptive.

Barnett and O'Neil (2010, p. 1) define maladaptation as "action taken ostensibly to avoid or reduce vulnerability to climate change that impacts adversely on, or increases the vulnerability of other systems, sectors or social groups." Anticipatory adaptation in our simulation has a much higher opportunity cost compared to the other options and likely compared to many other strategies not modeled. Anticipatory adaptation also creates path dependencies that may reduce the options for future adaptation. Here we simulate incremental adaptation but it is likely that systems in some settings (e.g., where freshwater and coastal flooding interact) will require transformative adaptation in the future, perhaps involving relocation of infrastructure; investing now in anticipatory infrastructure capacity makes those changes less likely to pay off (Barnett & O'Neill, 2010; Kates, Travis, & Wilbanks, 2012).

Additionally we found that under moderate levels of climate change, crossing characteristics, which influence the adaptability of infrastructure and its climate sensitivity, can be used to effectively predict which crossings are most likely to benefit from increased capacity. In developing a predictive model we assume these characteristics are known by agencies. Based on the current state of culvert information management systems, it seems reasonable to assume that many agencies would need additional research and field work to learn this information and benefit from the finer distinctions in choices allowed by this level of simulation modeling (Maher, 2015). The additional cost of that information may eliminate benefits gained by using it to choose more appropriate adaptation strategies. Future work should assess the uncertainty in important system characteristics and determine the cost of reducing that uncertainty to assess whether the benefits of flexibility are greater than the increased cost.

In this study we used a testbed of culverts that share many parameters, while differing in their design flows, cost, material, and expected service life. Because all cost and damages are based on a proportion of the original crossing value, we found no significant difference in the choice of best strategies for individual crossings and no difference in cost effectiveness for individual crossings. However, crossings are often elements in an interconnected infrastructure network that conveys flows and protects against flooding. Changing one piece of this infrastructure can have impacts on the rest of the system, and integrated modeling, including of system hydraulics, might yield different results.

Our simulation describes a simple but realistic testbed of road crossings served by culverts. Future work should elaborate on this model in several ways. We use a limited view of benefits associated with increasing the capacity of a crossing: only the decrease in flood damages and increased service level. Recent research shows that replacing traditional culverts with stream-simulation culverts can both increase the capacity of crossings and provide a number of environmental and aesthetic benefits (Gillespie et al., 2014). Economic analysis including these benefits has shown that increasing the capacity of crossings by installing stream-simulation culverts would be beneficial under the current climate (Levine & Keene Valley, 2013; Long, 2010).

Climate change is implemented in our model through a shift in the location parameter, the most simple way of simulating change (Mailhot & Duchesne, 2009). Changes in precipitation and streamflow may shift not only the location of the distribution but also the shape and even the distribution itself (Field et al., 2012; Read & Vogel, 2015). Future work should explore the nature of these changes, how they interact with system characteristics, and how they will influence adaptation decisions.

Finally, we treat our testbed of culverts as all having the same model parameters and we base strategy selection on these shared parameters. This useful simplification helps isolate the interaction of adaptation timing and system characteristics. Agencies manage large and diverse systems of culverts. As we saw in CDOT's design specifications, these systems are often given blanket regulations with little concern to individual crossing characteristics. In the second part of this study we investigate the impact of making adaptation decisions for individual crossings based on their system characteristics rather than applying monolithic rules to entire systems.

Chapter 3-Evaluating the efficiency of within-system flexibility

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), the question remains as to how and when they should adapt. 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, tends 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. Robust strategies may also be quite expensive. Strategic approaches thus are starting to favor choices that are scaled to the climate risk (Brown et al., 2012) 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). These strategies have predominantly been applied to high consequence decisions with a diverse options space.

Here we apply an exploratory modeling analysis (Bankes, 1993) to rural stormwater infrastructure associated with roadways, with a focus on culverts, covered water conveyances embedded in the roadbed whose main purpose is to convey 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). 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 in blanket standards. Culverts thus constitute a system of dispersed elements 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 (e.g. Irene floods, 2013 Colorado floods, etc.)

While climate models suggest increasing temperatures almost universally across the globe there is much less consensus regarding precipitation (Solomon, 2007). The hydrologic cycle is generally expected to intensify but predictions exhibit geographic variability and high uncertainty (Tebaldi et al., 2006). In the Southwestern United States where our testbed is located annual daily maximum precipitation is expected to increase anywhere between 11% and 21% under the Intergovernmental Panel on Climate Change (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, the converse 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 trend is towards increasing the design storm for infrastructure in the U.S. (Exec. Order No., 2015).

Infrastructure Adaptation Strategies

In Chapter 2 we investigated the effect of crossing characteristics on the choice of efficient, system-wide adaptation. That is, we posited and tested blanket adaptation policies, such as up-grading all culverts on a regular, or an anticipatory schedule. We found that under moderate levels of climate change, incorporating crossing characteristics into decisions is as important as knowing the future climate. In the current study we ask: do individual crossings with unique characteristics respond to climate change in ways that warrant individual-level adaptation strategies, or is system performance best served by blanket 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 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 low 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 and 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 looking at 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 5 (Colorado Department of Transportation, 2004).

Table 5-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 when President Obama issued an 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., 2015). 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 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, the challenge increasing 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 yr 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 4. 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 5 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. Though as opposed to horizontal or outcome flexibility, vertical flexibility can be incorporated based on a decisions maker’s current competencies.

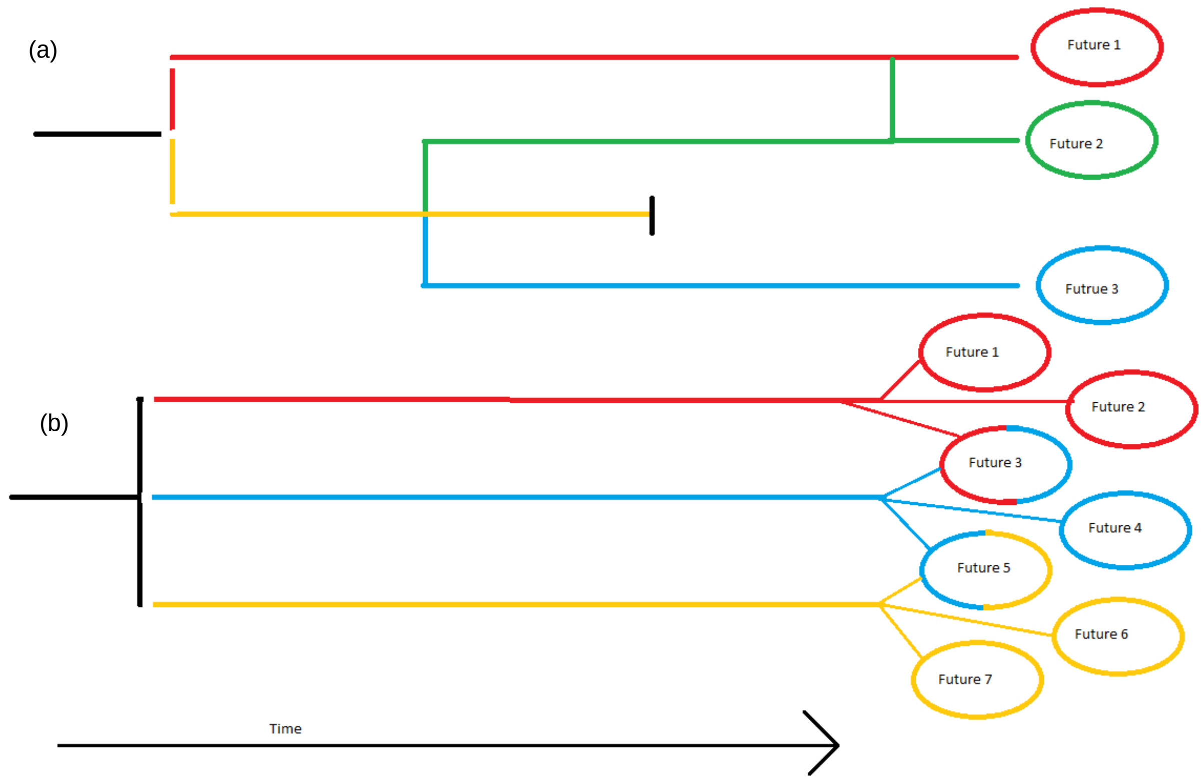


Figure 4-A simple schematic styled after the diagrams of Adaptation Pathways (Marjolijn Haasnoot et al., 2012) to compare Horizontal and Outcome flexibility. (a) A policy with Horizontal Flexibility: as time progresses a decision maker has multiple opportunities to change strategies based on recent information. (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

Chapter 2 we investigated 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 an earlier increase in capacity 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

(Upgrade Factor, Upgrade Cost, Resilience Factor, and Emergency Factor) to each crossing, but with a climate factor similar to all the crossings in the testbed.

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 Chapter 2

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 6). 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 being damaged by an extreme event.

Table 6- 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 and 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, road, design storm, design life, replacement delay (number of days with reduced traffic capacity or speed due to replacement), and cost (table 7).

Table 7-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 8). Upgrade Amount describes how much the capacity of a crossing is increased at the time of replacement. 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 8-Variable Culvert Characteristics

System Characteristic	Range
Upgrade Cost	1.0-4.0
Upgrade Amount	1.5-2.5
Post Upgrade Factor	.03-.07
Emergency Cost	1.3-1.7
Resilience Factor	.05-0.25

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).

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

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), but this potential is ignored in this study. 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 original 200 year event. Each year the location parameter is linearly increased to simulate this non-stationary risk.

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 crossing characteristics. Strategies are assigned using the multinomial regression model developed in Chapter 2. 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 a real world situation 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 predicted best strategy using 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 visually 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 5 shows the changes in mean and 90th 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).

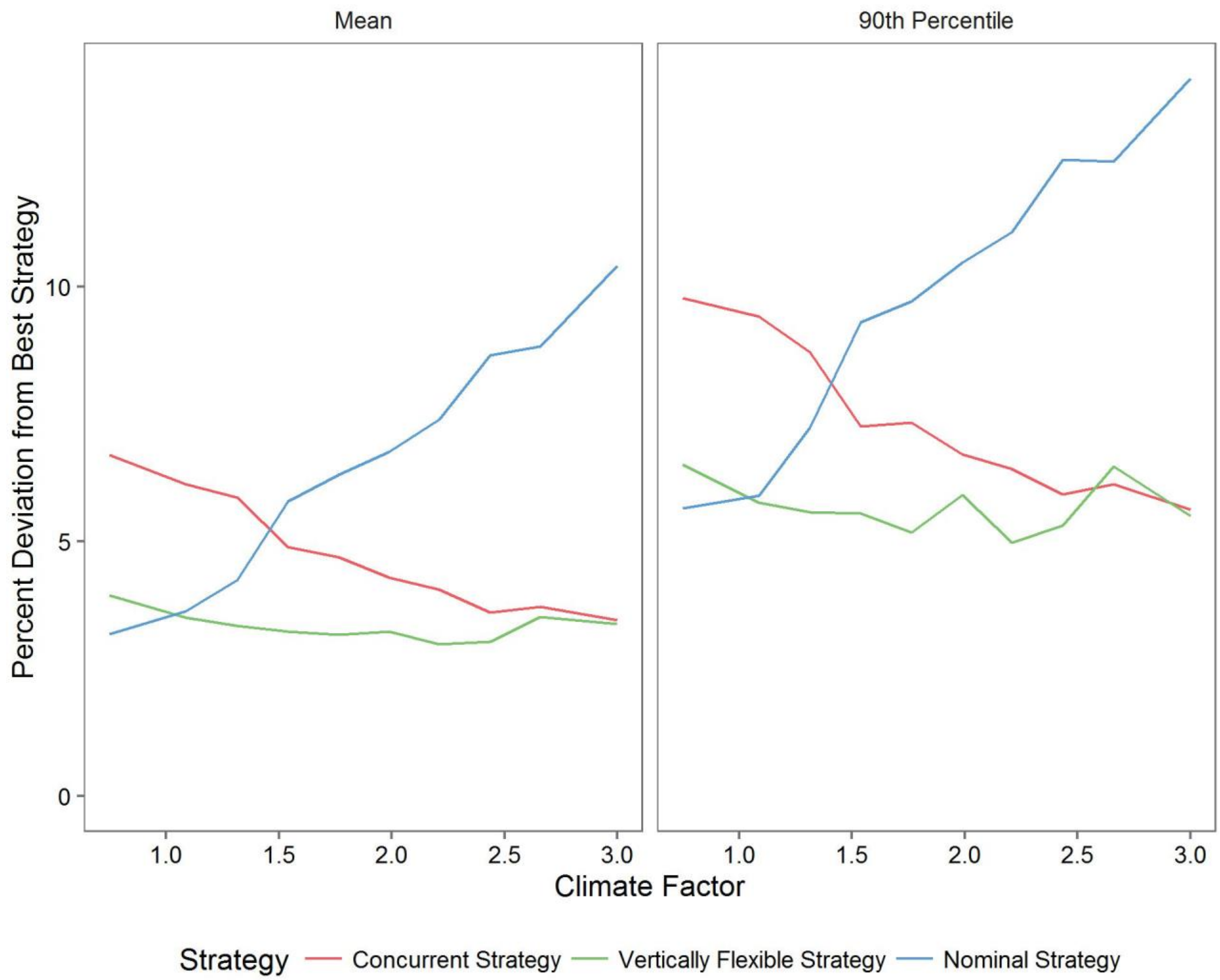


Figure 5- Percent deviation from the most cost-effective strategy vs changes in climate factor. (a) Mean percent deviation from the most cost effective strategy vs climate factor. (b) 90th percentile (results from the top decile) percent deviation from the most cost effective strategy vs climate factor. For example in low and high ranges of the climate factor, the nominal strategy is either the nearest to the least cost-effective strategy.

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 xx). 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. As we move more into the right tail of the distribution as shown by the 90th percentile (figure 5b), the nominal strategy exhibits a greater relative cost increase over the other strategies.

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 7).

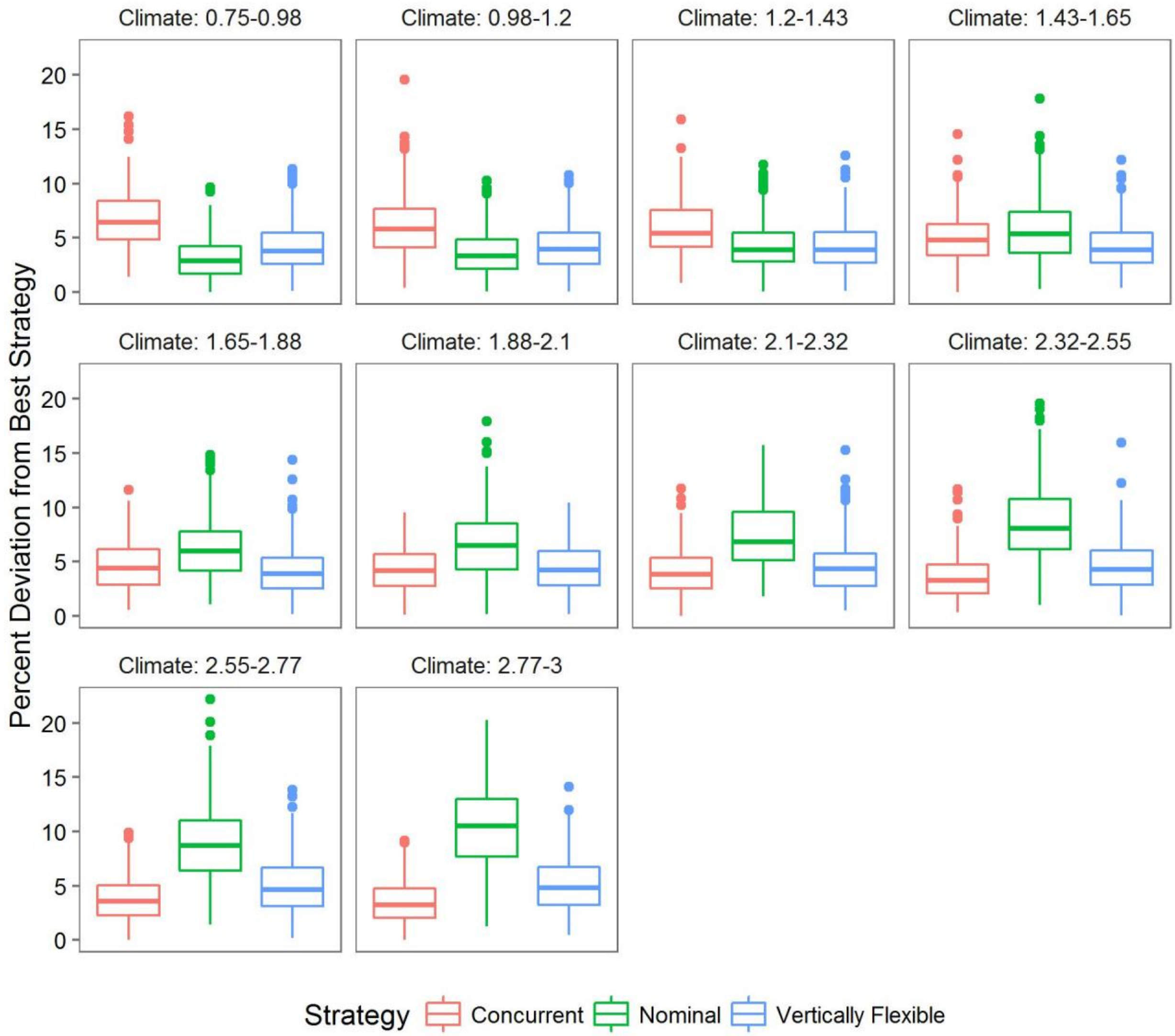


Figure 6-Percent deviation from the most cost-effective strategy grouped by climate factor. Middle line represents the 50th percentile, boxes extend from the 25th and 75th percentiles, and whiskers extend to the 1.5 times the interquartile range with observations outside of that plotted as dots. Each 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 7 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 knowledge of the difficulty of measuring crossing characteristics, we treated the standard error for each parameter as a fraction of its original range shown in table 8. 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 8 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.

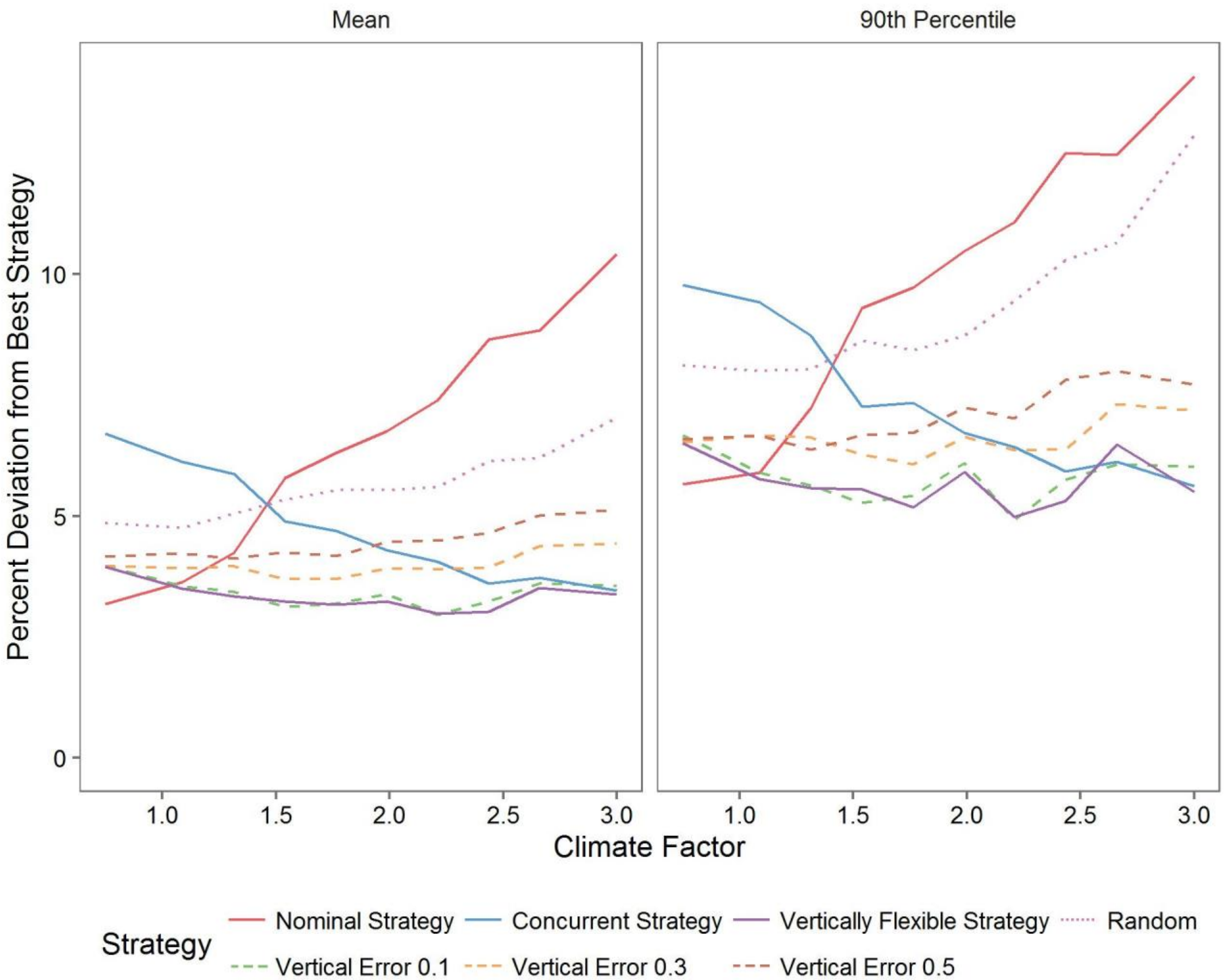


Figure 7- Percent deviation from the most cost-effective strategy vs changes in climate factor. (a) Mean percent deviation from the most cost effective strategy vs climate factor. (b) 90th percentile (results from the top decile) percent deviation from the most cost effective strategy vs climate factor. 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

In a testbed of realistic crossings, 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 other qualities 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. Based on the current state of culvert information management in the United States this likely varies dramatically by agency (Maher, 2015; Jay Meegoda et al., 2009), and experience suggests that culvert databases are often poor. 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.

Recent advances in decision-making strategies for climate adaptation under deep uncertainty provide a diverse set of options for managers to choose. For large infrastructure installation and maintenance, such as water supply, and coastal or urban flood protection, these techniques can help decision makers 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.

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 small installation will be minor, the collective costs, of either under- or over-adaptation, is potentially quite large. Our results show that even a naive 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) suggest 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.

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