U.S. Department of Transportation
Federal Highway Administration

TEACR Engineering Assessment

Comparison of Economic Analysis Methodologies and Assumptions:

Dyke Bridge in Machias, Maine

This is one of nine engineering case studies conducted under the Transportation Engineering Approaches to Climate Resiliency (TEACR) Project.[1] This case study focused on comparing the approaches and outcomes of two climate change adaptation economic assessments.

Case Study Snapshot

Purpose: (1) Assess the extent to which economic assessment results are affected by the methodology (area-under-the-curve or Monte Carlo) when estimating expected cumulative lifecycle damages of an asset due to extreme weather events; (2) evaluate the implications of using different discount rates in the analysis; and (3) test the sensitivity of the economic analysis findings to changes in the climate stressor-damage relationship.

Location: Dyke Bridge, Machias, Maine

Approach: (1) Compared the area-under-the-curve technique for developing cumulative lifecycle damages to a Monte Carlo method; (2) re-ran the economic analysis using multiple discount rates; and (3) re-ran the economic analysis using different climate stressor-damage relationships.

Key Findings: (1) The area-under-the-curve technique and Monte Carlo analysis produce similar cumulative lifecycle damage costs, although the Monte Carlo analysis offers some benefits in terms of calculating confidence intervals and other information; (2) the discount rate chosen has a substantial impact on project cost-effectiveness; and (3) economic analysis findings are highly sensitive to the specified climate stressor-damage relationship.

Key Lessons: (1) A scenarios approach to economic analyses is a useful way to balance climate change uncertainty with the costs of adaptation. (2) Either Monte Carlo analysis or the area-under-the-curve technique can be used to estimate project benefits. (3) Care should be taken when specifying the discount rate and climate stressor-damage relationship used as these substantially affect the estimated benefits of adaptive measures.

Overview

This assessment investigated different methodologies and assumptions for conducting an economic analysis on a climate change adaptation project. The purpose of the analysis was to determine the extent to which economic analysis results can be affected by the methodology chosen and the input assumptions such as the discount rate selected. There are not, as yet, established best practices for conducting economic assessments for climate change adaptation projects. This analysis examines two methodologies: the Monte Carlo method and the area under the curve method to determine how significantly results are influenced due to choice of methodology and assumptions.

The research team conducted this analysis using proposed

[1] For more information about the project, visit the project website at: https://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/teacr/

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replacement options for the Dyke Bridge in Machias, Maine as a case study. It is important to note that, unlike the other case studies prepared for this project, this assessment did not involve any original adaptive engineering analysis. Instead, it utilized design alternatives developed by the Maine Department of Transportation (MaineDOT) for a prior economic evaluation of replacement options.[2] This approach was used to take advantage of work already conducted and maximize the project resources available for studying different economic techniques.

This is an important analysis because economic assessments are critical to project decision-making and are a fundamental part of the Adaptation Decision-Making Assessment Process (ADAP- see Figure 1.). The analysis addressed certain gaps in knowledge identified earlier in this project[3] related to:

- Balancing climate change uncertainty with the cost of adaptation,
- Costs and benefits of adaptive measures.

These gaps were identified as critical ones to facilitate implementation of sound adaptation measures. With these gaps in mind, this assessment:

- Compared two different methodologies for considering the non-stationarity of extreme weather events when generating expected cumulative lifecycle damages for a project economic analysis, the area-under-the-curve technique (hereafter referred to as the "area technique") and Monte Carlo analysis;
- Evaluated the implications of using different discount rates in the analysis; and
- Tested the sensitivity of the economic analysis findings to changes in the climate stressor-damage relationship specified.

The research team found the following:

- The area technique and Monte Carlo analysis produce similar cumulative lifecycle damage costs;
- The discount rate chosen has a substantial impact on project cost-effectiveness measures; and
- Economic analysis findings are highly sensitive to the climate stressor-damage relationship specified.

This case study is organized according to the ADAP for consistency with the other cases although, as previously noted, no original adaptive engineering analysis was conducted. Figure 1 provides

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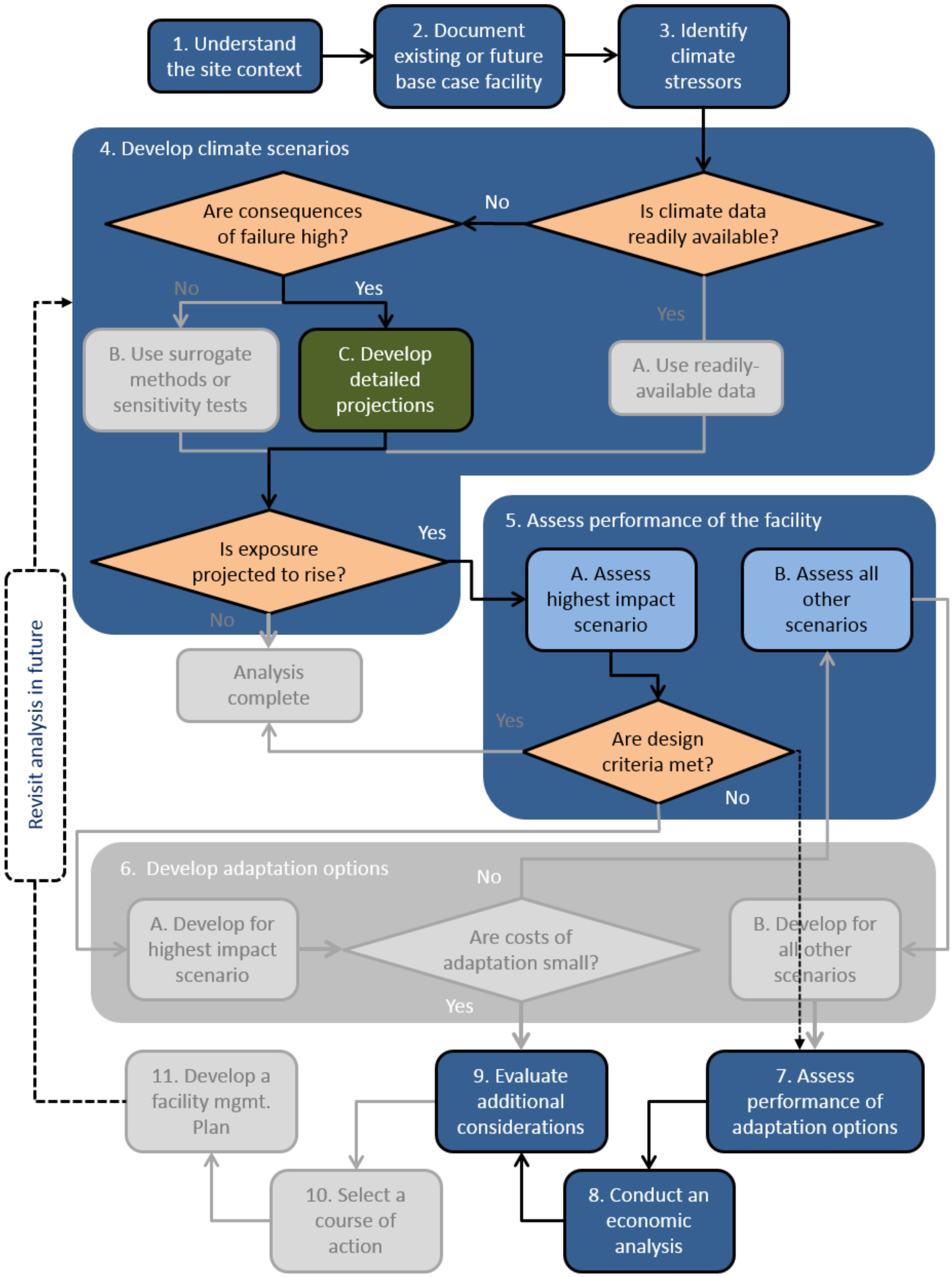
[2] Douglas, Kirshen, and Merrill 2013.

[3] FHWA 2014. Assessment of Key Gaps in the Integration of Climate Change Considerations into Transportation Engineering. FHWA-HEP-15-059. Available at https://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/teacr/.

an overview of the steps completed for this analysis. Readers will notice that some of the steps in the ADAP were not completed for this study, a result of pivoting off of the previous work done by MaineDOT. Also, since this study is focused on exploring the implications of different economic assessment techniques, Step 8, Conduct an Economic Analysis, is lengthier and involves more work than practitioners would normally undertake for this step. For example, practitioners will generally only perform a single economic evaluation for a project using either Monte Carlo analysis or the area technique, not both as was done here.

Figure 1: Adaptation Decision-Making Assessment Process (ADAP) Used for this Analysis (steps not completed are indicated in gray).



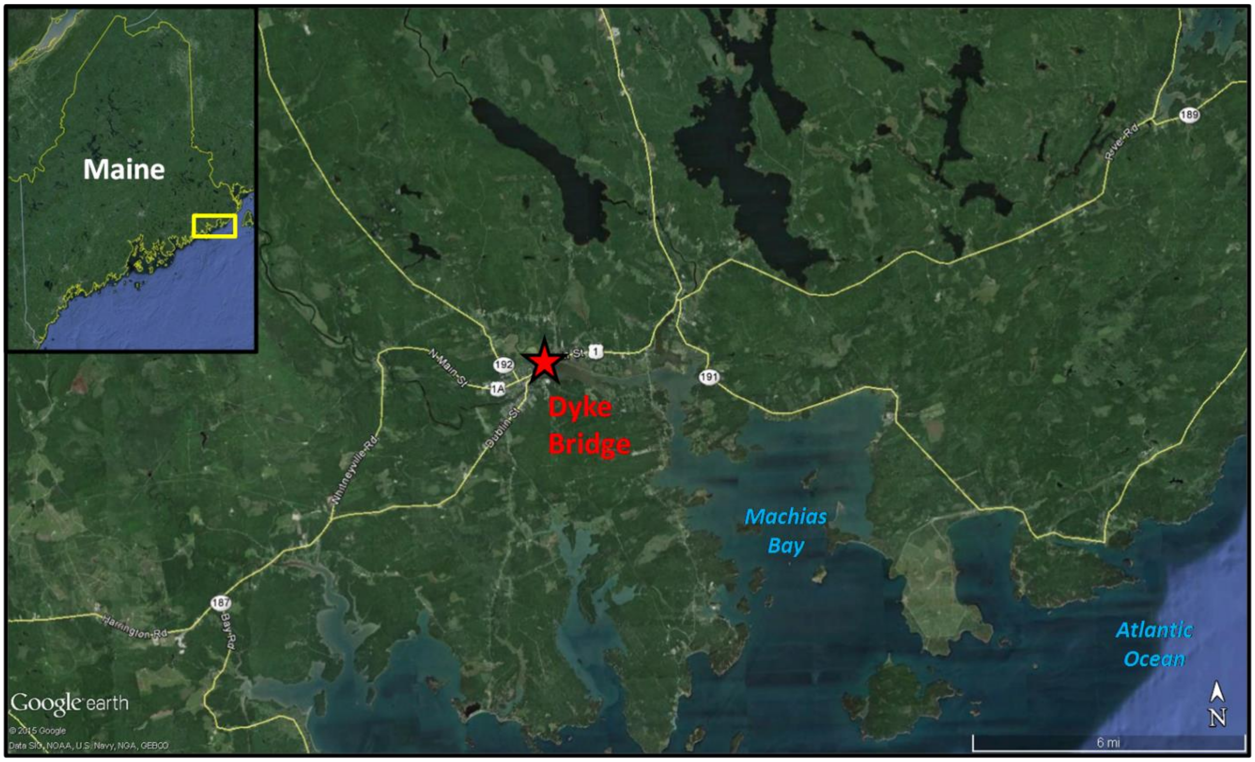
Contents

Details of the Analysis

Step 1: Understand the Site Context

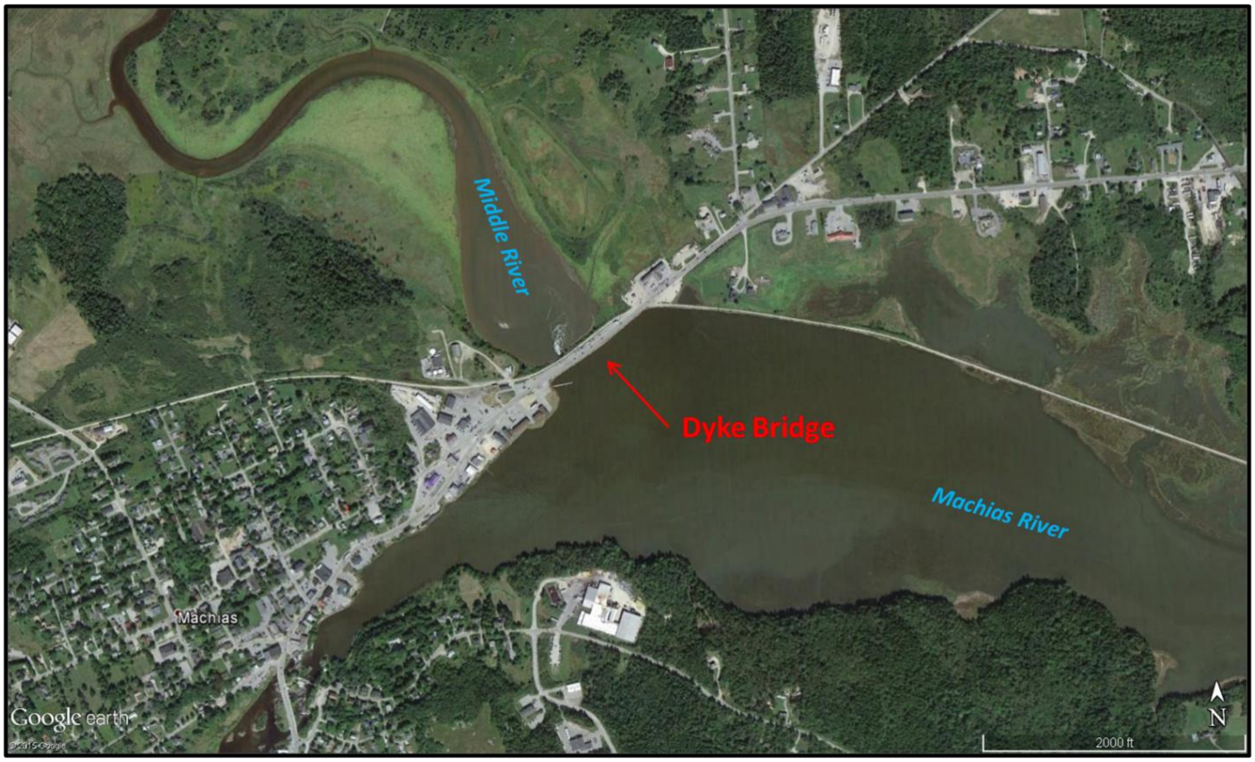
The Dyke Bridge is located in rural Down East Maine just east of the small town of Machias (see maps in Figure 2 and Figure 3). The bridge (actually a large culvert with an associated causeway) carries US 1 and the Down East Sunrise Trail over the Middle River.

Figure 2: Location of the Dyke Bridge.[4]



[4] Image sources: Google Earth (as modified).

Figure 3: Aerial Photo of the Dyke Bridge and Vicinity.[5]



Environmental Context

The Middle River is, at the Dyke Bridge crossing, a tidal estuary; one of the many that make up Maine's complex coastline. The bridge crosses at the mouth of the river where it meets the larger Machias River flowing in from the west. Together they form the northwestern arm of Machias Bay (see Figure 2).

The design of the Dyke Bridge, which includes flapper gates on the downstream ends of the culvert, significantly altered the ecosystem of the area by preventing tides (and saltwater) from progressing up the Middle River as they would naturally. This design was done intentionally to permanently expose part of the upstream mudflats so that grasses could grow on them and hay could be harvested; a common regional agricultural practice historically but one that is now less frequently used.

Transportation Network Context

US 1 parallels the Atlantic coastline and is the primary transportation artery linking Maine's coastal communities. It is an important route for local residents, regional commerce, and tourism. 2009 annual average daily traffic (AADT) at the Dyke Bridge was 9,380 vehicles and annual average daily truck traffic (AADTT) was 375 vehicles (4% of the total).[6] The projected AADT

[5] Image source: Google Earth (as modified).
[6] MaineDOT 2010.

for the crossing in 2030 is expected to be 11,360 vehicles and projected AADTT is forecast to be 454 vehicles.[7]

The Down East Sunrise Trail which shares the crossing with US 1 is an 85-mile hiker-biker rail trail maintained by the Maine Bureau of Parks and Lands. The trail, used primarily for recreation, parallels the coast in the southeastern portion of the state and is a link in the broader East Coast Greenway trail network extending from Maine to Florida. In addition to bicycles and pedestrians, all-terrain vehicles (ATVs) and snowmobiles are also permitted on the trail.

Land Use Context

A number of structures are in the immediate vicinity of the Dyke Bridge. On the west side of the bridge, these structures include Machias' historic railroad station, a restaurant, and motel. On the east side, there is a small shopping center. In addition, the town's municipal dock is also located just southwest of the bridge and farmers and flea markets regularly operate in the parking area on top of the structure. Loss of bridge service would inhibit access to these facilities.

Step 2: Design Base Case Facility

The current Dyke Bridge was constructed in two phases. The northern (upstream) side of the crossing (see Figure 4: Photo of Dyke Bridge, Upstream Side.) was built first in 1930 and was later widened to the south (the downstream side) in 1946. The causeway embankment consists of timber cribbing filled with rubble and earthen fill. The overall causeway length is approximately 900 feet. The Middle River passes through the causeway by way of four 80-foot long timber and stone masonry box culverts located towards the western side of the causeway. Each box culvert barrel has a six foot span and six foot rise. As previously noted, each of these culverts has a flapper gate on the downstream end (see Figure 5) that closes at high tide to prevent saltwater from progressing upstream.

[7] Ibid.

Figure 4: Photo of Dyke Bridge, Upstream Side.[8]

[8] Image source: WSP | Parsons Brinckerhoff.

Figure 5: Photo of Dyke Bridge at Low Tide, Downstream Side.[9]

Two travel lanes carry US 1 over the causeway. In addition, there is a single row of paved parking spaces on the north side of US 1 along the length of the crossing. Both the road and the parking spaces are at an elevation of 11 feet.10 The Down East Sunrise Trail, surfaced with gravel fines, is located on top of an old railroad bed on the northern side of the causeway and has an elevation of 12 feet.

Recent bridge inspections noted structural deficiencies in the crossing due to timber rot and loss of material within the embankment and along the culvert cells. This has led to settlement issues and necessitated emergency repairs. Due to these concerns, MaineDOT plans to replace the entire causeway by 2018. To help appropriately plan for the replacement, MaineDOT sponsored an economic evaluation by Douglas, Kirshen, and Merrill (DKM)11 that considered two replacement alternatives: (1) a new causeway with culverts having the same configuration, elevation, and dimensions as the existing facility and (2) a single-span bridge in lieu of the culverts.12 The single-span bridge was assumed to be 58 feet long with 20-foot long approach slabs, have the same deck elevation (11 feet) of the current roadway, a low chord13 elevation of

[9] Image source: WSP | Parsons Brinckerhoff.

[10] All elevations provided in this case study are in North American Vertical Datum of 1988 (NAVD88).

[11] DKM 2013.

[12] Additional more detailed design alternatives were developed in a more recent MaineDOT technical report (Stantec Consulting Services, Inc 2015) but, since this report did not include any economic analyses, this case study will focus on the two design alternatives noted above.

[13] The low chord elevation represents the elevation of the bottom of the structural members on the underside of the bridge span.

8.8 feet, and have its foundations anchored in bedrock. The cost of the replacement culvert was estimated to be $2.2 million whereas the cost of the bridge alternative was estimated at $2.4 million. It is the DKM economic evaluation that is the basis for much of the information used in this case study.

Step 3: Identify Climate Stressors

Three climate stressors are of paramount concern in the design of the new Dyke Bridge:

- Sea level rise
- More frequent and higher storm surges due to higher sea levels and, potentially, changing storm tracks and intensities
- More intense precipitation causing higher discharges and higher flood elevations along the Middle River

Climate Stressors

- More intense precipitation
- Sea level rise
- Storm surge

Sea level rise represents a serious threat to the facility: if waters rise high enough, frequent and, eventually, permanent closures will be necessary. Riverine flooding and storm surge have the potential to cause both loss of service and severe damage to either of the proposed design alternatives. Specific impacts could include loss of the causeway embankment and, if flood elevations are high enough, loss of the culvert cells or the bridge. For this analysis, as described in Step 4, storm surge was determined to exceed riverine flooding in all cases, so that only storm surge was quantified further in the analysis.

Step 4: Develop Climate Scenarios

The DKM study developed flood elevations for the Dyke Bridge at 2010, 2030, and 2050 considering potential changes in sea level rise, storm surge, and riverine flooding. This case study used the DKM projections to facilitate the comparison of economic evaluation approaches. A brief overview of the projections is provided here; readers interested in more detail on how they were developed are encouraged to consult the DKM study.

Climate Data Overview

Level of Detail: Developed detailed projections, used surrogate methods.

Data Source: NOAA tide gauge (extreme water level recurrence intervals), Vermeer and Rahmstorf (sea level rise projections), regression equation (peak stream flow recurrence intervals).

Scenarios: High and low sea level rise scenarios from Vermeer and Rahmstorf.

Is exposure projected to change in the future? Yes, sea levels will rise and storm surges and riverine flooding will become more frequent and severe.

First, it should be noted that projected changes in storm *probabilities* are necessary when conducting an economic analysis for climate adaptation projects: they are used to estimate the expected damage costs from storm events over the period of analysis. Techniques exist for estimating the projected changes in the probabilities of riverine flooding and storm surge *given* a certain climate scenario. These *conditional* probabilities can then be used to determine the expected damages to that facility assuming that scenario were to occur.

For sea level rise and storm surge, DKM developed projected storm surge elevations at the Dyke Bridge using National Oceanographic and Atmospheric Administration (NOAA) extreme water levels from the nearest tide gauge (located in Eastport, Maine, approximately 25 miles northeast) and sea level rise projections from Vermeer and Rahmstorf.[14] Two scenarios of future sea level rise were used, a low scenario and high scenario as shown in Table 1.

Table 1: Sea Level Rise Projections.[15]

Year	Low Scenario (Feet)	High Scenario (Feet)
2030	0.5	0.9
2050	1.0	1.7

Present day mean higher high water (MHHW)[16] and water level anomalies[17] for the 2, 5, 10, 20, 50, 100, 200, and 500-year storms were then obtained by the authors for the Eastport gauge and translated to the Dyke Bridge site. To develop storm surge elevations by return period for 2010, 2030, and 2050, DKM added to MHHW (7.44 feet at the bridge) the projected sea level rise amounts in 2030 and 2050, the water level anomalies associated with the given storm return periods, and assumptions on wave heights.[18] The resulting projections of storm surge elevation are shown in Table 2. Note that these projections did not include any possible changes in storm patterns or intensities with climate change.

DKM then assessed the chances that riverine and storm surge flooding could occur simultaneously.[19] DKM looked at historical data and established that riverine flood events and storm surge events happened independently. They assumed this relationship would hold into the future as climate changes and then compared the surge elevations to the flood elevations from riverine flooding. For all return period events, the storm surge elevations were greater. Thus, the

[14] Vermeer and Rahmstorf 2009.
[15] Ibid.
[16] Mean higher high water is the average elevation of the highest daily high tide as measured over the most recent National Tidal Datum Epoch (currently, 1983-2001).
[17] Water level anomalies were defined as the difference between the water level recorded during a given storm and the expected water level during normal tidal conditions.
[18] Waves were assumed to be 0.5 feet during all storm events in 2010 and one foot in both 2030 and 2050 during all storm events. Note that in reality these values would likely differ across storm events and time periods. This is because maximum wave heights are determined (partly) by the depth of water which will change based on the height of the storm surge and general sea levels.
[19] DKM determined riverine flows through a regression analysis. 10% was then added to the discharges to account for possible increases in flow due to more intense precipitation associated with climate change.

storm surge elevation probabilities shown in Table 2 were the probability values used for their economic analysis and, consequently, were used throughout the remainder of this case study as well.

Table 2: Storm Surge Elevation Projections.

Return Period (Years)	Annual Exceedance Probability	2010	2030		2050	
		Current Conditions (Feet)	Low Scenario (Feet)	High Scenario (Feet)	Low Scenario (Feet)	High Scenario (Feet)
2	50%	10.51	11.51	11.91	12.01	12.71
5	20%	11.29	12.29	12.69	12.79	13.49
10	10%	11.95	12.95	13.35	13.45	14.15
20	5%	12.70	13.70	14.10	14.20	14.90
50	2%	13.89	14.89	15.29	15.39	16.09
100	1%	14.98	15.98	16.38	16.48	17.18
200	0.5%	16.26	17.26	17.66	17.76	18.46
500	0.2%	18.34	19.34	19.74	19.84	20.54

Step 5: Assess Asset Performance

The culvert and bridge alternatives were evaluated against the high sea level rise scenario and their performance assessed through the year 2050 using MaineDOT's design standards.[20] For culverts in a tidal setting, the design standards state that the culvert should have a headwater depth versus structure depth ratio[21] that is equal to or less than 0.9 during the 50-year storm at mean high water (MHW).[22] For bridges over tidal waters, the design standards state that,

Facility Performance Overview

Highest Impact Scenario: The highest impact scenario corresponds with the high sea level rise scenario from Vermeer and Rahmstorf.

Asset Design Standards: Culvert: Headwater depth versus structure depth ratio equal to or less than 0.9 during the 50-year storm at MHW. Bridge: Two feet of freeboard over the ten-year storm at MHW (including waves).

Key models, tools, and assumptions: N/A.

Is the structure resilient? No.

[20] MaineDOT 2003.

[21] The headwater depth to structure depth ratio is a comparison between the elevation of the water relative to the bottom of the culvert opening. In this case water elevation is measured on the ocean side of the culvert (the direction from which the storm surge is coming) and compared to the total height of the culvert (as measured from the top of the culvert opening to the bottom of the opening).

[22] Mean high water is the average elevation of all the high tides as measured over the most recent National Tidal Datum Epoch (currently, 1983-2001). MHW differs from MHHW in that, for locations that have two high tides each day, MHW considers the elevation of both high tides in its computation whereas MHHW only considers the elevation of the higher of the two high tides each day. Thus, in such situations, MHW will be lower than MHHW.

for the bridge itself, there should be two feet of freeboard [23] above the ten-year storm at MHW, including waves (more frequent overtopping is permitted for the approach roadway).

Note that the design standards are expressed in terms of MHW whereas the storm surge scenarios developed by DKM used MHHW (by definition, a higher value that will more easily cause the design standard to be exceeded). MHW for the Dyke Bridge site is not readily available from the previous study and it was beyond the scope of this case study to compute it, however, a rough approximation can be obtained by applying the known difference between MHHW and MHW at the Eastport tide gauge (0.48 feet) and subtracting this value from MHHW at the Dyke Bridge (7.44 feet). Doing so yields an estimated MHW elevation of 6.96 feet at the Dyke Bridge. Combining this value with the climate projections that are available, it is quite apparent that the proposed culvert and bridge alternatives assessed in DKM are not likely to meet the stated design standards even under current conditions.

Consider the culvert alternative: at MHW, the *present day* 50-year storm (estimated elevation 13.41 feet) completely overtops the 12-foot high causeway. The culvert, being only 6 feet in height and within the causeway, will be completely submerged, causing the culvert's headwater depth to structure depth ratio to be 2.24 (13.41 feet / 6 feet), which is well above the design standard of 0.9.

Likewise, for the bridge alternative, at MHW, the *present day* 10-year storm (estimated elevation 11.47 feet) would overtop the bridge deck thereby clearly violating the requirement for there to be two feet of freeboard under the bridge at this return period. Performance will only continue to deteriorate as climate changes and sea levels rise. In fact, by 2030 the roadway will overtop for both alternatives at less than a two-year storm if it occurs at MHHW.

Step 6: Develop Adaptation Options

DKM did not develop adaptation options for their study: instead, they focused on assessing which of the two proposed design alternatives performed better. Since this case study intended to use their analysis to aid in the comparison of different adaptation assessment techniques, it was beyond the scope of the research team's work to develop adaptation alternatives for the new bridge. It is anticipated that MaineDOT would develop adaptation options if study progresses on this site.

Step 7: Assess Performance of Adaptation Options

This step was not completed for this case study since adaptation options were not developed.

[23] Freeboard is defined as the distance between the top of the water surface and the bottom of the bridge.

Step 8: Conduct Economic Analysis

Economic analyses are critical to project decision-making given the uncertainty of future climate. In climate adaptation analyses, costs are defined as the costs of constructing a given project alternative, as is typically the case in transportation economic studies. Benefits, on the other hand, are defined as the avoided or reduced expected lifetime weather-related damage costs achieved from undertaking an adaptation. This information can be combined into benefit-cost ratios, total costs, or net present values for each alternative to facilitate comparisons and decision-making. Adaptation economic analyses can either be done independently or integrated into a project's broader traditional economic evaluation.

There are not, as yet, established best practices for conducting economic assessments for climate change adaptation projects. In order to better understand the implications of different economic approaches, this case study went beyond the typical economic analysis of project alternatives one would perform with the ADAP and tested the results under different methodologies and analysis assumptions. The specific evaluations that were conducted include:

- **Damage estimation methodology comparison:** Use of the area technique versus a Monte Carlo analysis for estimating the cumulative lifecycle damage costs each alternative is likely to experience (part of the calculation of benefits) over a given time period.
- **Discount rate sensitivity test**: Results under a series of different discount rates (used to account for the time-value of money)
- **Climate stressor-damage relationship sensitivity test**: Results under different engineering assumptions about expected asset damage given certain flood elevations (part of the calculation of benefits)

These sensitivity tests were used to determine the robustness of the conclusions under various assumptions and are described in more detail below.

Specific ways in which this analysis differed from a typical economic analysis using the ADAP process are as follows. First, as noted above, the calculation of damage costs for each design alternative was conducted twice using different methods (the area technique and Monte Carlo analysis). Typically these calculations would only need to be done once using one of these methods. Also, conducting sensitivity tests of different discount rates and climate stressor-damage relationships is not necessary on projects although doing so might prove useful in some situations.

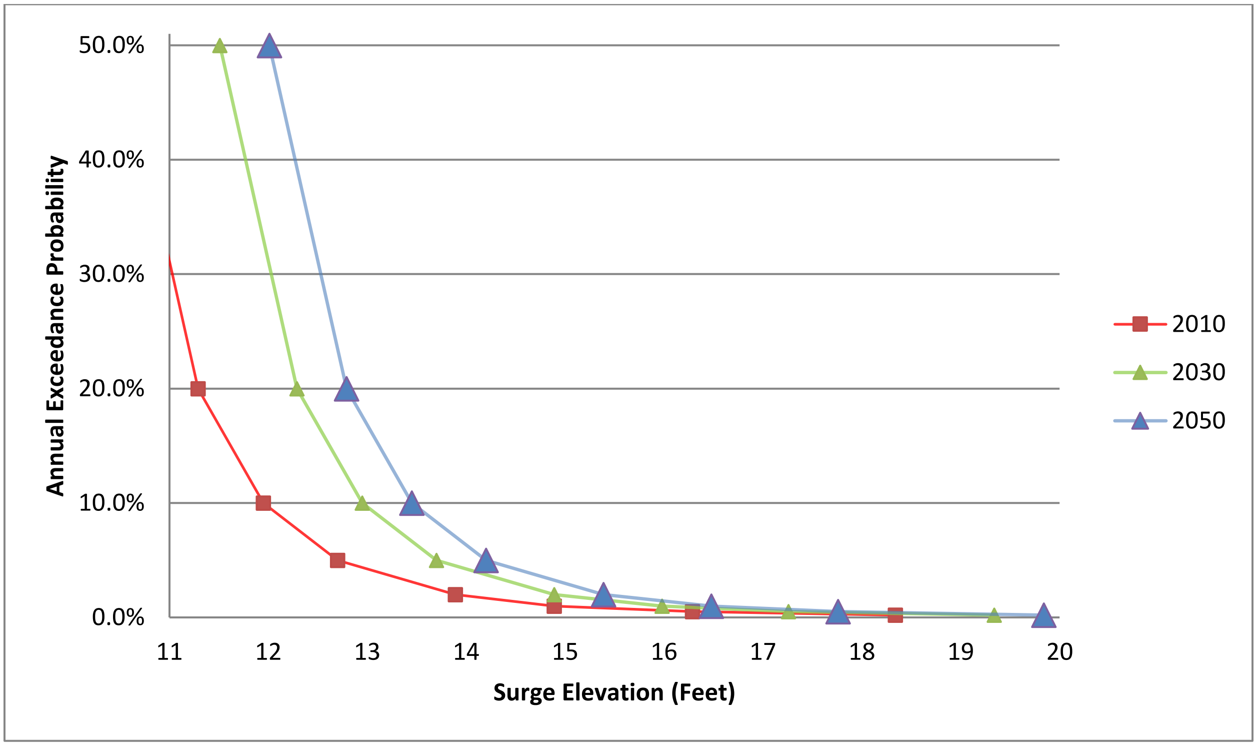
Furthermore, in order to mirror the work done by DKM, the study did not look at the cost-effectiveness of adaptation options as is typically done during the ADAP. On typical studies, the incremental cost of an adaptation option(s) would be compared to the benefits it is anticipated to provide (as previously mentioned, defined as the avoided damages from storm events / future climate conditions) in order to determine if the adaptation action is likely to be cost-effective. Instead, in this study, the research team, like DKM, looked at the costs of the two previously developed non-adapted replacement alternatives (the culvert and bridge options), determined the expected damage costs for each, and made an assessment as to which alternative would perform better. In other words, no adaptations were analyzed per se as is typically done. That said, the general approach to estimating damage costs is the same regardless if adaptive or non-adaptive project alternatives are being considered.

Also in order to parallel the work done in the DKM study, this analysis used a 41-year analysis period with 2010 as a base year and 2050 as the horizon year even though the replacement asset is expected to last beyond 2050. In practice, it is best to conduct the analysis throughout the entire expected lifespan of the asset in order to enable a full lifecycle cost analysis.[24]

Of note, all values in this case study are presented in base year (2010) dollars. Also, under each climate scenario, the probability distribution of weather events shifts over time: a defining feature of climate change economic analyses as the shifting distribution is what captures the change in climate. Figure 6 illustrates the concept of changing distribution of storm events over time using the storm surge projections from Table 2.

[24] Alternately, if the asset is expected to have a lifespan longer than available climate projections, it is recommended that the assessment be conducted up to the end date where climate projections are available; typically, at the time of publication, the year 2100.

Figure 6: Illustration of Changing Storm Probabilities over Time, Low Sea Level Rise Scenario.



Damage Estimation Methodology Comparison

When conducting climate change adaptation economic analyses involving storm events, a key step is calculating the expected value of the damages expected to be experienced by the facility over time as this is necessary in order to define the project benefits (i.e. the reduction in damage costs, if any, with a given alternative). Estimating damages can be done given two pieces of information:

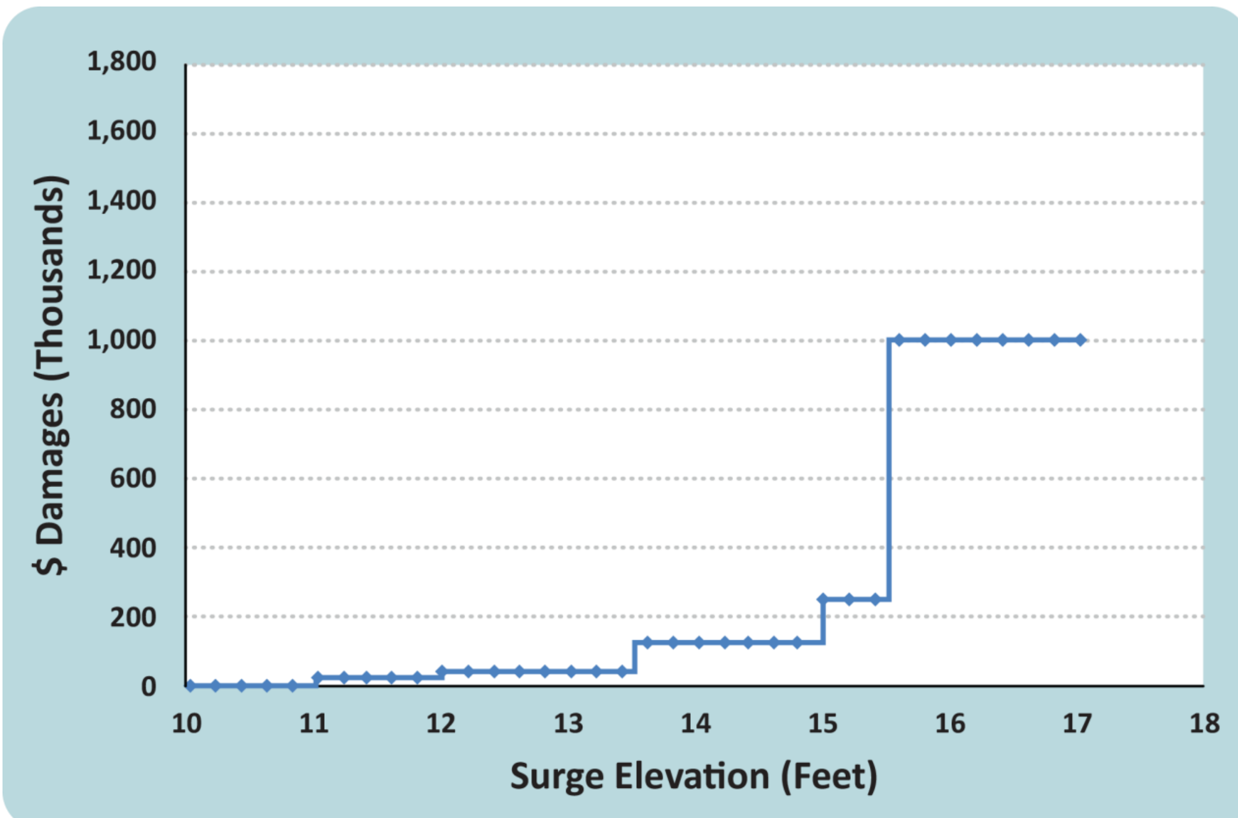
1. A probabilistic distribution of weather events (storm surge elevations, peak riverine flows, etc.) at different points in time. This assumes a particular climate scenario for the future (see Figure 6).
2. An understanding of the damage costs likely to be incurred at each level of the climate stressor (e.g. at each water elevation in this case study), referred to generically as a climate stressor-damage relationship / curve.

Two methodologies exist for bringing this information together into an estimate of damages for a facility over the period of analysis: (1) the area technique and (2) Monte Carlo analysis. Each of these is discussed in detail below. Note that for analyses where the climate stressor is not manifested in discrete storm events but rather in gradual changes in the climate stressor over time, different damage estimation methodologies are required. See the Alaska case study for examples of these types of analyses.

Area Technique

The area technique was first described by Paul Kirshen, Samuel Merrill, and others in a *Climactic Change* journal article in 2012[25] and was applied by DKM in their study of the Dyke Bridge. The first step involves developing the storm probability distribution and the climate stressor-damage relationship. Figure 6 illustrates the storm probability relationship for the Dyke Bridge location over the period of the analysis. Figure 7 shows the climate stressor-damage relationship for the culvert alternative, and Figure 8 the relationship for the bridge alternative.

Figure 7: Climate Stressor-Damage Relationships Specified by MaineDOT for the Culvert Alternative.



[25] Kirshen et al 2012.

Figure 8: Climate Stressor-Damage Relationships Specified by MaineDOT for the Bridge Alternative.

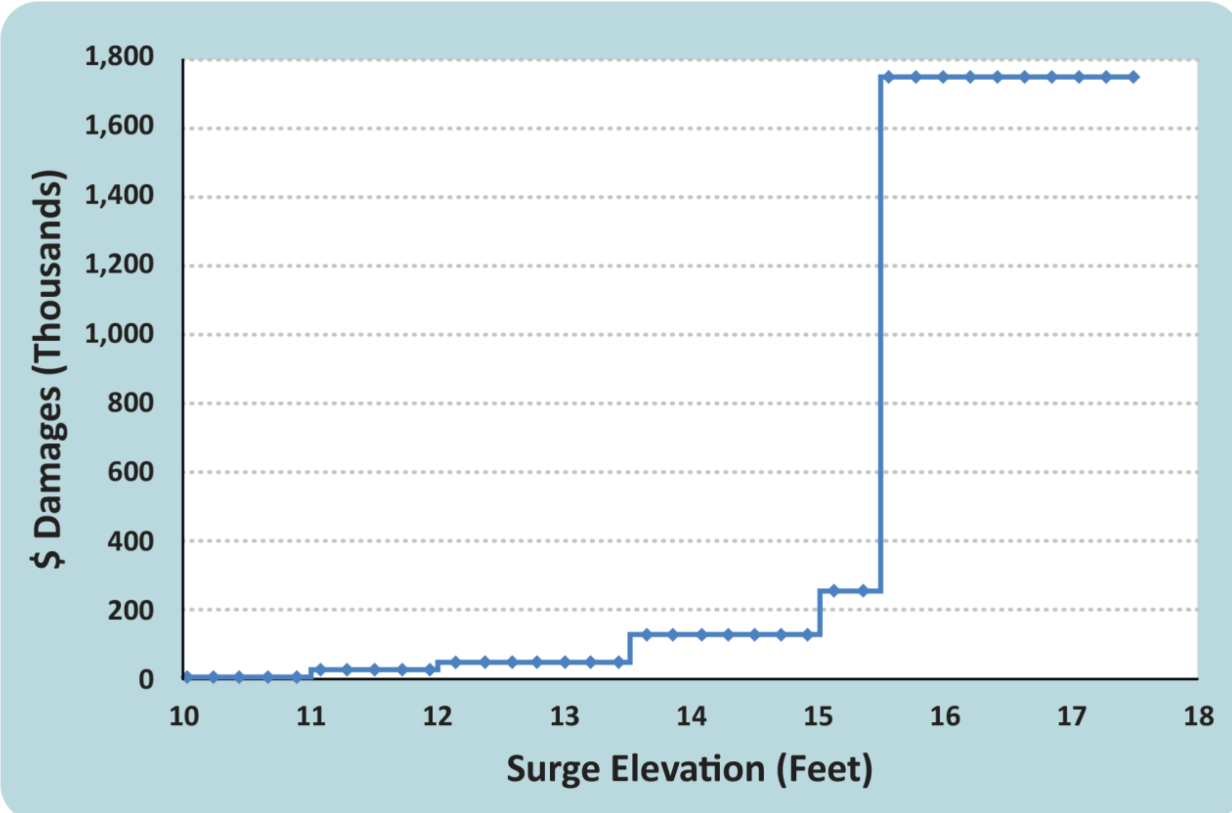


Table 3 presents the climate stressor-damage relationship information in tabular form. These items were all defined by MaineDOT and the authors for the previous study of Dyke Bridge.

Table 3: Climate Stressor-Damage Relationships Specified by MaineDOT for the Culvert and Bridge Alternatives.

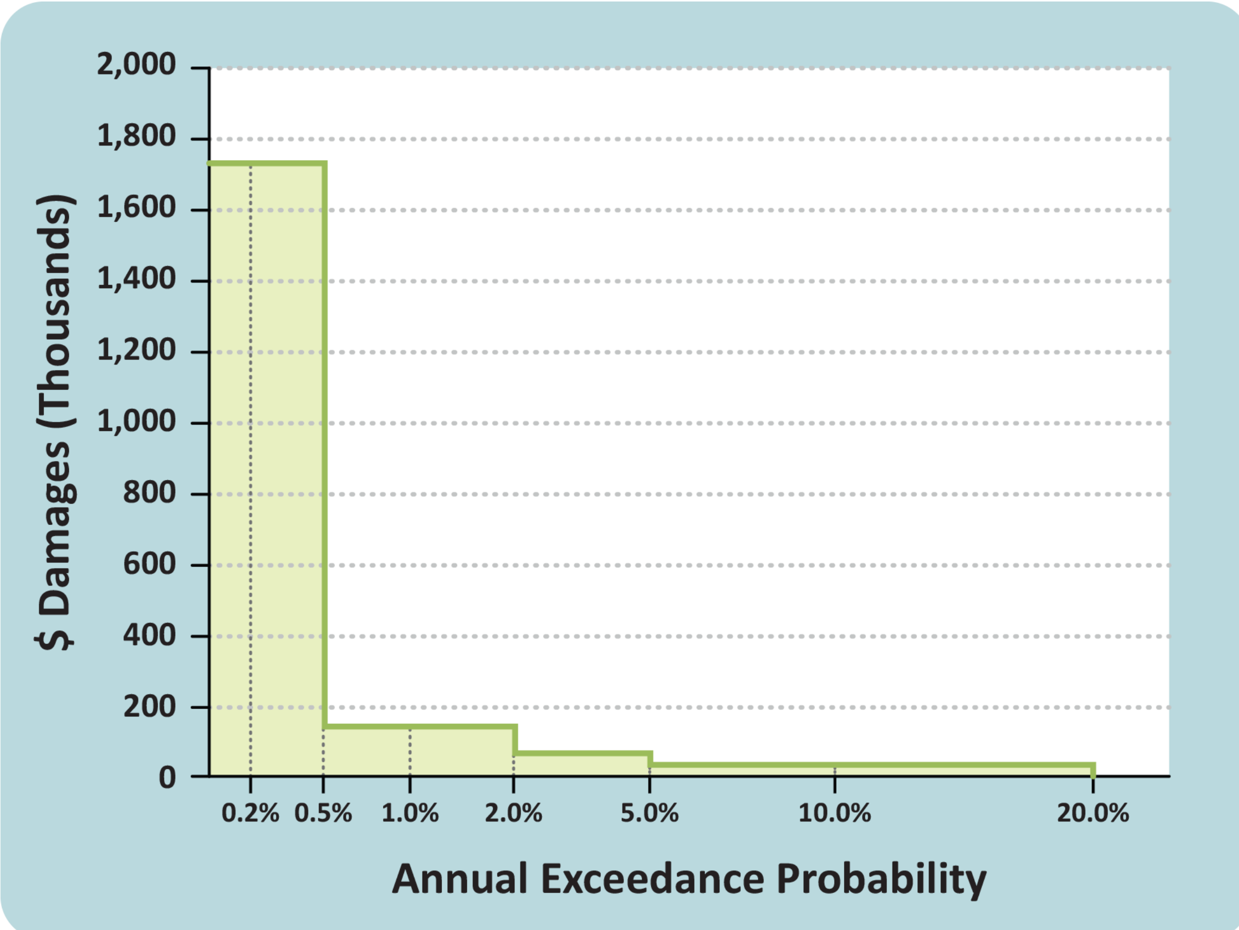
Storm Surge Elevation (feet)	Damage ($)	
	Culvert Option	Bridge Option
Less than 11.00	0	0
11.00 to 11.99	25,000	25,000
12.00 to 13.49	38,000	38,000
13.50 to 14.99	125,000	125,000
15.00 to 15.49	250,000	250,000
15.50 or greater	1,000,000	1,750,000

The development of climate stressor-damage relationship curves requires engineering expertise to define the damage likely to be incurred at different flood elevations and cost estimating to turn the expected damage into a dollar figure. In order to be consistent with the DKM study, this analysis only considered the physical damage costs of flooding: in other words, only those costs that MaineDOT would themselves have to pay. However, socioeconomic costs (e.g. user costs from added travel times and operating expenses, freight delay costs, damage costs to properties generated by water flow attributable to the project, injury costs) can also be included in the development of the climate stressor-damage curve to give a full accounting of damages. Environmental costs may also be included, if desired.

Notice that the climate stressor-damage relationships are shown as step functions implying that damages ramp up dramatically at certain flood elevations. While steps can happen at key thresholds where an asset component reaches a breaking point and is destroyed, it is unlikely that the entire damage relationship for each alternative is defined in steps. Given this, the research team explored the implications of using alternative climate stressor-damage relationships in the sensitivity test described later on. That said, in this section, for consistency with the DKM analysis, the research used the step function for comparing the area technique that they employed and Monte Carlo analysis.

The next step with the area technique involves using the information from the flood probability distributions to translate the climate stressor – damage relationship curve into a series of curves, one for each year, plotting damages versus flood *probabilities*. This relationship is typically an inverse one as higher probability events will generally have lower damages than lower probability events. In other words, the 100-year flood (1% annual probability) would likely be associated with more damage than the 20-year flood (5% annual probability). The green line in Figure 9 below shows an example of the relationship between storm event probabilities and asset damage; in this case, for the bridge alternative in 2010.

Figure 9: Relationship between Storm Event Probabilities and Asset Damage, Bridge Alternative, 2010.

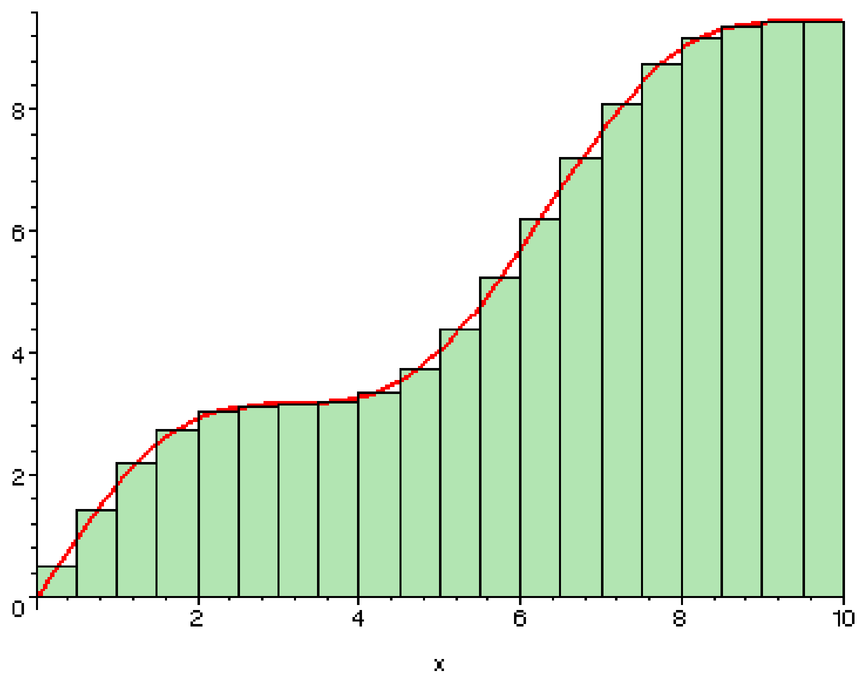


Using the damage versus flood probability curve, one can then determine the expected damages in each year by finding the area underneath each curve. For example, the total green shaded area in Figure 9 represents the expected value of damages for the bridge alternative in 2010 ($24,843). For each year throughout the analysis period and for each scenario, a similar graph can be generated showing damages to the bridge based on the shifting probability of storm events. In practice, however, graphs were only made for 2010, 2030, and 2050, the years in which climate projections had been developed, and an interpolation was done between them as described below. In a similar manner, a separate series of curves was developed for the culvert alternative under each scenario.

There are multiple ways to calculate the area under the damage vs. flood probability curves, depending on the shape of the curve itself and the degree of precision desired. In the case of this analysis, the climate stressor-damage relationship was defined as a step function so finding the total area (i.e. the damages in any given year) was simply a matter of adding up the areas of a series of rectangles. In Figure 9, the dashed vertical lines illustrate how the shaded area was divided up into rectangles whose areas can readily be calculated. As noted above, summing the areas of all these rectangles (i.e. the total green shaded area) provides an estimate of the expected damages in 2010 ($24,843).

If instead of a step function, the damage relationship ramps up steadily as flood elevations increase, the curve could take the shape of either a series of straight lines connecting data points or a smoothed curve. If drawn as connected straight lines, the exact area under the curve can be calculated by summing the area of the trapezoids under each line segment. If a smooth curve is specified, the exact area can be calculated using calculus or estimated by drawing a series of narrow rectangles underneath and summing their areas (Riemann sums, see Figure 10). It should be noted, however, that the level of precision in the basic data may not warrant these more sophisticated area calculations.

Figure 10: Example of Riemann Sum Approach to Calculating Area.[26]

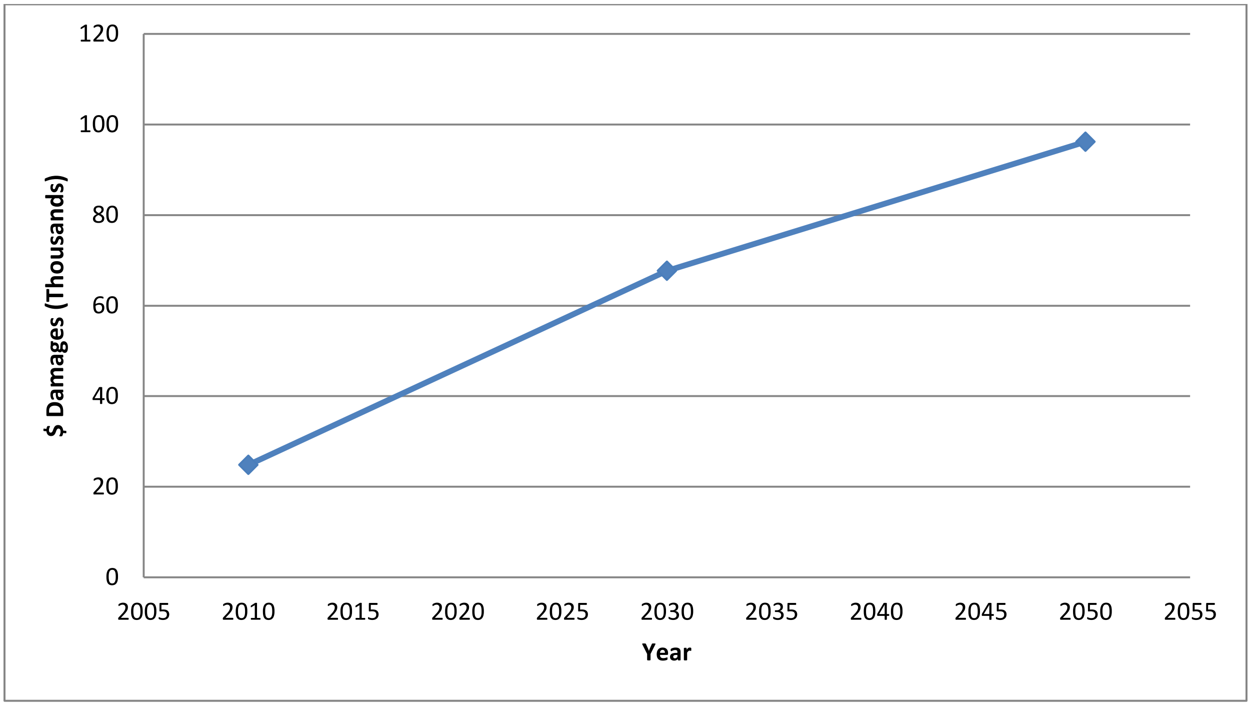


Once the damages (i.e. the areas under each curve) had been calculated for the years 2010, 2030, and 2050, these were plotted onto a new graph showing total damages versus time. Figure 11 below shows an example for the bridge alternative under the high emissions scenario. As one can see, the value for 2010 is $24,843, the sum of the shaded area in Figure 9. Likewise, the 2030 and 2050 values are the sum of the areas under those years' damage versus flood probability

[26] Image source: Steven Yarbrough, Reich College of Education, Teaching Telefolio. Available at: http://sy48497.tripod.com/artifacts/webquest/maple/images/rsintro3.gif.

curves. Damages were assumed to increase linearly between the three reference years so the data points were connected with straight lines.

Figure 11: Expected Storm Damages over Time, Bridge Alternative, High Sea Level Rise Scenario, Undiscounted.



Next, a discount rate of 3.5%, the same as used by DKM, was applied to the reference year figures reflecting the time value of money.[27] This had the effect of lowering the damage costs in the out-years as shown for the bridge alternative under the high scenario in Figure 12.[28] Once this was done, the area under this curve was calculated to arrive at an estimate of the cumulative expected damage costs for the asset over the period of analysis. The options for calculating the area under the damage versus time curve are the same as those mentioned above for the probability versus damage curve: since the damage versus time curve was defined here as a series of connected lines, the area was calculated by summing the area of the two trapezoids underneath the curve. The trapezoids are represented by the areas bounded on the top by the curve itself and on the sides by vertical lines drawn down from each data point to the horizontal axis (not shown in the figure). In the case of Figure 12, the total area of the trapezoids (i.e. the cumulative expected damages for the bridge alternative under the high sea level rise scenario)

[27] The formula for the discount rate is: Present $ Value = Future $ Value * (1 / (1 + Discount Rate)^(Future Year – Base Year)) where, in this study, the base year is 2010.
[28] Note that the value for 2010 remains the same, $24,843, because it is the base year of the analysis.

was calculated to be $1,171,299. A similar procedure was then followed for calculating the cumulative expected damages for each alternative under each scenario.

Figure 12: Expected Storm Damages over Time, Bridge Alternative, High Sea Level Rise Scenario, 3.5% Discounting.

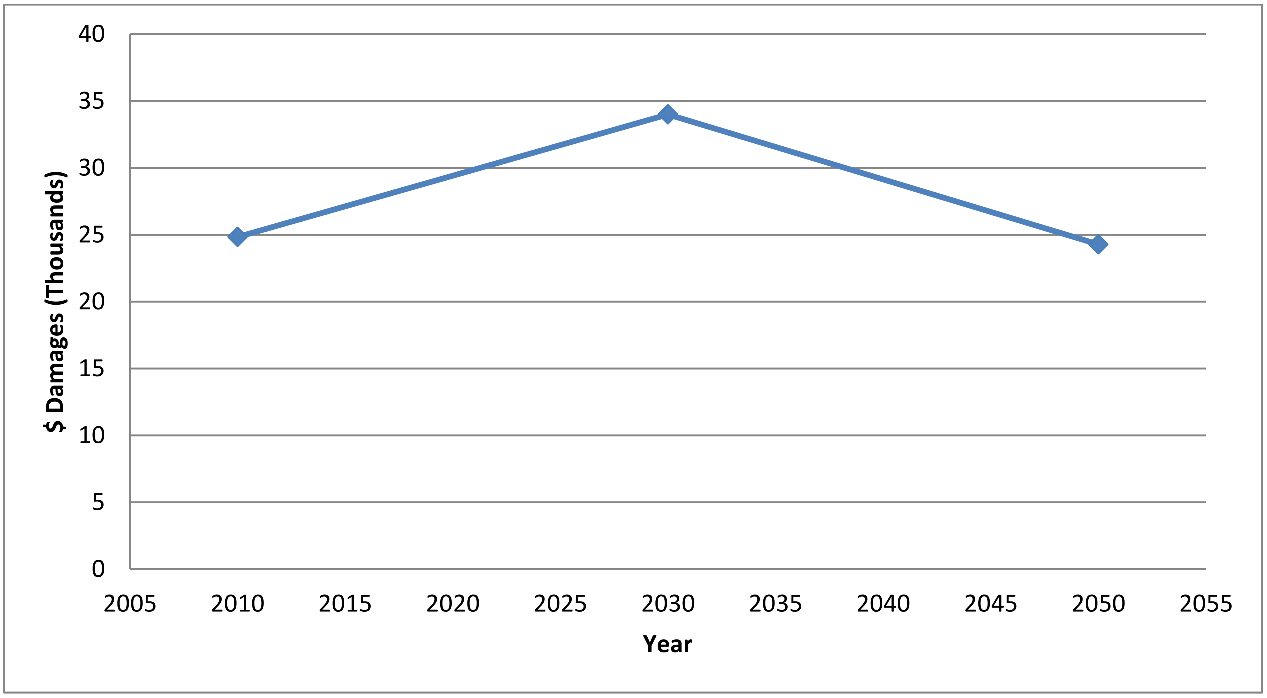


Table 4 presents the results of these area calculations and shows the cumulative expected damages for each alternative under each scenario using the area technique. As expected, the high scenario results in greater damages than the low scenario. Also, regardless of scenario, damages were found to be higher for the bridge alternative than for the culvert. Note that the figures shown differ from those in the DKM study. This is because their study did not account for damages from very large storms or very small storms and it was necessary to do so to provide comparable figures to the Monte Carlo analysis. They also interpreted the climate stressor – damage function developed by MaineDOT as a series of lines connecting the mid-points of each data class shown in Table 3 rather than step functions.

Table 4: Cumulative Expected Damage Costs Using the Area Technique, 2010-2050.

Sea Level Rise Scenario	Design Option	3.5% Disc. 2010 $ Total Discounted Damage ($)
Low	Culvert	729,212
High	Culvert	927,148
Low	Bridge	914,471
High	Bridge	1,171,299

Monte Carlo Analysis

Monte Carlo analysis is a commonly employed statistical technique in a number of disciplines to help understand risk when there is uncertainty as to the value of a particular variable but that variable is known to follow a certain statistical distribution. In the case of extreme weather events, the uncertainty lies in the intensity and timing of storm events. Monte Carlo tackles the issue of uncertainty by trying out thousands of different permutations of what *could* happen (given the probability distribution, which can be thought of as bounding the realm of possible storms), seeing what the impacts are under each, and synthesizing the results to provide meaningful conclusions. The following section walks through the process using the Dyke Bridge as an example.

First, however, it should be noted that no specialized software is needed to perform a Monte Carlo analysis: in fact, the analysis in this study was done entirely using Microsoft Excel. [29] That said, various software programs have been specifically developed for performing Monte Carlo analyses (e.g. @Risk). These software packages offer a user-friendly interface and various analytical and graphical tools to summarize the results.

In terms of process, the first step in a Monte Carlo analysis, as with the area technique, involves developing probability distributions for the climate stressor over time (see Figure 6) and climate stressor-damage relationships for each alternative (see Figure 7 and Figure 8). When developing the probability distributions for Monte Carlo analysis, special attention is needed as to exactly how the curves are drawn from the sample points provided (i.e. those shown in Table 2), a process known as parameterizing the distribution. A separate probability distribution curve is needed for each year of the analysis to reflect the gradual change in the climate.

It is important to know that there are different families of pre-defined distributions that can be fit to the data points, each with their own unique shapes. Some have a lot of mass in the tails of

[29] Note that Excel does not provide a predefined function for Monte Carlo analysis, however, various standard functions can be combined to perform the analysis.

the distribution, others less (see Figure 13). Those with more mass (fat tailed distributions) indicate that more severe events have a higher probability of occurring than would be assumed given a normal distribution. Also, some distributions are skewed, others not (see Figure 14). In other words, distributions can be asymmetric meaning the mass (probability of occurrence) is not even about the mean, as in a normal bell-shaped distribution. Those that are positively skewed (more of the distribution to the right of the graph) indicate a greater likelihood of more extreme events.

Figure 13: Examples of Normal, Fat, and Long Tail Distributions.[30]

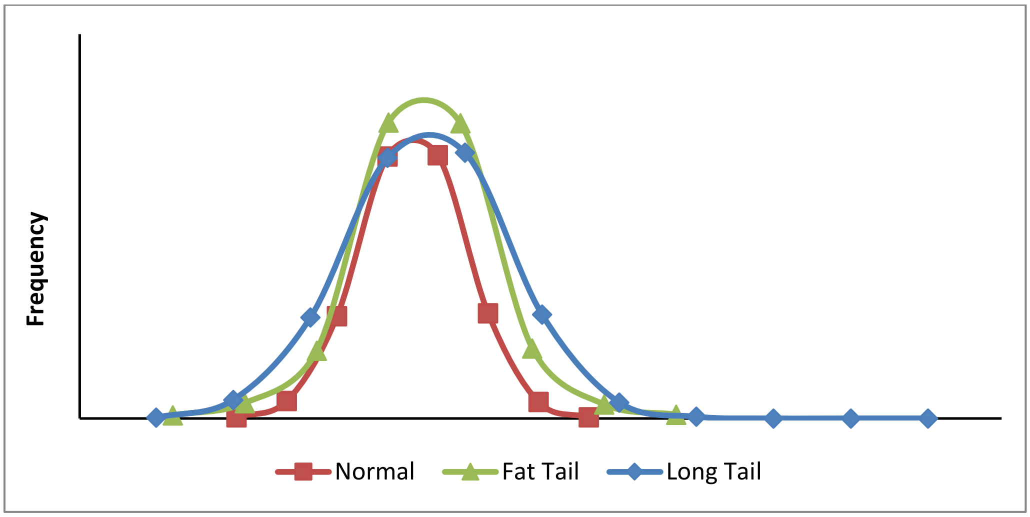
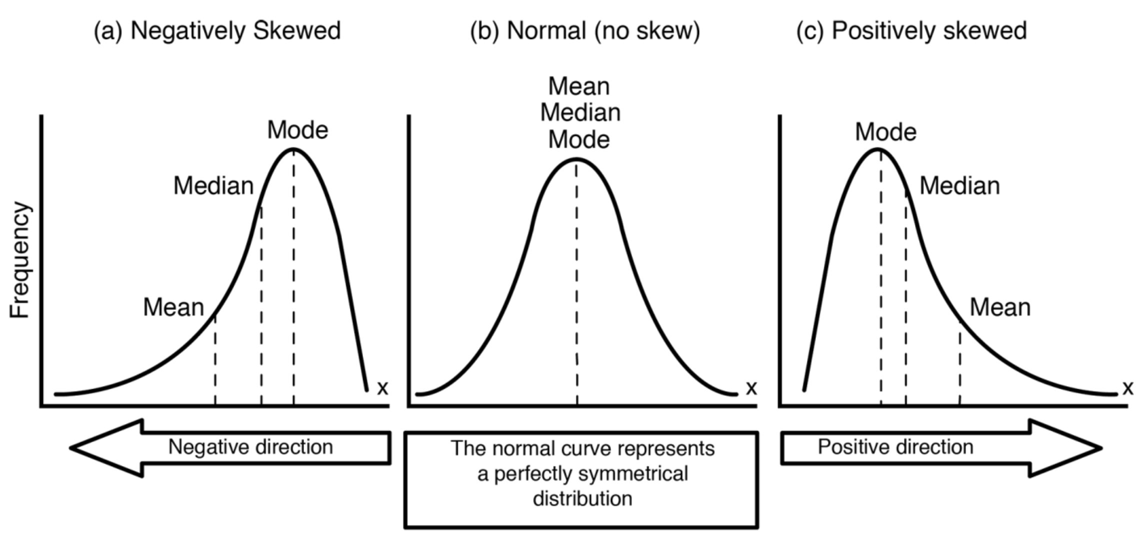


Figure 14: Illustrations of Skewness in Probability Distributions.[31]



[30] Image source: Financial Times.
[31] Image source: Marshall University School of Medicine Graphic Design Department.

Which distribution to use is a function of the nature of the climate stressor being studied and the characteristics of the data used to develop the probabilities. The storm surge return periods/probabilities developed in Step 4 and shown in Table 2 were created from annual maxima: in other words, they were developed from data recording the worst storm surge elevation in each year. Because of this, the generalized extreme value (GEV) theorem applies. The GEV theorem is associated with its own type of probability distribution, the GEV distribution[32]; the distribution selected for this analysis.

In order to parameterize the distributions (i.e. fit a curve to the data points), three points from each set of climate scenarios were selected (in this case, it was decided to use the 2, 100, and 200-year storm surge events[33]) using the data for 2010, 2030, and 2050. Three values were chosen because the GEV is a three parameter distribution with elements that capture the scale, shape, and location of the curve. Since a separate distribution was needed in each intervening year between the reference years in order to capture the gradual shifting of the distribution over time with climate change, the 2, 100, and 200-year storm values were interpolated for each of the intervening years (e.g. 2011, 2012, etc.) assuming a constant annual growth rate.[34] With these projected values available for each year and a type of distribution set, the next step was to do the parameterization.

The research team set up a system of equations based on the inverse cumulative distribution function (CDF) for the distribution and the three points. The inverse cumulative distribution function is an equation that relates the percentiles of a distribution to its values. That is, for a given percentile (e.g. 50th or 99th) the function is able to determine the corresponding value in that distribution. Figure 15 provides an example of the cumulative distribution function for 2010. In this case, the 2010 storm surge probability curves showed that the 50th percentile corresponds to an 11.01 foot surge elevation. Therefore, evaluating the inverse cumulative distribution function for this data-set at the 50th percentile would yield a value of 11.01.

The three points can be recast as percent probabilities as follows: the two-year storm is the storm where there is a 50% probability of other storms being less than it in a given year, the 100-year storm is the storm where there is a 99% of other storms being less than it in a given year, and the 200-year storm is the storm where there is a 99.5% chance of other storms being less than it in a

[32] The GEV distribution is actually a family of different distributions unified under a common theory of extreme values. There are four types of distributions: Gumbel, Frechet, Weibull, and Pareto. The distribution type depends on the value of the parameters. In this case study, a Frechet distribution was used.
[33] Note: It does not make a difference which return periods are selected for parameterization.
[34] A constant annual growth rate was used since sea level rise in the early part of the 21st century is expected to be gradual enough that a linear assumption is reasoned to be a close approximation of the expected trend and, as previously noted, no change in storm patterns or intensities was assumed by DKM. Later in the century, as sea level rise rates are expected to increase more rapidly, use of exponential growth rates is likely to be more prudent. Projected changes in storm intensities and patterns that drive surge should also be considered in the interpolation.

given year. These percent probabilities are actually the percentiles of the underlying distribution and they can be used to solve for the distribution parameters such that,

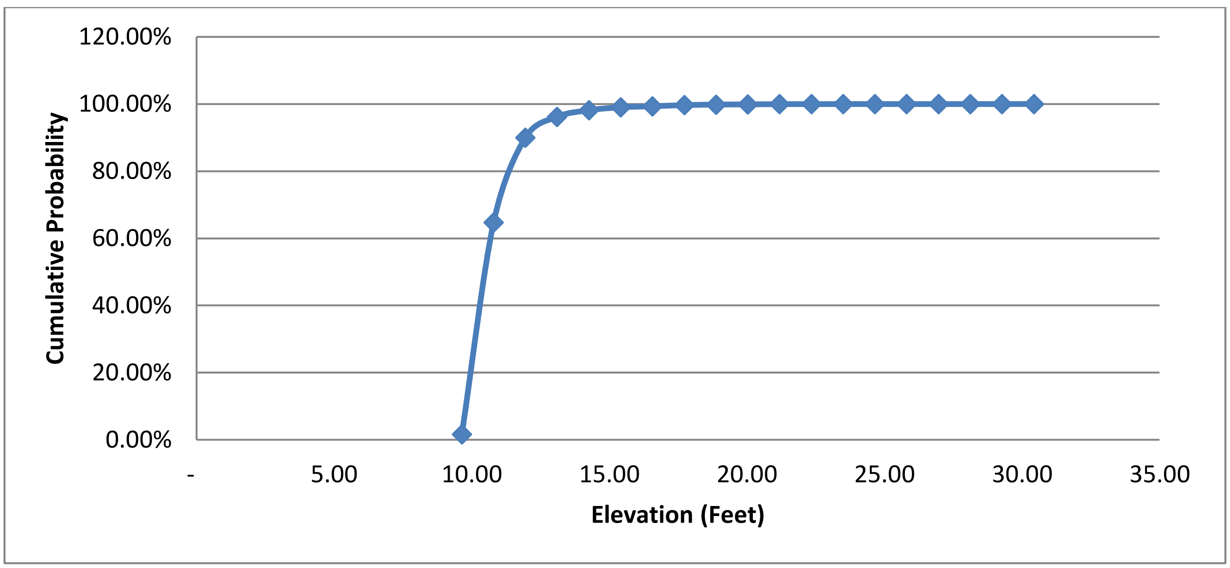
$$P(50\%) = F^{-1}(50\%,\Phi)$$

$$P(99\%)= F^{-1}(99\%,\Phi)$$

$$P(99.5\%)= F^{-1}(99.5\%,\Phi)$$

Where, P is the percentile, F^{-1} is the inverse cumulative distribution function, and Φ is a vector of parameters. The non-linear system now contains three equations and three unknowns (Φ, the vector of parameters). Solving this system yields one unique solution. That is, one Φ (vector of parameters) that generates the appropriate storm surge projections. This parameterization procedure was performed for every year and for every scenario resulting in a unique GEV distribution for each.

Figure 15: Storm Surge Cumulative Distribution Function, 2010.



For example, in 2010 the 50th, 99th, and 99.5th values are 10.51, 14.98, and 16.26 feet, respectively (see Table 2). Now we set the three equations (inverse CDF) equal to each of these values. The GEV distribution has three parameters the shape (α), the location (μ), and the scale (σ). Accordingly, our vector $\Phi = (\alpha, \mu, \sigma)$.

$$10.51 = F^{-1}(50\%, \alpha, \mu, \sigma)$$

$$14.98= F^{-1}(99\%, \alpha, \mu, \sigma)$$

$$16.26 = F^{-1}(99.5\%, \alpha, \mu, \sigma)$$

The inverse cumulative distribution function for the GEV (when α > 0) is:

$$\mu + \sigma \frac{\left(EXP\left(-\alpha * \left(\mathrm{Log}\left(-\mathrm{Log}(\mathrm{F})\right)\right)\right)\right) - 1}{\alpha}$$

Where F is a particular percentile, one replaces the right-hand side of each of the three equations above with the inverse CDF and finds the parameters that make this system solve. There is one unique set of α, μ, σ that makes all three equations solve simultaneously.

Suppose for instance that one chooses shape (α), location (μ), and scale (σ) equal to 0.25, 10.3, and 0.55 for the first iteration. Plugging in these values into the inverse CDF yields:

$$10.3 + 0.55 \frac{\left(EXP\left(-0.25 * \left(\mathrm{Log}\left(-\mathrm{Log}(50\%)\right)\right)\right)\right) - 1}{0.25}$$

$$10.3 + 0.55 \frac{\left(EXP\left(-0.25 * \left(\mathrm{Log}\left(-(-0.69315)\right)\right)\right)\right) - 1}{0.25}$$

$$10.3 + 0.55 \frac{\left(EXP\left(-0.25 * (-0.36651)\right)\right) - 1}{0.25}$$

$$10.3 + 0.55 \frac{\left(EXP(0.09)\right) - 1}{0.25}$$

$$10.3 + 0.55 \frac{0.09405}{0.25}$$

$$10.3 + 0.21 = 10.51 = F^{-1}(50\%)$$

As demonstrated in the sample iteration above, the parameter selection proves correct for the 50th percentile. The process iterates for the other two percentiles simultaneously to arrive at a solution. The end result is a vector of parameters from which one can fit a distribution and sample from it. Figure 16 presents the resulting GEV distribution for the year 2010. Much like fitting a normal distribution where one uses the mean and the standard deviation to specify the curve, one can think of the process above as a method for finding the appropriate parameters that generate a distribution that fits the data.

Once the probability distributions had been developed, the next step in the Monte Carlo analysis was to randomly sample storm events from the series of distributions. Since the probability distributions were developed from annual maximum values, it was only appropriate to sample one storm per year (the worst in that year) from the distribution. Thus, the cumulative damage estimates from the Monte Carlo analysis (and the area technique) may actually be underestimations of actual damages to the extent that more than one damaging storm event happens in each year.

Figure 16: Fitted Storm Surge Probability Density Function, 2010.

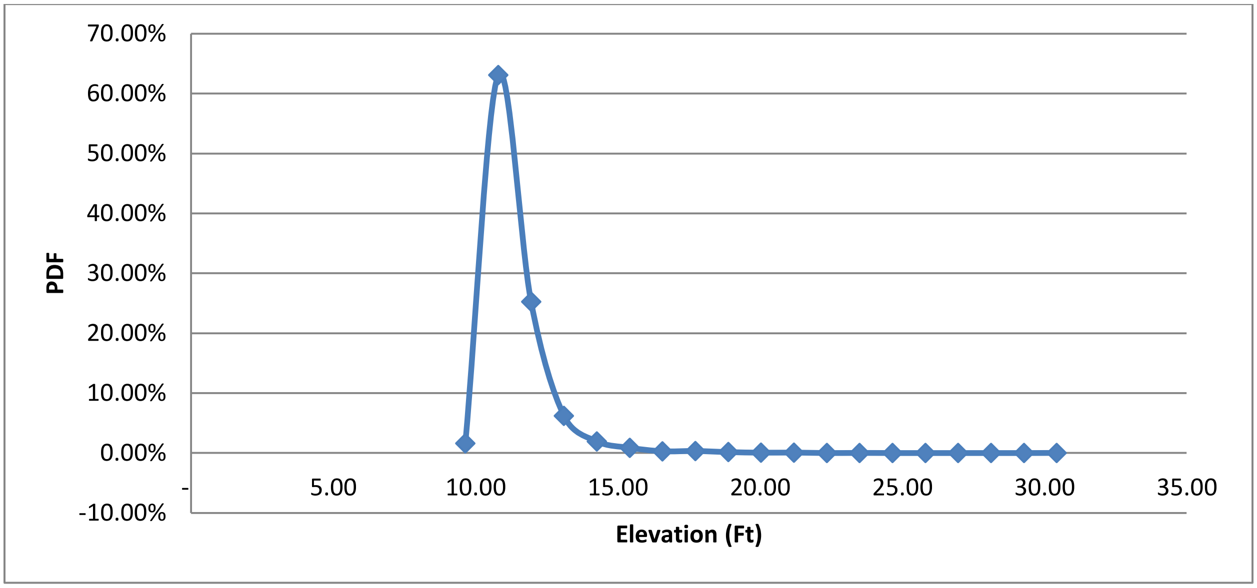
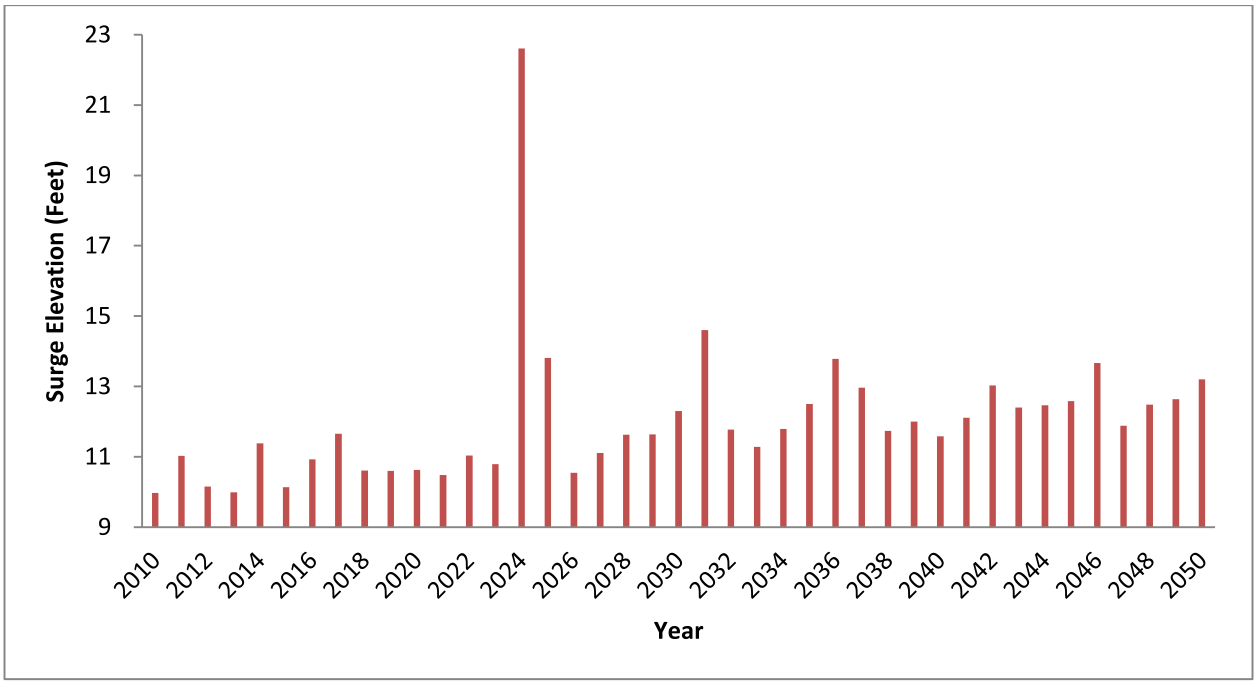


Table 5 shows a sample of the storm events randomly selected for the bridge alternative during the first ten years of the analysis period and Figure 17 shows the same information graphically over the entire analysis period. In the table, the flood elevations are shown along with the undiscounted and discounted damage costs (if any) each storm is anticipated to cause; values derived from referencing the climate stressor-damage relationship. Note that in many years no damage is recorded but in some years there is notable damage. This process is continued for every year over the period of the analysis to derive one possible sequence (known as a simulation) of storm events and damage costs that the asset may experience. The discounted damage costs can then be summed to produce the cumulative expected damage cost for that that simulation. Note in Figure 17 the general trend of events becomes increasingly severe over time due to sea level rise.

Table 5: Sample Monte Carlo Simulation for the Bridge Alternative, High Sea Level Rise Scenario.

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Elevation in Feet	10.0	11.0	10.2	10.0	11.4	10.1	10.9	11.7	10.6	10.6
Undiscounted Damages ($)	-	25,000	-	-	25,000	-	-	25,000	-	-
Discounted Damages (2010 $)	-	24,155	-	-	21,786	-	-	19,650	-	-

Figure 17: Sample Monte Carlo Simulation for the Bridge Alternative, High Sea Level Rise Scenario.



Since there is uncertainty in the timing of when storms of particular intensities will hit and this is important to the costing because of the discounting, the random storm selection process is repeated thousands of different times, 5,000 in the case of this study, leading to the creation of thousands of different possible sequences of storms for each climate scenario. Each of these simulations can be thought of as being a different possible future. Some sequences will show many big storm impacts, some fewer. Some will show big storms hitting earlier in the period of analysis, others later. All are theoretically possible given the probability distributions provided. Since in this case climate change shifts the storm probability distribution in a way that makes damaging storms more likely, the Monte Carlo analysis will tend to feature more frequent damaging storms later in each sequence. Once the sequences were run and the cumulative expected damage costs tallied for each, the average of these values can be calculated. This average, the expected value[35], represents the best estimate of the cumulative expected value of the damages for the given asset under the given scenario; a value that can be compared directly to the value calculated through the area technique. Ninety-five percent confidence intervals around this mean value were also developed by re-running the entire analysis 1,000 times and analyzing the range of mean values.

Table 6 shows the cumulative expected damage costs as estimated from the Monte Carlo analysis along with their 95% confidence intervals.[36] The cumulative expected damage costs from the area technique are repeated here as well for ease of comparison. Figure 18 shows this information graphically and Table 7 shows the findings in terms of total cost outlays to MaineDOT when the capital costs of the projects are added in.

Table 6: Cumulative Expected Damage Costs Using the Monte Carlo and Area Techniques, 2010-2050.[37]

Cumulative Expected Damage Costs Using the Monte Carlo and Area Techniques	Culvert		Bridge	
	Low SLR ($)	High SLR ($)	Low SLR ($)	High SLR ($)
*95% CI upper bound**	*822,531*	*1,023,886*	*1,067,176*	*1,325,937*
Expected value (Monte Carlo)**	754,301	948,698	948,490	1,195,277
*95% CI lower bound**	*688,834*	*877,555*	*835,555*	*1,071,884*
Expected value (area technique)**	729,212	927,148	914,471	1,171,299

[35] Expected value, as opposed to average, is the more technically correct term to use when referring to theoretical quantities such as this.

[36] The 95% confidence Interval represents the bounds that envelope 95% of the simulated expected values. These limits specify the range which the true estimate of the expected value is expected to take. For example, as shown in the table, in the culvert low scenario case, the true expected value will lie between ~$822K and ~688K about 95% of the time.

[37] All values shown in 3.5% discounted 2010 dollars.

Figure 18: Cumulative Expected Damage Costs Using the Monte Carlo and Area Techniques, 2010-2050.

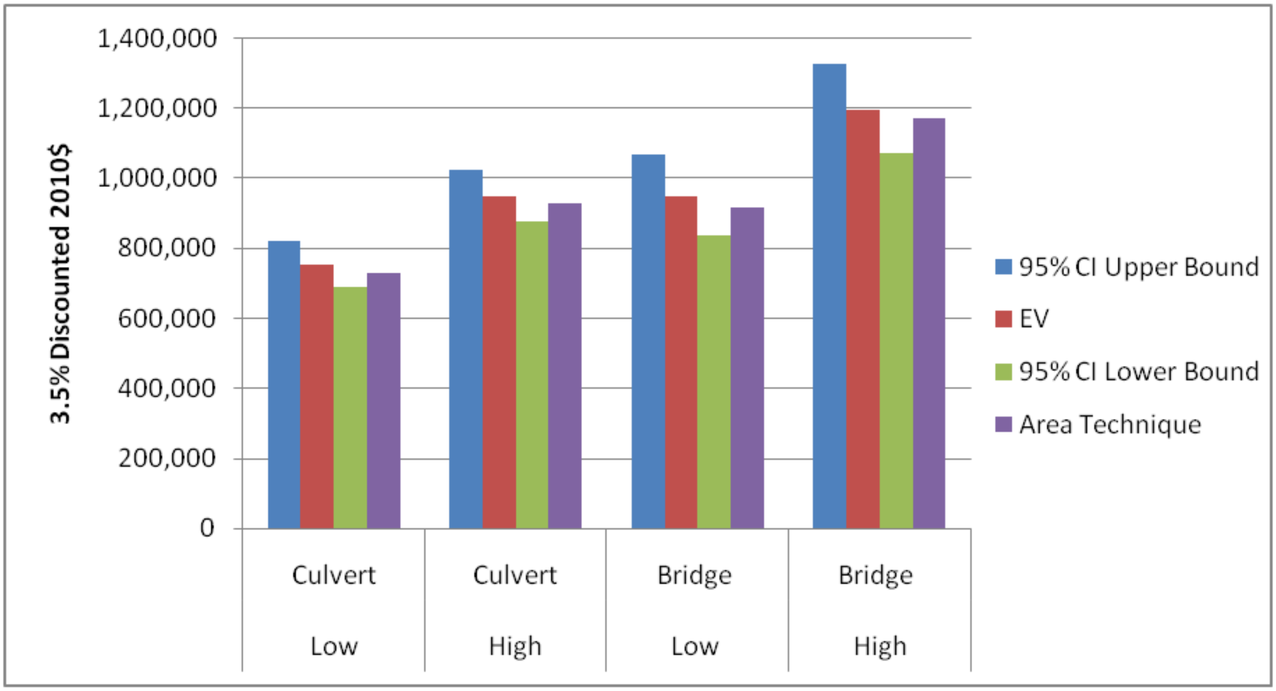


Table 7: Total Cost Outlays to MaineDOT for the Bridge and Culvert Alternatives, 2010-2050.[38]

Design	Emissions Scenario	Methodology	Total Discounted Damages 3.5% ($)	Asset Cost ($)	Total Costs ($)
Culvert	High	*MC (95% CI lower)*	*877,555*	*2,200,000*	*3,077,555*
		MC (Expected Value)	948,698	2,200,000	3,148,698
		MC (95% CI higher)	*1,023,886*	*2,200,000*	*3,223,886*
		Area	927,148	2,200,000	3,127,148
	Low	*MC (95% CI lower)*	*688,834*	*2,200,000*	*2,888,834*
		MC (Expected Value)	754,301	2,200,000	2,954,301
		MC (95% CI higher)	*822,531*	*2,200,000*	*3,022,531*
		Area	729,212	2,200,000	2,929,212
Bridge	High	*MC (95% CI lower)*	*1,071,884*	*2,400,000*	*3,471,884*
		MC (Expected Value)	1,195,277	2,400,000	3,595,277
		MC (95% CI higher)	*1,325,937*	*2,400,000*	*3,725,937*
		Area	1,171,299	2,400,000	3,571,299
	Low	*MC (95% CI lower)*	*835,555*	*2,400,000*	*3,235,555*
		MC (Expected Value)	948,490	2,400,000	3,348,490
		MC (95% CI higher)	*1,067,176*	*2,400,000*	*3,467,176*
		Area	914,471	2,400,000	3,314,471

[38] Note: MC denotes the Monte Carlo analysis.

Findings

The tables and graphic reveal that the two techniques produce similar results with the conclusions being very robust to the methodology chosen. Under each scenario and for each alternative, the present value of damages is roughly equal and the conclusions remain the same: the culvert alternative results in less damage and less total costs to MaineDOT than the bridge alternative regardless of the scenario. In no case is the estimate from the area technique outside the 95% confidence interval of the Monte Carlo analysis.

Discussion

The above analysis has shown that the results are similar regardless of whether one uses the area technique or Monte Carlo analysis. That said, there are advantages and disadvantages to each method as summarized below:

- Area technique:
  - Advantages
    - Requires less familiarity with statistics
    - Less computationally intensive (for a single climate stressor)
  - Disadvantages
    - Can provide only point estimates of benefits, benefit-cost ratios, and net present values which may engender a false sense of confidence in the findings
    - Prone to errors based on how one specifies the curves and calculates the areas underneath them
    - Limited ability to explore the sensitivity of the findings to the timing and intensity of storm events
- Monte Carlo method:
  - Advantages
    - Can provide point estimates and associated confidence intervals of benefits, benefit-cost ratios, and net present values
    - Enables one to evaluate the probability that a benefit-cost ratio or net present value is above a certain critical threshold (e.g. the probability that the benefit-cost ratio is greater than one or that the net present value of the adaptation is greater than zero)
    - Offers the ability to explore the sensitivity of the findings to the timing and intensity of storm events through investigation of individual simulations
  - Disadvantages
    - Requires more familiarity with statistics
    - More computationally intensive

Overall, the area technique is generally less computationally intensive but the Monte Carlo approach provides a richer set of outputs such as confidence intervals around the mean and the ability to look at specific simulations (storm sequences) to aid in the understanding of the estimates for each scenario. These characteristics generally make Monte Carlo analysis a more attractive methodology to follow provided that appropriately trained staff are available to perform the work and interpret the results.

Discount Rate Sensitivity Test

When forecasting impacts over time and performing economic analyses, the time value of money needs to be considered in order to properly account for the fact that a dollar today is worth more than a dollar tomorrow. For this reason, exponential discounting is incorporated into the analysis. In so doing, the project impacts are reduced by a discount factor that increases over time given a constant rate and base year. The selection of the discount rate will greatly impact the dollar value of the discounted cumulative expected damage costs. Although the *relative* results would remain consistent regardless of the rate chosen, the dollar values will generally decline with a higher discount rate.

The choice of a higher discount rate can reflect a variety of things. A desire to capture unquantifiable risks (and uncertainty) and the opportunity cost of undertaking a project over some other alternative can both be expressed via the use of a higher discount rate. In general, the discount rate should represent a concept of the opportunity cost of capital. In other words, if capital were not tied up in this project what would it have earned had one chosen another option? For this reason, public sector projects tend to be evaluated using relatively lower discount rates as opposed to private sector ones (private sector projects general require profits while public ones do not).

Moreover, if estimates of future benefits are regarded as unreliable or embedded with significant uncertainty, then a higher discount rate can be used to account for these issues. Typically, costs are incurred early in the project lifecycle; this is because one first needs to make the investment in order to reap its benefits. Accordingly, the bulk of the costs are not impacted as much by higher discount rates, as they occur closer to the base year. Project benefits, on the other hand, are typically captured further out in the lifecycle and therefore are significantly affected by higher discount rates. For this reason, a higher discount rate, all else equal, would lead to a lower net present value and benefit-cost ratio for adaptation projects. Effectively, a higher discount rate sets a higher hurdle for a project to achieve in order to be considered cost-efficient.

The choice of the appropriate discount rate can be crucial for adequately assessing a project's efficiency. In the private sector, a weighted average cost of capital approach is typically implemented. That is, if a firm needed to raise capital right now, what interest rate would it effectively have to pay? Since the interest rate faced by firms would theoretically capture both the opportunity cost of capital and the perceived risk of lending to the firm, this method is a simple way of determining an appropriate discount rate. By contrast, when evaluating public sector projects it is customary to rely on either governmental guidance on the issue and/or historical real interest rate data as captured by the market for inflation adjusted Treasury bonds. The rate these bonds pay are essentially real interest rates and as such can be used as a guide for selecting a discount rate.

Although it is known that choosing a higher discount rate reduces the overall net present value, the research team wanted to investigate how the choice of discount rate drives what would be considered viable adaptation strategies. For the purposes of this analysis, a range of discount rates were used to test the sensitivity of the results produced using the Monte Carlo analysis. The baseline real discount rate[39] used in this analysis was 3.5% with a 2010 base year; the same value used by DKM in their study and employed in the methodology comparison above. In addition to the 3.5% rate, the cumulative expected damage costs were also calculated using the following values (all with 2010 as a base year):

- No discounting
- 1.4%: The value used in the Stern Review[40] on the economics of climate change
- 3%: The alternative rate suggested for use in the U.S. Department of Transportation's (USDOT) Transportation Investment Generating Economic Recovery (TIGER) grant program
- 7%: The official U.S. Office of Management and Budget (OMB) rate and the primary rate used in the TIGER program

Note that higher discount rates that might be associated with the private sector were not investigated. This bridge, like most roadway infrastructure, is government owned and managed.

Table 8 below summarizes the results of the sensitivity analysis on the cumulative expected damage costs for each replacement alternative under each climate scenario. As discussed above, the choice of rates does not affect the relative performance of each alternative: the culvert option consistently outperforms the bridge across both climate scenarios regardless of the rate used. Notice, however, the large differences in the cumulative expected damage costs depending on which discount rate is used. This indicates that economic analyses for climate adaptation projects are highly sensitive to the rate chosen.

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[39] A real discount rate is the discount rate that applies after the effects of inflation have been accounted for. This is in contrast to a nominal discount rate which are typically larger because they include, embedded in the rate, an implicit rate of inflation. The 3.5% rate used in the methodology comparison is a real discount rate. Accordingly, all values were expressed in 2010 dollars and no real growth in repair costs is assumed over the analysis length.

[40] Stern 2007.

Table 8: Discount Rate Impacts on Cumulative Expected Damage Costs, Monte Carlo Analysis, 2010-2050.

Culvert or Bride Option	Sea Level Rise Scenario	7%	3.5%	3.0%	1.4%	Undiscounted
Culvert Option	Low	$423,598	$754,301	$830,103	$1,154,993	$1,589,586
	High	$514,960	$948,698	$1,049,056	$1,481,584	$2,064,265
Bridge Option	Low	$536,484	$948,490	$1,042,801	$1,446,754	$1,986,703
	High	$650,611	$1,195,277	$1,321,399	$1,865,279	$2,598,595

Net Present Value

Next, the research team tested the net present value (NPV, benefits – costs) under the range of discount rates. This exercise shows the sensitivity of values to the choice of discount rates. The project cost estimates for both options were derived from the DKM study (see Table 7). Table 9 and Table 10 show the results of this analysis in tabular form and Figure 19 and Figure 20 show the same information graphically. The costs represent the difference between the two projects' costs. The benefits, in this case, are estimated by taking the difference between the damages incurred under each alternative. In this particular case, the culvert always produces less cumulative damages and its project costs are also less therefore the net present value will always be positive although it decreases as the discount rate is increased. Effectively, the culvert option is preferred to the bridge in all cases, as it leads to a lower cumulative damage and costs less. In cases where the outcome is not as clear cut, it is possible that choosing a higher discount rate could cause a project alternative to switch from having a positive net present value to a negative one: thus, the specification of the discount rate is very important in climate change adaptation analyses.

Table 9: Discount Rate Impacts on Project Net Present Value and Benefit-Cost Ratios, Low Sea Level Rise Scenario, Monte Carlo Analysis, 2010-2050.

Discount Rate	Result Type	Culvert-Bridge Difference in Cost	Culvert-Bridge Difference in Damages (Benefits)	NPV
Undiscounted	*95% CI lower*	*$(200,000)*	*$494,628*	*$694,628*
	Expected Value	$(200,000)	$397,117	$597,117
	95% CI higher	*$(200,000)*	*$305,609*	*$505,609*
1.4%	*95% CI lower*	*$(200,000)*	*$365,016*	*$565,016*
	Expected Value	$(200,000)	$291,760	$491,760
	95% CI higher	*$(200,000)*	*$222,918*	*$422,918*
3.0%	*95% CI lower*	*$(200,000)*	*$267,515*	*$467,515*
	Expected Value	$(200,000)	$212,698	$412,698
	95% CI higher	*$(200,000)*	*$161,136*	*$361,136*
3.5%	*95% CI lower*	*$(200,000)*	*$244,644*	*$444,644*
	Expected Value	$(200,000)	$194,189	$394,189
	95% CI higher	*$(200,000)*	*$146,721*	*$346,721*
7.0%	*95% CI lower*	*$(200,000)*	*$143,842*	*$343,842*
	Expected Value	$(200,000)	$112,886	$312,886
	95% CI higher	*$(200,000)*	*$83,774*	*$283,774*

Table 10: Discount Rate Impacts on Project Net Present Value and Benefit-Cost Ratios, High Sea Level Rise Scenario, Monte Carlo Analysis, 2010-2050.

Discount Rate	Result Type	Culvert-Bridge Difference in Cost	Culvert-Bridge Difference in Damages (Benefits)	NPV
Undiscounted	*95% CI lower*	*$(200,000)*	*$645,258*	*$845,258*
	Expected Value	$(200,000)	$534,330	$734,330
	95% CI higher	*$(200,000)*	*$429,667*	*$629,667*
1.4%	*95% CI lower*	*$(200,000)*	*$465,894*	*$665,894*
	Expected Value	$(200,000)	$383,695	$583,695
	95% CI higher	*$(200,000)*	*$306,185*	*$506,185*
3.0%	*95% CI lower*	*$(200,000)*	*$332,897*	*$532,897*
	Expected Value	$(200,000)	$272,342	$472,342
	95% CI higher	*$(200,000)*	*$215,287*	*$415,287*
3.5%	*95% CI lower*	*$(200,000)*	*$302,051*	*$502,051*
	Expected Value	$(200,000)	$246,580	$446,580
	95% CI higher	*$(200,000)*	*$194,328*	*$394,328*
7.0%	*95% CI lower*	*$(200,000)*	*$168,656*	*$368,656*
	Expected Value	$(200,000)	$135,651	$335,651
	95% CI higher	*$(200,000)*	*$104,615*	*$304,615*

Figure 19: Discount Rate Impacts on Project Net Present Value, Low Sea Level Rise Scenario, Monte Carlo Analysis, 2010-2050.

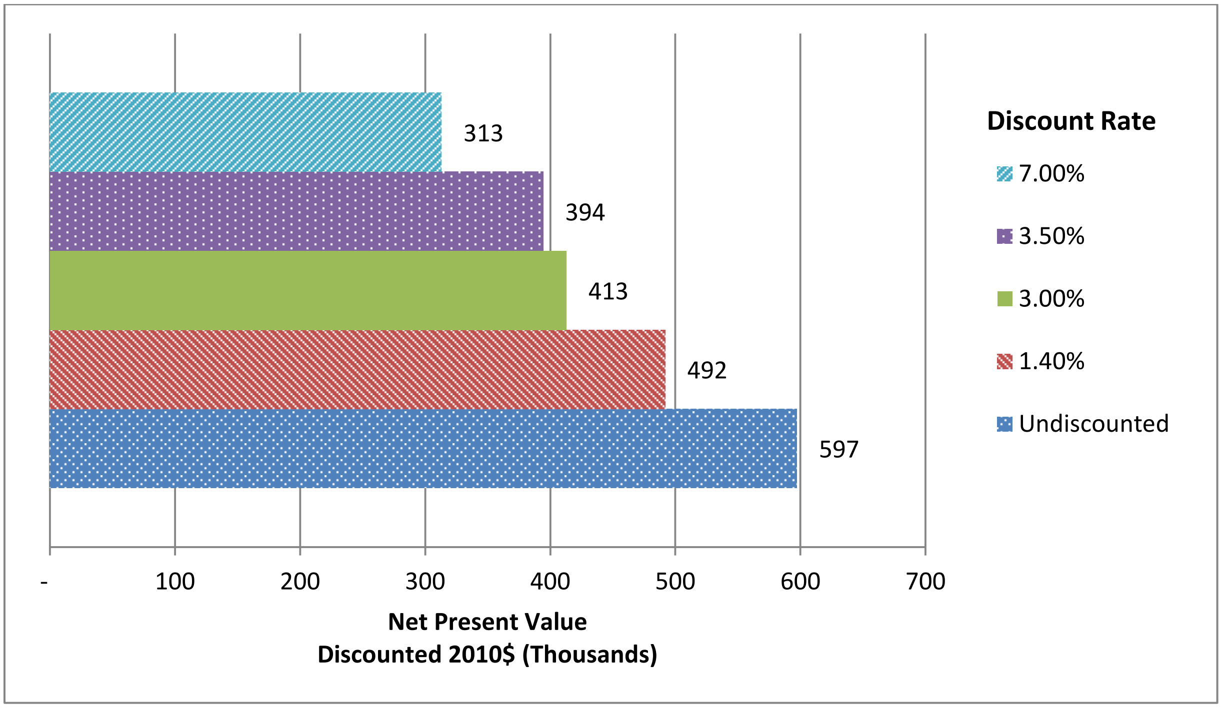
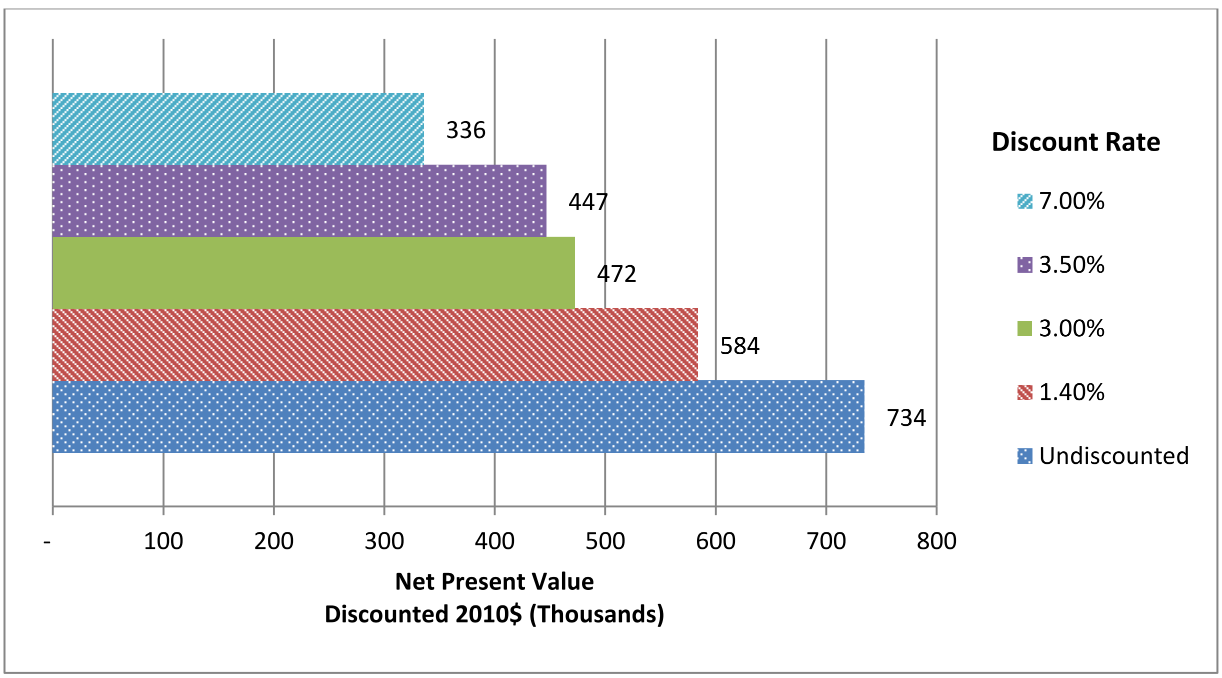


Figure 20: Discount Rate Impacts on Project Net Present Value, High Sea Level Rise Scenario, Monte Carlo Analysis, 2010-2050.



Climate Stressor-Damage Relationship Sensitivity Test

A major source of uncertainty in climate change economic analysis is the asset's response to the weather event: how much damage is incurred if a particular weather event takes place? There is likely to always be some degree of uncertainty in answering this question when developing the climate stressor-damage relationship curves. Furthermore, for this specific case study, there were some aforementioned concerns about the validity of the step function depth-damage relationship employed on the methodology comparison. In order to understand how much uncertainty in the climate stressor-damage relationship can affect the conclusions of an economic analysis, a sensitivity analysis was performed using an alternate climate stressor-damage relationship. Separate damage curves were developed for the culvert and bridge alternatives as described in detail in the section below.

Development of the Alternate Climate Stressor-Damage Curves

In order to develop the alternative climate stressor-damage relationships for use in the sensitivity test, the research team worked with available information on hydrologic interactions at the project site from previous studies: no new hydraulic analyses were conducted for this case study. The research team also made a field visit to the project site. During the field visit, current construction materials at the site were observed, measured (if applicable), and documented. The damage functions developed assumed that similar materials and protection measures would be used for the replacement alternatives. Some of the specific observations that influenced the assumptions about the replacement design are as follows:

- The downstream embankment for the entire causeway was armored with riprap rubble stone. The riprap was placed with a finer gradation of stone below the top of the existing culvert and a coarser gradation above the culvert. The smaller stones were measured to have a median diameter (D_{50}) of 6 inches. The coarser riprap placement had a measured D_{50} of 18 inches. The divide between the materials was roughly along the top elevation of the existing culverts. Similar downstream embankment materials were assumed to be used on both replacement alternatives with an identical arrangement of riprap with respect to the culvert on that option.
- The upstream embankment for the entire causeway was armored with a continuous placement of riprap rubble stone that was overgrown with pioneer woody vegetation. The upstream stone was measured to have a D_{50} of 16 inches. Similar upstream embankment materials were assumed for both replacement alternatives.
- US-1 and the adjacent parking area on the current Dyke Bridge and causeway are paved with bituminous asphalt and the Down East Sunrise Trail is a fine gravel. It was assumed that, when replaced, the roadway, parking areas, and trail would have the same dimensions and elevations as today and that the paving materials would also be identical.

Other important assumptions that influenced the development of the damage relationships were as follows:

- The culvert alternative was assumed to have concrete box culverts instead of the current timber and masonry structures.
- For the bridge alternative, the DKM study noted that the abutment foundations would be driven to bedrock. Based on this information it was assumed that there is no risk for abutment failure or shifting due to foundation scour.
- Also for the bridge alternative, the research team assumed that, if water levels reached high enough, the bridge deck would become detached from the substructure and wash downstream. This could occur due to shear failure of the anchor bolts or other failures as the surge forces over-powered the bridge deck.
- The roadway over the bridge deck was assumed to be concrete and not subject to the same failure mechanism as the asphalt.

Using these assumptions, basic engineering analyses were undertaken to determine the performance of each replacement option under different water levels. Specific analyses included wave impact, weir flow, and roadway overtopping assessments. The wave impact analysis considered the maximum wave height identified in the DKM study, which was one foot. Damages due to wave impact would be limited to erosion and movement of the riprap rubble stone and erosion of gravels and soils along the roadway shoulders. The Riprap Analysis for Wave Attack module in the FHWA Hydraulic Toolbox[41] was utilized to determine the sufficiency of the riprap present at the Dyke Bridge. Based on this analysis, it was determined that a rock size of six inches would protect against the one foot maximum wave. Since the assumed protection on the ocean side of the causeway ranged from a minimum rock size of six inches up to a maximum of 18 inches, the research team concluded that failure of the riprap under current or future climate conditions due to wave attack is not likely.

The Embankment Overtopping Module, also in the FHWA Hydraulic Toolbox, was utilized to analyze the riprap protection on the landward side of the causeway to determine its sufficiency against overwashing flows. This module considers the depth of overtopping flow above the roadway and determines the erosive forces along the backside of an embankment due to supercritical flows[42] over the structure. The embankment overtopping analysis concluded that the 16 inch riprap protecting the landward side of the embankment would be susceptible to erosion and failure at one foot of flooding over the causeway. Based on the elevation values discussed in Step 2, this one foot of flooding / weir flow was set at elevation 13 feet in

[41] The FHWA Hydraulic Toolbox, Version 4.20. Available at: http://www.fhwa.dot.gov/engineering/hydraulics/software/toolbox404.cfm.

[42] Supercritical flow is generally high velocity, shallow flow (less than critical depth) on a steep slope.

consideration of the gravel trail as the high point on the causeway. Once the riprap protection of the landward side of the causeway is compromised, the causeway will become susceptible to breaching failure and washout of the causeway fill material.

Lastly, the potential for erosion of the bituminous asphalt roadway surface due to overwashing hydraulic forces was considered. A flow depth of between one and four feet above the pavement has been shown to deteriorate asphalt pavements in laboratory experiments.[43] Based on the roadway crest elevation of 11 feet, this correlates to loss of asphalt pavement starting at a flood elevation of 12 feet and complete pavement loss at 15 feet.

Figure 21 displays the climate stressor–damage relationship developed for the culvert replacement alternative. In this relationship, damage is shown to start at a flood elevation around 11 feet with the loss of some minor pavement areas due to wave action affecting the gravel roadway shoulder. Damage increases at 12 feet when roadway overtopping reaches one foot and the asphalt pavement begins to washout due to overtopping forces (20% loss of pavement is assumed). At a 13 foot surge, damage escalates as the landward side riprap on the causeway is compromised and breaching of the causeway and roadway commences. Damages continue to compound based upon the loss of higher percentages of pavement increasing the size of the roadway breach. The next key damage threshold involves full exposure and shifting of the culvert barrels at a flood elevation of 15 feet requiring movement and resetting of the culvert barrels. Loss of the concrete culverts, due to washing downstream, was estimated to occur at a flood elevation around 21 feet and near complete washout of the causeway fill due to breaching was estimated to occur at a flood elevation of 26 feet. Beyond this flood elevation, damage costs plateau as the facility is a total loss.

[43] Powledge et al. 1989a and 1989b.

Figure 21: Alternate Climate Stressor-Damage Curve for the Culvert Alternative.

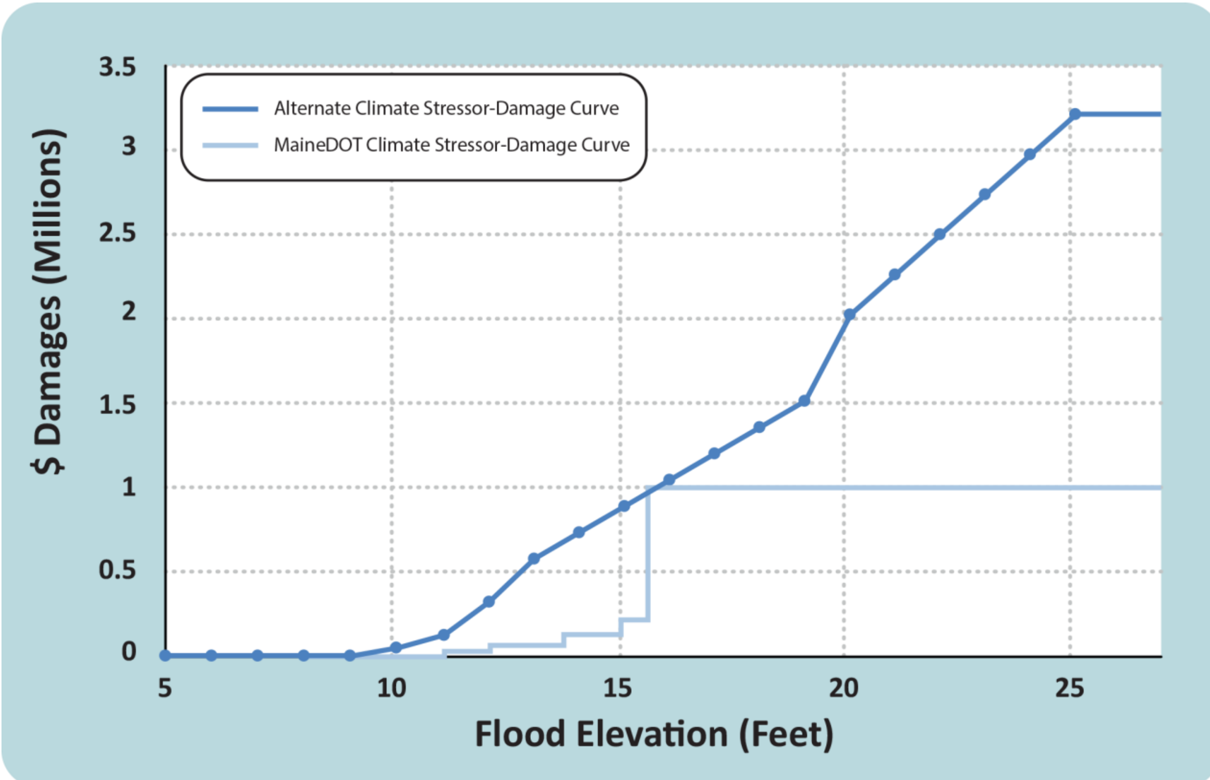
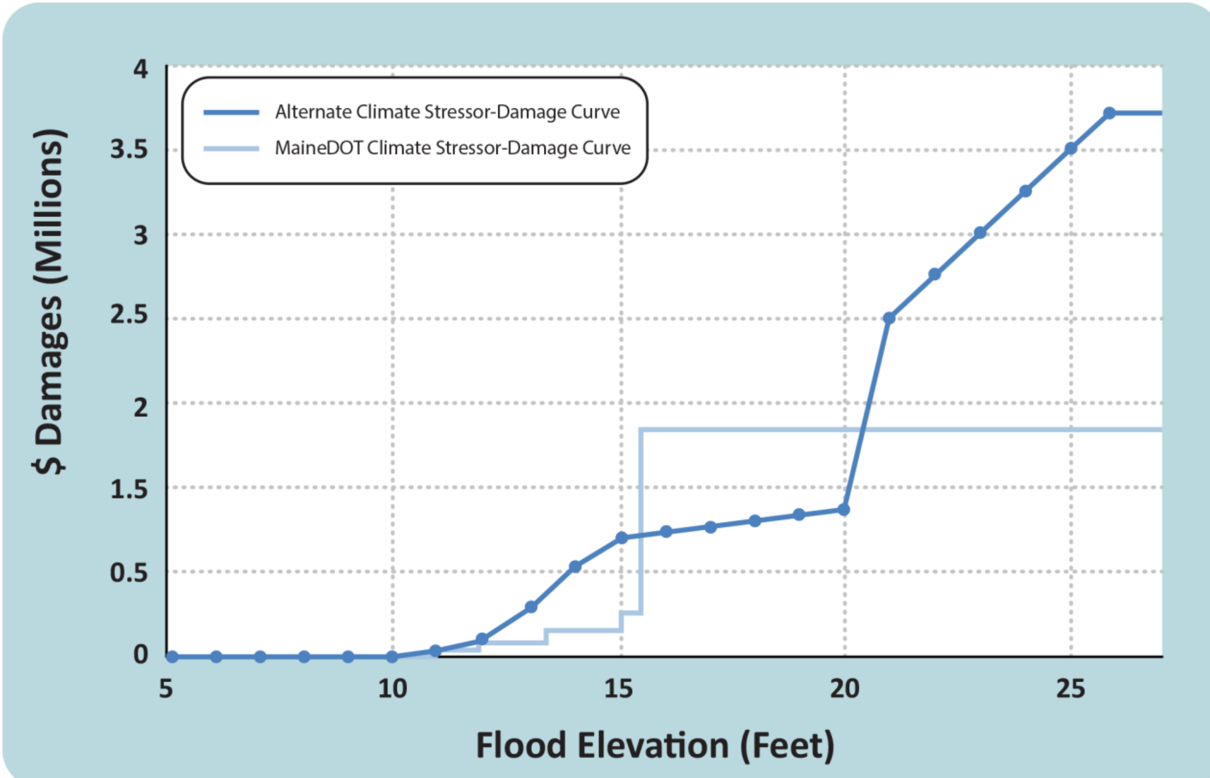


Figure 22 displays the climate stressor–damage relationship developed for the bridge alternative. As with the culvert, damage is shown to start at a flood elevation of 11 feet due to wave action affecting the roadway shoulder gravels which are situated at the same elevation as with the culvert. Damages at flood elevations 12 feet and 13 feet due to the roadway pavement and landward riprap failures follow the same pattern as with the culvert although the damages are slightly less because there is less fill material and pavement to be lost. Performance of the two options starts to deviate more significantly at a flood elevation of 15 feet where, with the bridge alternative, the breaching of the causeway is assumed to undermine and cause the loss of one concrete approach slab. Further damages for the bridge include loss of the second concrete approach slab at a flood elevation of 20 feet and then loss of the bridge superstructure / deck at an elevation of 21 feet.

Figure 22: Alternate Climate Stressor-Damage Curve for the Bridge Alternative.



The alternate climate stressor-damage relationships were developed independent of the relationships developed by MaineDOT for the DKM study, to prevent bias in the results. Once completed, the new curves were back-compared to the prior study to determine the differences in the independent estimates of damage cost and performance. In general, the cross comparison between the methods revealed some differences in opinion related to the types of damage speculated to occur and the elevations at which damage occurs, but the damage costs at corresponding failure thresholds were within a reasonable range between the two methods. Some specific differences included:

- The MaineDOT curves included failure of the ocean side riprap due to wave action, whereas the new study concluded that this was an unlikely failure mechanism.
- The MaineDOT curves included estimates for damage and replacement to the outfall flap gates for the culvert option, whereas the new study concluded that this damage would be unlikely during smaller storm events as the gates would be submerged and wave impact would not impact the gates. Also, during larger events, the loss of the gates and associated costs would be inconsequential compared to the larger scale damages.
- On average, the MaineDOT curves consistently equated similar damage costs at one foot of elevation lower when compared to the new curves. This difference may be due to the assumed implications of the gravel trail on the overall causeway hydraulics.

- The MaineDOT curves had maximum damage estimates of $1.5 million for the culvert alternative and $3 million for the bridge alternative while the new curves have maximum damage estimates of $3.2 million and $3.7 million, respectively.[44] The maximum costs are different primarily because the new damage relationships included the more catastrophic damages likely from more severe storms; the new study included damages up to elevation 26 feet, the point of total loss, while the prior study only considered damages up to a flood elevation of 15 feet. Damage curves should be constructed up to the point of complete failure otherwise the cumulative expected damage costs will be underestimated.

Economic Analysis Using the Alternate Climate Stressor-Damage Curves

The Monte Carlo method was re-run using the alternate climate stressor-damage curves. The results are shown in Table 11 along with the previously reported outputs using the MaineDOT curves. As one can see, the analysis conclusions were significantly affected by using the alternative curves. Firstly, the overall dollar value of the impacts increased significantly for both replacement alternatives under either climate scenario. This was due largely to the fact that the MaineDOT curves did not consider the possibility of more catastrophic damages.

Additionally, the conclusion as to which asset has lower cumulative expected damage costs was reversed. With the alternate curves, the bridge option outperformed the culvert option under every scenario. A key reason for this reversal was the difference in how the MaineDOT and revised curves characterized the damage from smaller storm events. The MaineDOT curves viewed the damages from smaller storm events to be comparable for both the culvert and bridge alternatives. In contrast, the alternate curves included slightly lower damage costs for the bridge alternative during these events. The rationale for this was that slightly less embankment material and pavement would need to be replaced with the bridge alternative at a given flood elevation because the more resilient concrete bridge deck would occupy this area instead. Since smaller storms happen more frequently, this difference made a noticeable impact on the cumulative damage costs.

[44] Note that the total possible damages under the alternate curves exceed the project costs from the Douglas, Kirshen, and Merrill study because the project costs only included replacement of the portion of the causeway with the waterway opening whereas the alternate curves considered damages to the entire causeway.

Table 11: Cumulative Expected Damage Costs with Alternate Climate Stressor-Damage Curves, Monte Carlo Analysis, 2010-2050. [45]

Climate Stressor Damage Curve	Confidence Intervals/ Expected Value	Culvert Low	Culvert High	Bridge Low	Bridge High
Alternate Climate Stressor-Damage Curve	95% CI* Upper Bound	$5,176,986	$6,884,224	$4,923,647	$6,579,531
	Expected Value**	$4,952,445	$6,650,873	$4,681,218	$6,324,411
	95% CI Lower Bound	$4,733,448	$6,420,666	$4,446,905	$6,075,580
MaineDOT Climate Stressor-Damage Curve	95% CI Upper Bound	$822,531	$1,023,886	$1,067,176	$1,325,937
	Expected Value	$754,301	$948,698	$948,490	$1,195,277
	95% CI Lower Bound	$688,834	$877,555	$835,555	$1,071,884

*Confidence Interval: The bounds that envelope 95% of the simulated expected values. These limits specify the range which the true estimate of the expected value is expected to take. In Culvert Low case, the true expected value will lie between ~$822K and ~688K about 95% of the time.

** Expected Value: this is the point estimate of the long-run average impact.

The sensitivity of the results under the different damage curve assumptions demonstrates the importance of developing accurate climate stressor-damage relationships. Small nuances in the curves, such as the observation that damage costs may be lower for the bridge than the culvert during smaller storms, can make a big difference in the conclusions. Accordingly, when there is significant uncertainty in the failure mechanism of a particular asset, it is wise to consider sensitivity tests of different climate stressor-damage relationships. It is recommended that the engineer acknowledge the areas of greatest uncertainty, develop alternate curves that shift the data points within range of the uncertainty, and run additional Monte Carlo simulations to document the uncertainty. Note that this process typically requires engineering knowledge and is not a simple exercise of changing the curve by set percentages: that said, it should be relatively straightforward for most engineers to make such tweaks.

Step 9: Evaluate Additional Considerations

Economic analyses provide important information for decision-making but not all items that need consideration are able to be fully monetized. Some specific items that may have more qualitative elements worth considering include:

[45] All values shown in 3.5% discounted 2010 dollars.

- The environmental and land use implications of re-introducing saltwater and tidal influence to the Middle River estuary with the bridge alternative
- The implications of disrupting the farmers and flea markets that occur on the causeway
- If the crossing is raised, the effect this might have on properties adjacent to it and the town dock
- The aesthetics of the replacement design

Step 10: Select a Course of Action

Choosing a preferred course of action was beyond the scope of this case study, however, given the findings of this case study, it is highly recommend that MaineDOT consider adaptive actions for the replacement bridge including the raising of the entire crossing.

Step 11: Develop a Facility Management Plan

A facility management plan for the new Dyke Bridge should consider, among other things, an emergency operations component in which monitoring of the crossing for flooding will be performed when water levels that threaten the facility are forecast. In conjunction with this, the DOT should consider the signing of formal detour routes for US 1 in case the crossing is impassible due to flooding; events that will happen more frequently in the future if no adaptive measures are taken.

Lessons Learned

During the course of this study, the project team identified the following lessons learned related to the gaps discussed at the beginning of this case study:

- A scenarios approach to climate change adaptation economic analyses is an effective way to consider the range of climate change uncertainty. By calculating projected project lifecycle costs, benefit-cost ratios, and/or net present values for each adaptation option under each climate scenario, decision-makers are provided with the information needed to make wise investment choices. Ideally, one is searching for the adaptation option that performs the best across the range of scenarios (the robust performer) or, if no such option exists, the option that has the lowest downside across the possible climate scenarios.

  The area technique and Monte Carlo analysis produce similar estimates of the benefits of adaptation options. That said, each technique has its advantages and disadvantages. The main advantage of the area technique is its computational simplicity relative to Monte Carlo analysis. However, with this simplicity comes more limited output information and, potentially, a tendency towards a false sense of confidence in the findings engendered by the single point estimate of the benefits. Monte Carlo analysis' chief advantages are its richer outputs including confidence intervals around the benefit estimates, the ability to determine probabilities that critical values will be crossed (e.g. that the benefit-cost ratio will be over one), and information for evaluating the sensitivity of the findings to different storm timings and intensities. Thus, the Monte Carlo method is preferable to use in most instances provided that trained staff are available to perform the analysis.

- The discount rate chosen has a substantial impact on the benefits estimated and, consequently, project cost-effectiveness measures such as the benefit-cost ratio and net present value. It is worth exploring the sensitivity of economic analysis findings to different discount rates.
- Cost-effectiveness measures are also highly sensitive to the climate stressor-damage relationship specified. Therefore, when there is significant uncertainty in the failure mechanism of a particular asset, it is wise to consider sensitivity tests of different climate stressor-damage relationships.

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