# Addressing Resilience in Project Development

U.S. Department of Transportation
Federal Highway Administration

## Comparison of Economic Analysis Methodologies and Assumptions

Using proposed replacement designs for a coastal culvert, this case study focused on comparing the outcomes of two different economic analysis techniques. The study also considered the sensitivity of the findings to various discount rates and different assumptions on damage to the roadway during coastal storms.[1]

## Site Context and Facility Overview

This study focused on a causeway and associated culvert (known locally as the Dyke Bridge) along US 1 in rural eastern Maine near the town of Machias (see Figure 1). Although only a two-lane roadway at the study site, US 1 is an important regional transportation route in coastal Maine connecting many small towns along the coastline.

**Figure 1: Map of study area (red star).**
Image Source: Google Maps

The causeway, approximately 900 feet in length, spans the Middle River where it empties into Machias Bay. It is made of timber cribbing filled with rubble and soil. The culvert component, whose oldest portions date to the 1930s, consists of four square timber and masonry cells with flap gates on the downstream end to prevent tides from propagating upriver (see Figure 2).

## Design Options

**Figure 2: Photo of Dyke Bridge at low tide, downstream side.**
Image Source: WSP

Recently, some of the timbers within the embankment have deteriorated to the point where emergency repairs were required to address issues with roadway settlement. This prompted the Maine Department of Transportation (MaineDOT), the causeway owner, to develop design alternatives for a replacement facility. Two conceptual designs were created: (1) a new causeway with culverts having the same configuration, elevation, and dimensions as the existing facility and (2) a 58-foot long single-span bridge in lieu of the culverts. The bridge and its approaches would be built at the same elevation as the current causeway.

## Environmental Stressors and Scenarios

According to a prior study,[2] the primary environmental stressor affecting the Dyke Bridge will be sea level rise and associated changes in storm surge elevations.

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[1] This snapshot summarizes one of nine engineering-informed adaptation studies conducted under the Transportation Engineering Approaches to Climate Resiliency (TEACR) Project. See https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/ for more about this study and *Synthesis of Approaches for Addressing Resilience in Project Development*.

[2] Douglas, Ellen, Paul Kirshen, and Sam Merrill. 2013. Cost-Efficient and Storm Surge-sensitive Bridge Design for Coastal Maine.

Although future increases in precipitation may also increase the peak flows through the culvert, the flood elevations associated with these flows were determined to be lower than the storm surge heights.

Table 1 shows the local sea level rise projections for the site and Table 2 shows their effect on storm surge elevations for various return period events.

| Year | Low Scenario | High Scenario |
|---|---|---|
| **2030** | 0.5 | 0.9 |
| **2050** | 1.0 | 1.7 |

**Table 1: Sea level rise projections, feet.[3]**

| Return Period | 2010 | 2030 | | 2050 | |
|---|---|---|---|---|---|
| | | Low | High | Low | High |
| **2** | 10.5 | 11.5 | 11.9 | 12.0 | 12.7 |
| **5** | 11.3 | 12.3 | 12.7 | 12.8 | 13.5 |
| **10** | 12.0 | 13.0 | 13.4 | 13.5 | 14.2 |
| **20** | 12.7 | 13.7 | 14.1 | 14.2 | 14.9 |
| **50** | 13.9 | 14.9 | 15.3 | 15.4 | 16.1 |
| **100** | 15.0 | 16.0 | 16.4 | 16.5 | 17.2 |
| **200** | 16.3 | 17.3 | 17.7 | 17.8 | 18.5 |
| **500** | 18.3 | 19.3 | 19.7 | 19.8 | 20.5 |

**Table 2: Projected storm surge elevations, feet**

## Economic Analysis

### Overview

Although the crossing is exposed to future sea level rise, neither of the conceptual designs explicitly took this into account. Nonetheless, MaineDOT completed an economic analysis of sea level rise to explore its implications on the alternatives being considered. This TEACR study then expanded on that initial work to test an alternative economic analysis technique and explore the sensitivity of the findings to different assumptions.

### Area Technique

MaineDOT's economic analysis was conducted using a method called the area technique or area-under-the-curve (AUC) technique. This technique involves calculating the areas under a series of curves to arrive at an estimate of lifecycle damage costs to the facility due to extreme weather events (in this case, storm surge events). The lifecycle damage costs can then be added to the costs to build and maintain a facility to arrive at the total expected costs for a design option under a given scenario.

Two inputs are needed for the area technique: (1) the probability of different storm events occurring and (2) a stressor-damage relationship curve for each design option. Probabilities are used to quantify the chances that a stressor will reach a particular intensity level; in this case, the probability that storm surge will reach a given height. Figure 3 shows surge elevation probabilities for the low sea level rise scenario. Note how the curves shift to the right over time as sea level rise increases the probabilities of higher storm surges.

Stressor-damage relationship curves show the estimated costs (due to physical damage and/or socioeconomic impacts) caused by a stressor reaching a certain intensity level. Each design alternative has a different curve. The curve for the bridge option is shown in Figure 4.

[3] Vermeer, Martin and Stefan Rahmstorf. Global sea level linked to global temperature. Proceedings of the National Academies of Sciences, 106 (51).

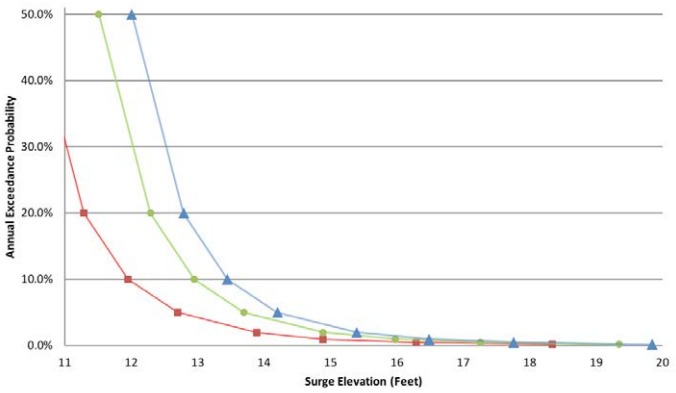


**Figure 3: Storm surge elevation probabilities under the low sea level rise scenario in 2010 (red line with squares), 2030 (green line with circles), and 2050 (blue line with triangles).**

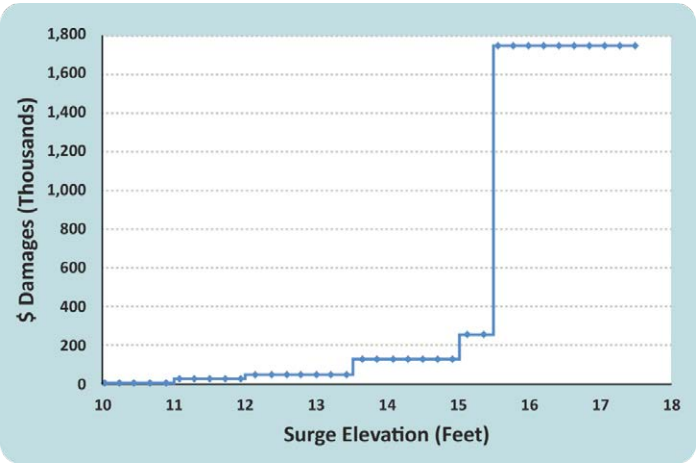


**Figure 4: Stressor-damage relationship curve for the bridge alternative.**

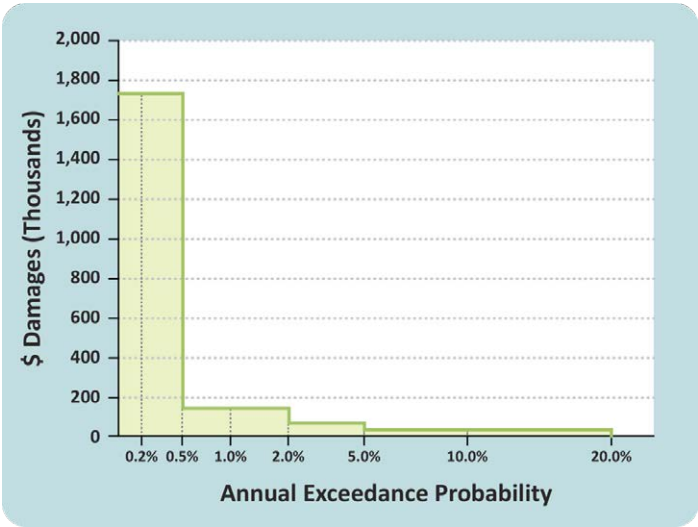


**Figure 5: Relationship between storm event probabilities and asset damage, bridge alternative, 2010.**

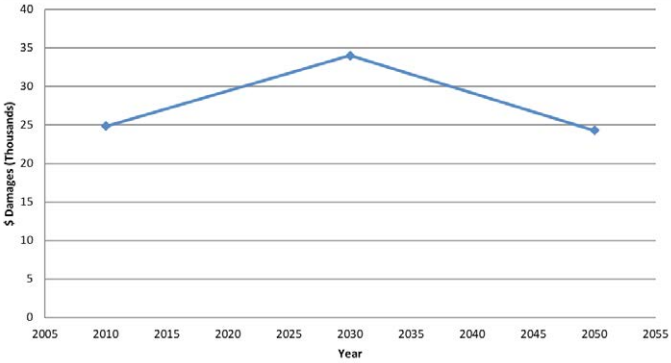


**Figure 6: Expected storm damages over time, bridge alternative, high sea level rise scenario.**

The first step in the area technique is to combine the storm probability information with the information from the stressor-damage curve. This results in a new curve showing the probability of a certain amount of damage occurring in a given year (see Figure 5).

The area under these curves in each year (i.e. the expected damages in that year) can then be calculated, discounted (to reflect the time value of money), and combined into a new curve showing damages over time (see Figure 6).

Finally, the area under this curve can be calculated to get an estimate of total lifecycle damage costs. Combining these costs with the costs to build and maintain the facility yields an estimate of total costs for the design option.

## Monte Carlo Analysis

The alternative technique tested by the research team was Monte Carlo analysis. Monte Carlo analysis uses the same inputs as the area technique but processes them differently. Using the storm probability data, a

computer randomly selects storm events for each year of the analysis. The damage cost from each storm is then determined using the stressor-damage relationship curve. The values are discounted and then summed over the analysis period to arrive at an estimate of total lifecycle damage costs for that simulation. This process is repeated thousands of times and the total lifecycle damage costs of each simulation are averaged to give the final lifecycle damage cost estimate.

### Input Parameter Sensitivity

In addition to testing whether the area technique and Monte Carlo analysis yielded similar results, the research team was also interested in understanding how sensitive the findings were to different discount rates and different stressor-damage relationship curves. Thus, sensitivity tests were performed using different values for these inputs.

### Results

The research team found that both the area technique and Monte Carlo analysis gave similar estimates of cumulative damage costs (see Figure 7). In both the low and high sea level rise scenario, the bridge option had the highest lifecycle damage costs. Since it cost more to construct, it also had the highest total costs.

The research team also found that the findings are highly sensitive to the discount rates chosen and the way the stressor-damage relationship curves are constructed.

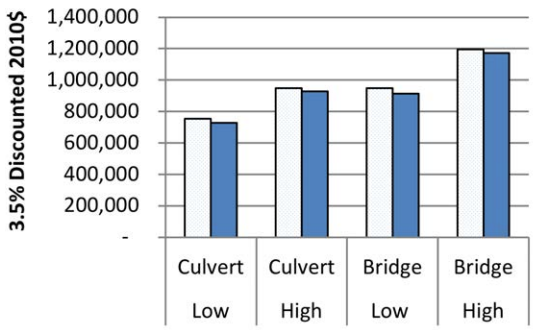


**Figure 7: Cumulative expected damage costs using the Monte Carlo (stippled bars) and area (solid blue bars) techniques, 2010–2050.**

## Lessons Learned

- Risk-enhanced economic analyses provide a useful means of exploring the impacts that different storm surge scenarios have on the cost-effectiveness of different design alternatives.
- Both the area technique and Monte Carlo analysis provide similar results. Although the area technique may be easier to implement, its outputs are not as robust.
- Analysis findings are sensitive to the discount rates chosen and the way the stressor-damage relationship curves are constructed.

## For More Information

### Resources:

**Transportation Engineering Approaches to Climate Resiliency (TEACR) project website**
www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/index.cfm

**HEC 25 Volume 2: Assessing Extreme Events**
www.fhwa.dot.gov/engineering/hydraulics/library_arc.cfm?pub_number=192&id=158

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