# MnDOT Flash Flood Vulnerability and Adaptation Assessment Pilot Project

## DISTRICT 1 SILVER CREEK  CASE STUDY

NOVEMBER 2014

This document is part of a series of short reports based on the full Flash Flood Vulnerability and Adaptation Assessment Pilot Project.

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# CASE STUDY – MN 61 CULVERT #5648 OVER SILVER CREEK

## Introduction

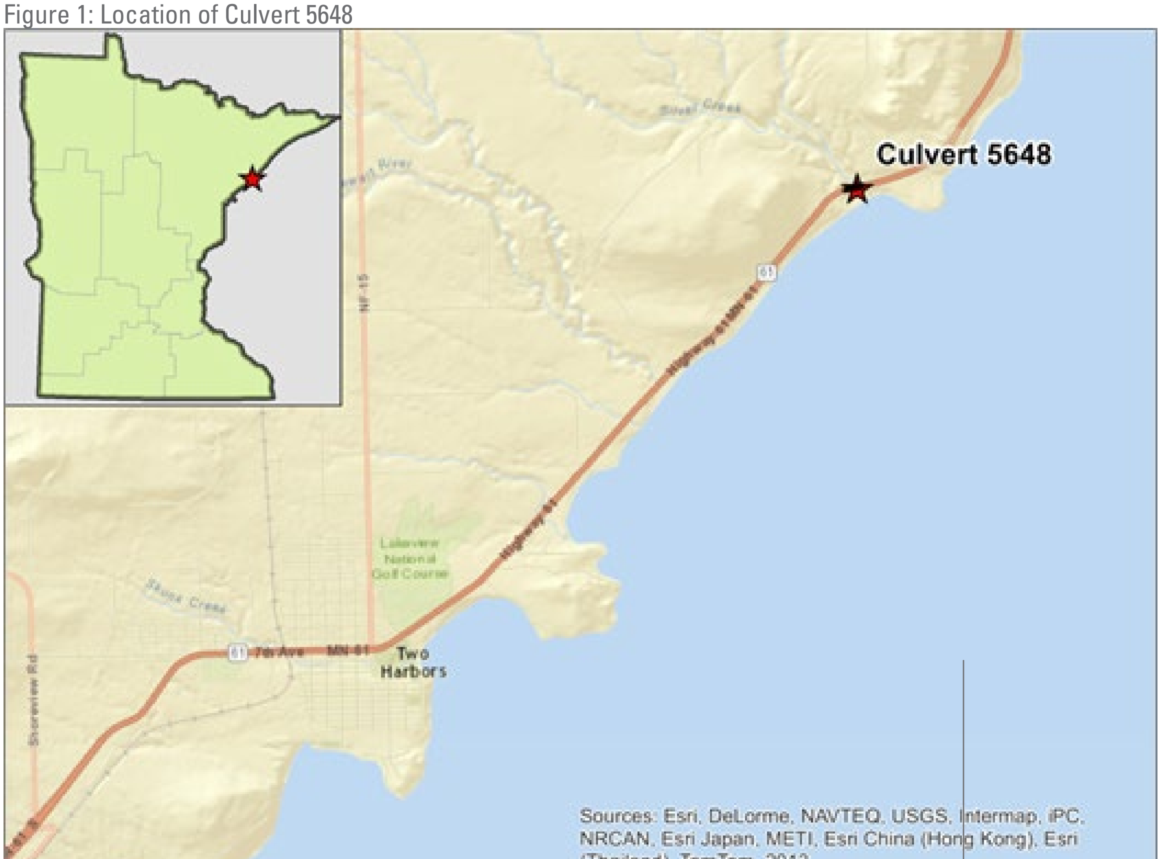
This case study of Culvert #5648 was part of a larger pilot project investigating the vulnerability of assets to climate change in two of the Minnesota Department of Transportation's eight districts. The 11-step process (see sidebar at right) used to consider the impacts of climate change on a selected asset was developed by the U.S. Department of Transportation. It was originally used for the USDOT's Gulf Coast Phase 2 study[1], and was modified slightly to better fit MnDOT's needs. This process provides a framework to consider climate change at the project level.

## Step 1 – Describe the Site Context

Culvert 5648 carries MN 61 over Silver Creek and is located northeast of Two Harbors and immediately adjacent to Lake Superior. MN 61 is an important state highway and link in the National Highway System that runs from Duluth to the Canadian border and connects the city of Thunder Bay, Ontario to the Midwestern United States. The road is also a critical link to tourist destinations along Lake Superior and in the Superior Uplands and Boundary Waters regions. Average

| The USDOT General Process for Transportation Facility Adaptation Assessments |
|---|
| 1. Describe the Site Context |
| 2. Describe the Existing/Proposed Facility |
| 3. Identify Climate Stressors that May Impact Infrastructure Components |
| 4. Decide on Climate Scenarios and Determine the Magnitude of Changes |
| 5. Assess Performance of the Existing/ Proposed Facility |
| 6. Identify Adaptation Option(s) |
| 7. Assess Performance of the Adaptation Option(s) |
| 8. Conduct an Economic Analysis |
| 9. Evaluate Additional Decision-Making Considerations |
| 10. Select a Course of Action |
| 11. Plan and Conduct Ongoing Activities |

Figure 1: Location of Culvert 5648




1: https://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/task_3.2/

annual daily traffic (AADT) at the facility is currently 5,900 vehicles per day and heavy commercial average daily traffic (HCADT) is currently 500 trucks per day. Figure 1 shows the location of the culvert.

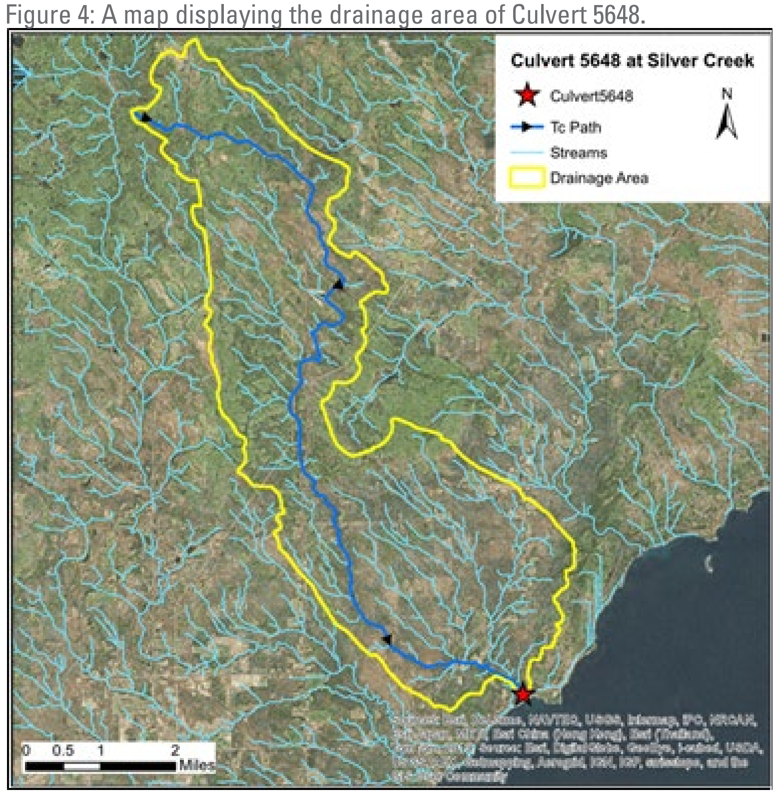
### HYDROLOGIC SETTING

Silver Creek is a stream coming off the Superior Uplands that discharges into Lake Superior near Culvert 5648. The total drainage area to the culvert is 19.65 square miles. The segment upstream of the culvert (Figure 2) is a natural channel with steep slopes before emptying into Lake Superior (Figure 3). A map of the drainage area is shown in Figure 4 below.

Figure 2: A view upstream from Culvert 5648

Figure 3: A view downstream from Culvert 5648

Figure 4: A map displaying the drainage area of Culvert 5648.




Note: The Tc path line shown denotes the path used to compute the time of concentration for this facility. Time of concentration is the time needed for water to flow from the most hydrologically remote point of the drainage area to the discharge point of the area.

## Step 2 – Describe the Existing Facility

Culvert 5648 has two cells —each having a 10 foot span (width) by 10 foot rise (height). The longitudinal length of the culvert is approximately 90 feet. Built in 1936, the culvert is at the end of its useful life. A 2013 inspection report describes the presence of cracks and spalling with exposed rebar on the culvert barrel. In addition, the culvert headwall is heavily cracked and the southeast wing wall is detached and lying in the channel bed. The slope of the cells was estimated to be 0.8 percent based on information derived from the as-built plans. Figure 5 shows a plan view of the culvert crossing and its proximity to Lake Superior and Figure 6 and Figure 7 show ground level photos of the culvert.

## Step 3 – Identify Environmental Factors that may Impact Infrastructure Components

Precipitation (and the resulting stream flow) is the primary environmental factor affecting culvert design that is expected to be affected by climate change and is the focus of this study.

## Step 4 – Decide on Climate Scenarios and Determine the Magnitude of Changes

It is generally believed that precipitation intensity levels will go up over time with climate change, since a warmer atmosphere is capable of holding more water vapor. Three future precipitation scenarios were considered for this adaptation assessment based on projected climate changes. The projections of future climate were developed using outputs from global climate models (GCM) that were translated to projections for the nearest weather station to Culvert 5648 using a software tool called SimCLIM. GCMs are computer models of the Earth's climate system calibrated to historic climate conditions. Future climate projections are developed by feeding plausible scenarios of future greenhouse gas emissions into the models and observing the impacts on climate variables like temperature and precipitation.

The three greenhouse gas emissions scenarios used in this study were selected to bound the range of possible future climate conditions. The scenarios pivot off the future emission trajectories, known as representative concentration pathways (RCP), that were used in the United Nations' Intergovernmental Panel on Climate Change's (IPCC) 5th Assessment Report (AR5) on climate science. The specific scenarios included:

- Low emissions scenario: RCP4.5
- Medium emissions scenario: RCP6.0
- High emissions scenario: RCP8.5

An even lower emissions scenario, RCP2.6, was considered for the analysis but the project's Climate Advisory Committee felt this scenario was highly optimistic and therefore unlikely to actually occur. Figure 8 provides a graph showing the assumed radiative forcing levels throughout the remainder of this century under the three RCPs used on this project and RCP2.6. The higher the radiative forcing values, the more warming occurs.

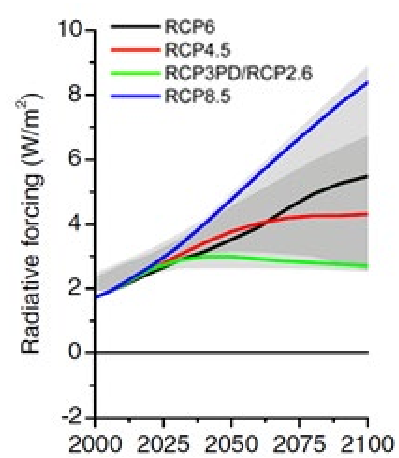
With respect to GCMs, dozens of research institutions have developed their own models, each with a slightly different take on how the Earth's climate system functions. Thus, for any given emissions scenario, each individual climate model will produce a somewhat different precipitation projection. A total of 22 GCMs were queried in this study to provide a broad perspective on the range of possible

Figure 5


Figure 6

Figure 7

Figure 8



future conditions. Using the SimCLIM software tool, the range of GCM outputs for each scenario was developed and the median output from that range used to provide the precipitation values employed in this analysis.

All three scenarios considered 24-hour precipitation depths; the storm duration most relevant to the watershed being studied and one readily generated from climate models. Storm return periods analyzed included the two-, five-, 10-, 25-, 50-, 100-, and 500-year events. Projections were obtained for three time periods through the year 2100, the anticipated end of the facility's design life.

When designing culverts using rainfall runoff models, current practice is to use precipitation frequency statistics developed from historical data by the National Oceanographic and Atmospheric Administration (NOAA) on their Atlas 14 project. It was recognized during the course of this study that, due to differences in statistical techniques, there is a discrepancy in current precipitation depths between NOAA Atlas 14 and values derived from the climate models. To correct for this bias, instead of using the raw precipitation depths directly from the climate models, the percentage change in precipitation levels between the modeled present day conditions and those in the future were recorded and those percentage changes applied to the official NOAA Atlas 14 values.

Table 1 through Table 3 show the projected precipitation levels for the drainage area of Culvert 5648 under the low, medium, and high scenarios. The current NOAA Atlas 14 value is also shown for reference in each case. The NOAA value used was derived from a frequency analysis of the annual maxima series at the centroid of the watershed. The projected data, used to the scale the NOAA values, was obtained for the Two Harbors weather station (located approximately four miles from the culvert). The range of 24-hour precipitation values for each scenario and return period are also shown in the tables along with the percent change between observed and projected precipitation depths.

## Step 5 – Assess Performance of the Existing Facility

Assessing the performance of a culvert first requires detailed hydrologic and hydraulic modeling of the watershed in the vicinity of the facility to understand expected peak flows. These peak flows can then be used to evaluate the culvert's performance relative to its design standards.

### HYDROLOGIC MODELING

Peak flows through the culvert were modeled for various storm events (two-, five-, 10-, 25-, 50-, and 100-year storms) and climate scenarios using the U.S. Department of Agriculture (USDA)-Natural Resources Conservation Service (NRCS) WinTR-20 program. The TR-20 program utilizes NRCS hydrologic analysis methodology to calculate runoff using the following inputs: drainage area, land cover, soils, time of concentration, and precipitation.

Table 1: 24-Hour Precipitation Depths at Culvert 5648, Low Scenario

| 24-Hour Storm Return Period | Atlas 14 Precipitation Depth (in)[1] | Low Scenario Precipitation Depth (in) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 2040 | | 2070 | | 2100 | |
| | | % Increase | Depth | % Increase | Depth | % Increase | Depth |
| 2-year storm | 2.48 | 3.08% | 2.56 | 4.72% | 2.60 | 5.48% | 2.62 |
| 5-year storm | 3.26 | 3.12% | 3.36 | 4.77% | 3.42 | 5.55% | 3.44 |
| 10-year storm | 3.89 | 3.22% | 4.02 | 4.93% | 4.08 | 5.74% | 4.11 |
| 25-year storm | 4.8 | 3.43% | 4.96 | 5.25% | 5.05 | 6.11% | 5.09 |
| 50-year storm | 5.53 | 3.63% | 5.73 | 5.55% | 5.84 | 6.46% | 5.89 |
| 100-year storm | 6.31 | 3.85% | 6.55 | 5.90% | 6.68 | 6.86% | 6.74 |
| 500-year storm | 8.26 | 4.47% | 8.63 | 6.85% | 8.83 | 7.96% | 8.92 |

Table 2: 24-Hour Precipitation Depths at Culvert 5648, Medium Scenario

| 24-Hour Storm Return Period | Atlas 14 Precipitation Depth (in)[1] | Medium Scenario Precipitation Depth (in) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 2040 | | 2070 | | 2100 | |
| | | % Increase | Depth | % Increase | Depth | % Increase | Depth |
| 2-year storm | 2.48 | 4.57% | 2.59 | 7.60% | 2.67 | 10.81% | 2.75 |
| 5-year storm | 3.26 | 4.63% | 3.41 | 7.69% | 3.51 | 10.95% | 3.62 |
| 10-year storm | 3.89 | 4.78% | 4.08 | 7.95% | 4.20 | 11.33% | 4.33 |
| 25-year storm | 4.8 | 5.09% | 5.04 | 8.46% | 5.21 | 12.05% | 5.38 |
| 50-year storm | 5.53 | 5.38% | 5.83 | 8.95% | 6.02 | 12.75% | 6.23 |
| 100-year storm | 6.31 | 5.72% | 6.67 | 9.51% | 6.91 | 13.55% | 7.16 |
| 500-year storm | 8.26 | 6.64% | 8.81 | 11.04% | 9.17 | 15.73% | 9.56 |

Table 3: 24-Hour Precipitation Depths at Culvert 5648, High Scenario

| 24-Hour Storm Return Period | Atlas 14 Precipitation Depth (in)[1] | High Scenario Precipitation Depth (in) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 2040 | | 2070 | | 2100 | |
| | | % Increase | Depth | % Increase | Depth | % Increase | Depth |
| 2-year storm | 2.48 | 8.51% | 2.69 | 17.33% | 2.91 | 25.90% | 3.12 |
| 5-year storm | 3.26 | 8.62% | 3.54 | 17.57% | 3.83 | 26.29% | 4.12 |
| 10-year storm | 3.89 | 8.91% | 4.24 | 18.17% | 4.60 | 27.18% | 4.95 |
| 25-year storm | 4.8 | 9.48% | 5.26 | 19.34% | 5.73 | 28.93% | 6.19 |
| 50-year storm | 5.53 | 10.03% | 6.08 | 20.45% | 6.66 | 30.60% | 7.22 |
| 100-year storm | 6.31 | 10.66% | 6.98 | 21.74% | 7.68 | 32.54% | 8.36 |
| 500-year storm | 8.26 | 12.37% | 9.28 | 25.26% | 10.35 | 37.89% | 11.39 |

Land cover can be expected to change over the period of analysis as land development occurs in the drainage area. Analysis of both existing and future land cover conditions was necessary to evaluate current flows and predicted future flows at Culvert 5648. Existing land cover was obtained from the latest (2011) National Land Cover Dataset (NLCD). Future land cover assumed a build-out of current zoning. This was accomplished by reclassifying the Lake County zoning districts within the drainage area to match the classifications of NLCD 2011 as summarized in Table 4.

Table 4: Translation between Lake County Zoning Districts and NLCD Classifications

| Zoning Code | Zoning Code Meaning | NLCD Class |
|---|---|---|
| R-1 | Residential 10 acre minimum lot, 300' minimum lot width. | Developed, Open Space[1] |
| R-2 | Residential 5 acre minimum lot , 200' minimum lot width. | Developed, Open Space |
| R-3 | Residential 2.5 acre minimum lot, 200' minimum width. | Developed, Open Space |
| R-4 | Residential 2 acre minimum lot size, 200' minimum width. | Developed, Open Space |

[1]Developed, Open Space areas include some structures, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.

When developing the future land cover assumptions, attention was paid to the runoff curve numbers for each land cover type. If the curve number of the existing land cover was higher than that of the potential future land use, a conservative assumption was made to maintain the existing land cover classification. Overall, throughout the drainage area, the existing land cover resulted in a curve number (CN) value of 75, while the future land use had an increase of 2.1 for a final value of 77. The observed precipitation depths were run utilizing existing land use conditions, while the derived precipitation depths were run with the future land cover to determine the corresponding peak flows.

The time of concentration was calculated following the longest flow path from the most distant boundary of the watershed to the point of interest. A time of concentration value of approximately nine hours was used for existing and future condition models.

The hydrologic analysis also considered a range of temporal rainfall distributions for the evaluation of flows at the culvert to determine the appropriate values. The rainfall distribution selected was the NOAA temporal distribution for the 24-hour duration storm corresponding to the study area.

Table 5 shows the model outputs comparing current peak flows to projected future peak flows. In order to validate the model results, a comparison was performed between the existing condition TR-20 model discharges and the regional regression estimates developed by USGS. These regional regression

Table 5: TR-20 Projected Peak Flows at Culvert 5648

| 24-Hour Storm Return Period | Existing Discharges (cfs) | Low Scenario Discharges | | | Medium Scenario Discharges | | | High Scenario Discharges | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 2040 (cfs) | 2070 (cfs) | 2100 (cfs) | 2040 (cfs) | 2070 (cfs) | 2100 (cfs) | 2040 (cfs) | 2070 (cfs) | 2100 (cfs) |
| 2-year storm | 770 | 1070 | 1100 | 1120 | 1090 | 1160 | 1230 | 1180 | 1370 | 1550 |
| 5-year storm | 1350 | 1760 | 1810 | 1830 | 1800 | 1900 | 2000 | 1930 | 2190 | 2460 |
| 10-year storm | 1880 | 2360 | 2420 | 2450 | 2420 | 2540 | 2660 | 2580 | 2920 | 3250 |
| 25-year storm | 2690 | 3260 | 3350 | 3390 | 3340 | 3500 | 3670 | 3550 | 4010 | 4460 |
| 50-year storm | 3370 | 4010 | 4120 | 4170 | 4113 | 4300 | 4500 | 4360 | 4920 | 5480 |
| 100-year storm | 4140 | 4810 | 4940 | 5000 | 4930 | 5170 | 5420 | 5240 | 5940 | 6610 |
| 500-year storm | 6090 | 6870 | 7060 | 7150 | 7040 | 7410 | 7800 | 7520 | 8590 | 9630 |

curves are applicable to non-urban areas statewide with drainage areas between one and 43 square miles. Since the regression equations are empirically derived and regionally specific, they provide a reasonable basis for calibration of the theoretical model.

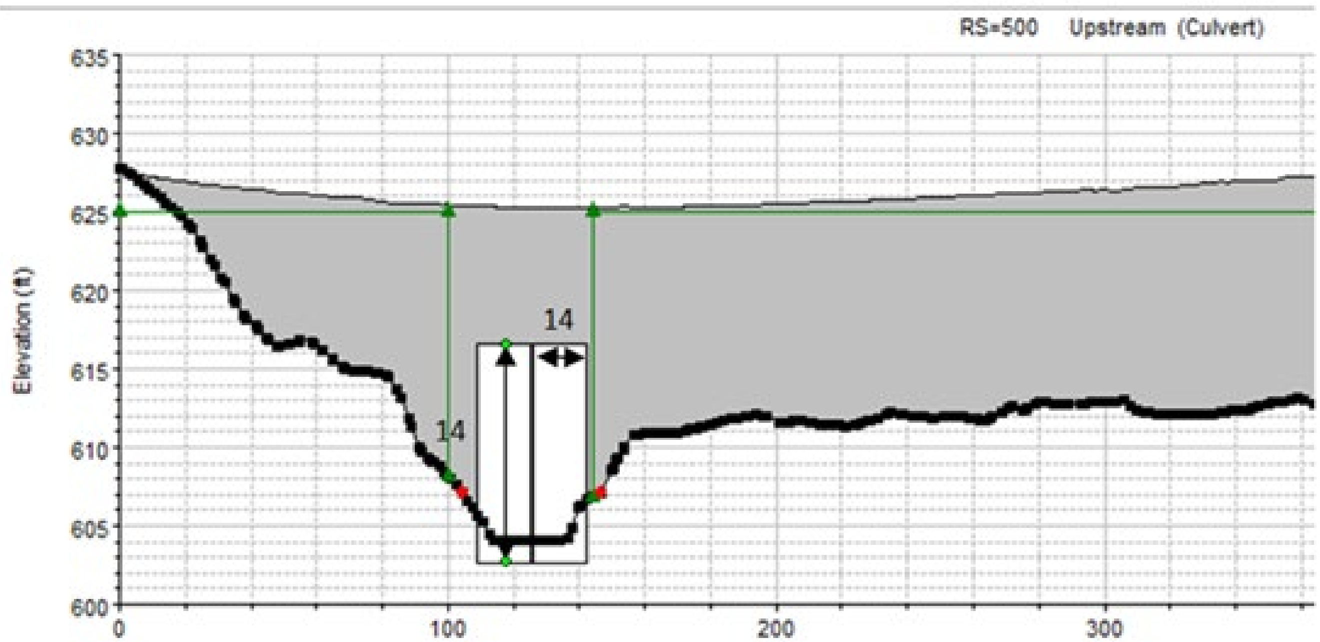
## HYDRAULIC MODELING AND PERFORMANCE OF THE EXISTING CULVERT

Hydraulic culvert analyses were conducted to evaluate the performance of Culvert 5648 under current and future peak flows using a HEC-RAS model developed using elevations derived from LIDAR data. Since the hydraulic performance of a culvert depends on its design, an assumption had to be made regarding the likely design of the planned replacement culvert to be built in 2018. When conducting an analysis of a new facility or a facility planned for replacement, the base case design for the analysis should be whatever design would most likely be implemented if climate change were not being considered and only historical data were to be used for engineering the facility.

If the existing facility meets current design criteria, the base case can be to simply replace the existing facility in kind. Current MnDOT design criteria state that, for a large culvert over a non-navigable waterway, a three feet minimum clearance (freeboard) between the 50-year flood stage and the low point on the large culvert is desirable in many cases. The actual clearance requirements, however, are determined on a case by case basis. Additional criteria state that the allowable headwater must be non-damaging to upstream property, be non-damaging to the roadway, meet stage increase criteria set forth by regulatory agencies, and should not cause disruption to traffic flow. In addition, if velocity is six feet per second or greater at the outlet a check should be made that scour will not occur. If scour may occur, outlet protection should be provided. For culverts located on public waters where fish passage has been identified as an issue, the culvert velocity should be consistent with the natural channel velocity at the two year event or be two feet per second or less.

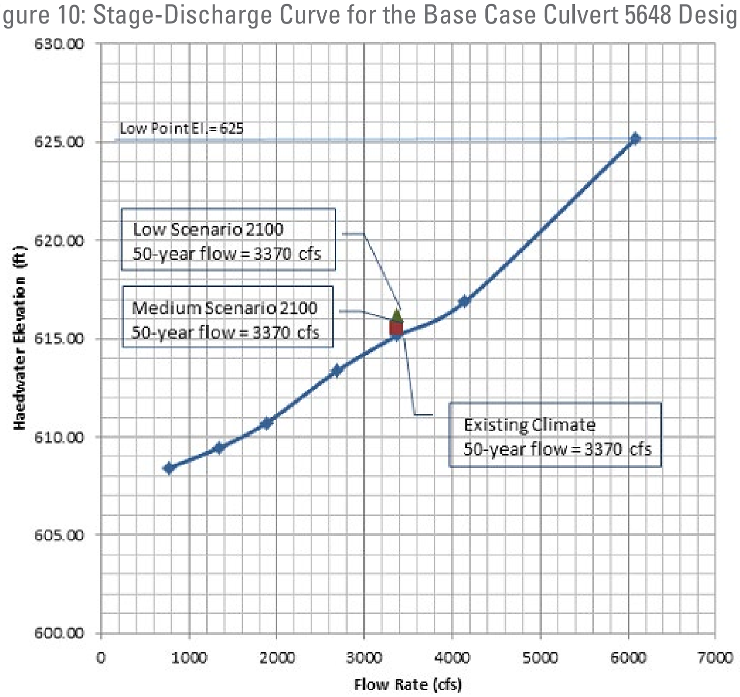
Culvert 5648 meets the MnDOT allowable headwater depth design criteria for passing the 50-year storm without overtopping, however, the existing culvert design does not comply with current fish passage requirements. In addition, velocities at the culvert exit are much higher than the velocities in the natural channel creating a scour pool at the culvert exit. Due to these deficiencies, it was decided that the existing culvert would most likely not be replaced-in-kind even if climate change were not considered. Thus, a base case culvert design was developed that addresses the velocity issues and fish passage requirements.

Figure 9: Upstream Cross-Section of the Base Case Design for Culvert 5648




The base case design, a cross-section of which is shown in Figure 9, involves replacement of the existing culvert structure with a two-cell culvert having a 14 foot span (width) by 14 foot rise (height). The estimated cost for this design is $710,000. Both culvert cells were designed to be sunk two feet into the stream bed to comply with the fish passage provision. The amount that a culvert is buried will vary at each site. In areas without fish passage issues, culverts are not buried while in areas where fish passage is important culverts are buried one foot or more.

Figure 10: Stage-Discharge Curve for the Base Case Culvert 5648 Design




Note: Headwater elevation is the level of water immediately upstream of the inlet (upstream end) of a culvert or any other conduit.

Figure 10 provides a stage-discharge curve (a graphic representation of headwater elevations at different flow levels) for the base case design. The curve shows that that MnDOT 50-year storm allowable headwater depth design criterion for culverts is readily met under current climate. The curve also illustrates that the three foot freeboard requirement is met by the base case design for both the low and medium climate scenarios. However, some of the additional design criteria such as velocities and prevention of damage to the roadway are not met under these climate scenarios so a series of adaptation options were developed that were capable of handling projected flows.

## Step 6 – Develop Adaptive Design Options

Since the existing structure does not meet the design criteria under all climate scenarios, adaptation alternatives were developed. Adaptation options were developed taking into consideration the different climate scenarios discussed in Step 5. The designs were based on year 2100 peak flow projections so that the facility would uphold design criteria throughout its assumed 75 to 100 year lifespan.

### OPTION ONE

Option One is optimized to meet design criteria for the low climate scenario in 2100. It involves replacement of the existing culvert with a two-cell 16 foot span (width) by 14 foot rise (height) culvert. This assumes the culvert will be sunk into the stream bed two feet; thus, the water opening height will be 12 feet. Figure 11 provides a cross-section of the Option 1 design.

The work as estimated includes:

Figure 11: Upstream Cross-Section of Design Option 1 for Culvert 5648

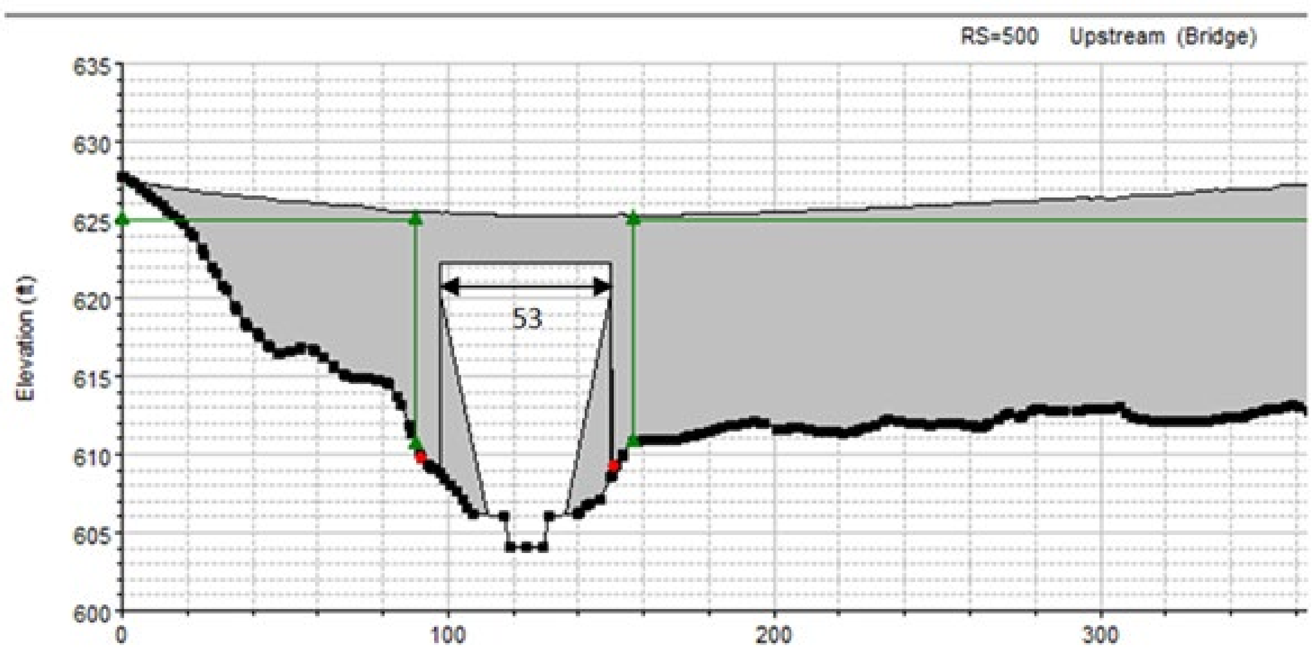
- Traffic control
- Riprap for the outfall scour pool
- Erosion control and stream diversion
- Guardrail
- Demolition , excavation, and structural backfill
- New culvert cells and culvert end section
- Pavement restoration

The estimated project cost is $770,000.

## OPTION TWO

Option Two is optimized to meet design criteria for the medium climate scenario in 2100. Although a larger culvert design would likely be feasible, after discussions with District 1 staff, it was revealed that there is pressure to convert culverts along MN 61 to bridges to further improve fish passage beyond what a culvert can provide. Thus, this option includes the replacement of the existing culvert with a 52 foot simple span bridge. The bridge would have abutments with a one percent slope on both sides. For the bridge model, the roadway alignment was assumed to remain the same as the current culvert. Due to the length of the bridge span, the deck depth is three feet. The design follows MnDOT bridge design criteria for crossings of non-navigable waterways. Figure 12 provides a cross-section of the Option 2 design.

Figure 12: Upstream Cross-Section of Design Option 2 for Culvert 5648



The work as estimated includes:

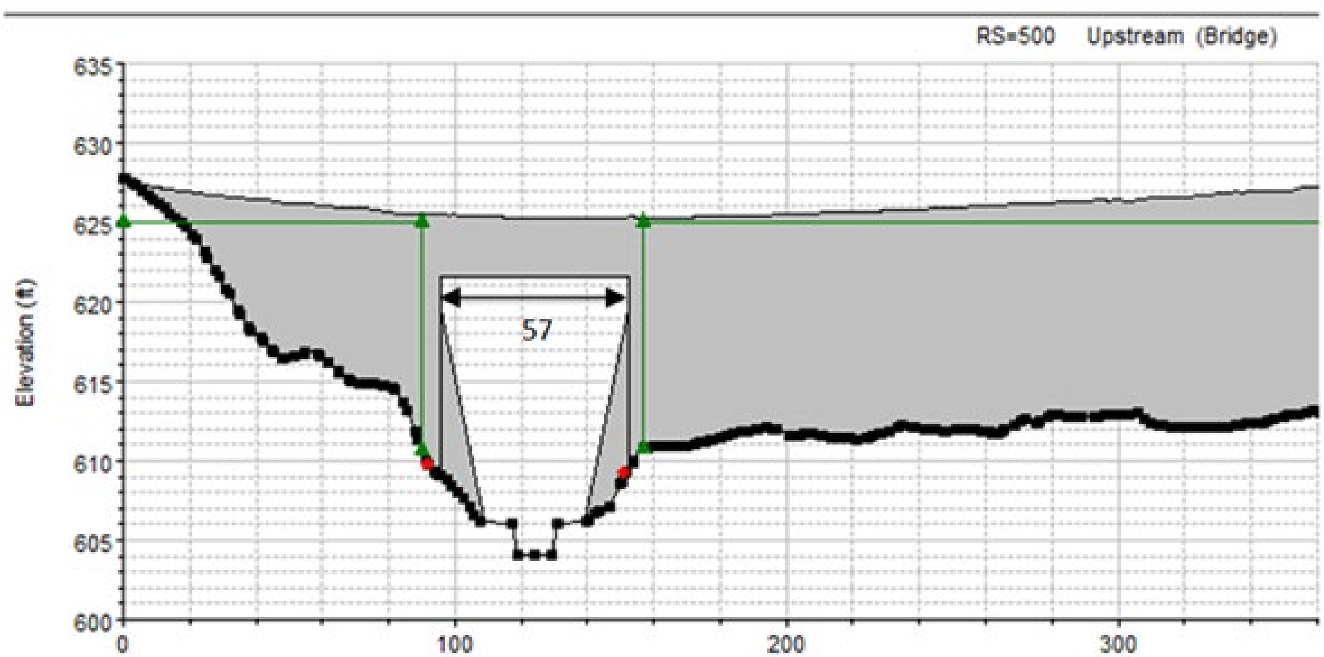
- Traffic control
- Riprap for abutment protection
- Erosion control and stream diversion
- Demolition , excavation, and structural backfill
- Guardrail
- New 52 foot simple span bridge

The estimated project cost is $1,130,000.

## OPTION THREE

Option Three is optimized for the high climate scenario in 2100. In keeping with the emerging practice of replacing culverts with bridges to satisfy fish passage requirements, it includes the replacement of the existing culvert with a 57 foot simple span bridge. Similar to Option Two, the bridge would have abutments with a one percent slope on both sides and the roadway alignment is assumed to be the same as the existing facility. Due to the length of the bridge span, the deck depth is 3.4 feet. Figure 13 provides a cross-section of the Option 3 design.

Figure 13: Upstream Cross-Section of Design Option 3 for Culvert 5648



The work as estimated includes:

- Traffic control
- Riprap for abutment protection
- Erosion control and stream diversion
- Demolition , excavation, and structural backfill
- Guardrail
- New 57 foot simple span bridge

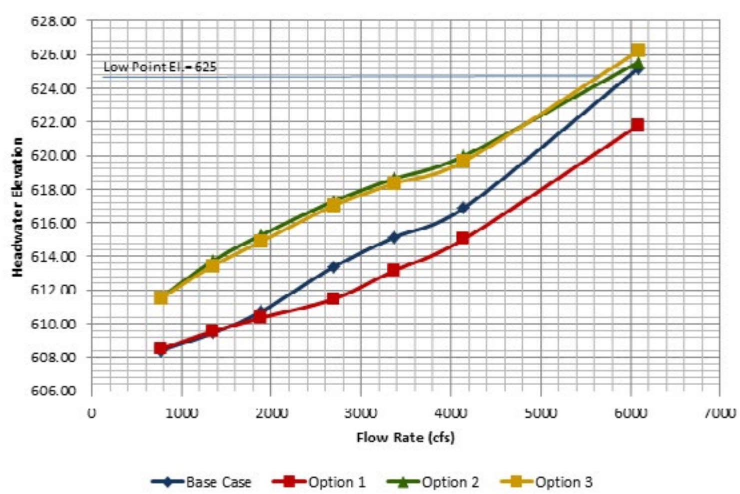
The estimated project cost is $1,210,000.

## Step 7 – Assess Performance of the Adaptive Design Options

The degree of flooding was analyzed for each adaptive design option using the 50-year storm event under each climate scenario. The degree of flooding is an important input for the benefit-cost analysis that allows impacts to be quantified across the scenarios and adaptation options.

Figure 14 shows the stage-discharge curves for the different adaptation options along with the base case curve. These curves illustrate the performance of each option under the range of flows that could be experienced with the climate change scenarios studied. Each of the adaptation options prevents overtopping of the roadway at the 50-year flow rate under the climate scenarios they were designed to accommodate. The three foot freeboard requirement is also met in each instance with the exception of Option 3 which passes the 50-year storm with only about one foot of freeboard.

Figure 14: Stage-Discharge Curves for Culvert 5648 Adaptation Options



## Step 8 – Conduct an Economic Analysis

An economic analysis was performed to determine which adaptation option, if any, would be most cost-effective under the range of possible climate scenarios evaluated. The analysis was undertaken using a software tool called COAST. COAST was initially developed with funding from the U.S. Environmental Protection Agency at the University of Southern Maine, for the purposes of furthering the development of benefit-cost analysis of climate adaptation actions, based on user-specified scenarios of climate change.

The COAST software is designed to calculate expected cumulative damages to transportation facilities over time, using curves relating water depths to their probabilities and water depths to damage costs incurred (depth-damage functions). Water levels at the facility are assessed using the heights and probabilities (return periods) provided in the depth-probability tables shown in Figure 12. Every time the facility is flooded, damage is calculated according to the depth-damage function and summed for all such events over time. Each design option has its own depth-damage function.

Damage costs accounted for the depth-damage functions include:

- Physical damage repair costs: Estimates of the cost to repair each adaptation option given various levels of damage. These costs include the costs for parts and labor along with contingency and mobilization factors.
- Incremental travel time costs to motorists from the detour: Time is valuable and there is a cost imposed on motorists when a trip takes longer because of the need to detour a damaged facility. An estimate of the costs of lost time for detouring Culvert 5648 was developed by considering the additional 42 minutes of travel time required to take the detour route (shown in Figure 15) then comparing this with traffic volumes and MnDOT recommended travel time values for motorists and freight. In addition, there is also an increase in vehicle operating costs (fuel, wear and tear, etc.) due to the 24 additional miles required to detour the facility. This cost was computed using MnDOT recommended operating costs and added to the travel time costs to arrive at a total estimated detour cost of approximately $140,000 per day. The length of time the detour is likely to be in place for various levels of damage was also accounted for and used to multiply the daily detour cost to arrive at a total detour cost per flooding incident. The maximum number of days a detour would be required was assumed to be 15 days for each option.
- The potential for injury to motorists: When a culvert fails, there is a possibility for accidents and associated injuries. An estimated cost of injury of $80,000 per flood event was included to reflect this possibility. The value chosen was approximately the same as the MnDOT recommended costs for a crash with moderate injuries (Type C). This value was selected to balance the likelihood that no accident will occur with the unlikely (but still possible) chance of an accident with fatalities.

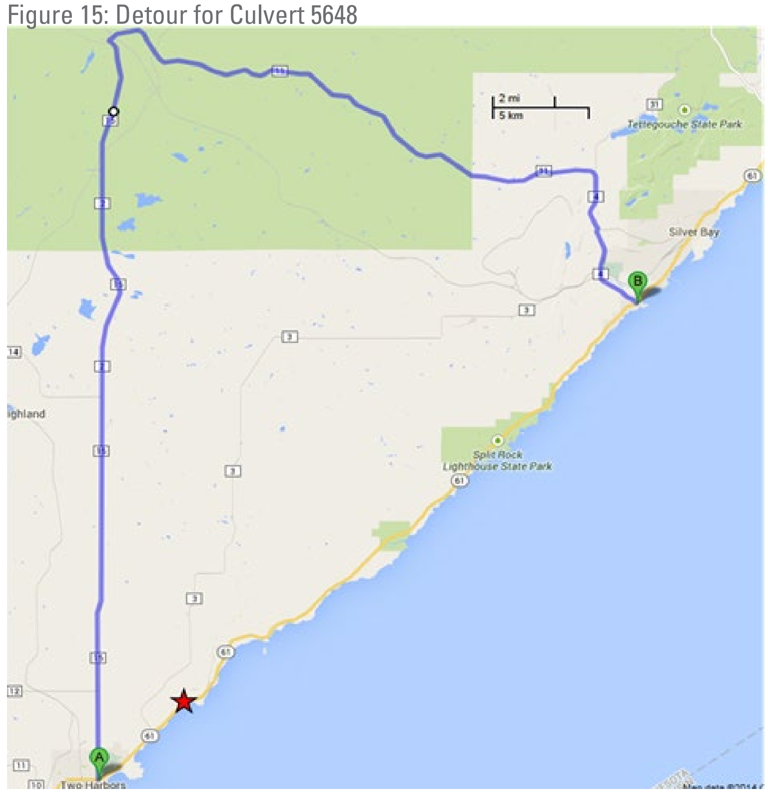
Detour Cost Assumptions

| Parameters | Silver Creek |
|---|---|
| Increase in Length | 24 miles |
| Increase in Travel Time | 0.7 hours |
| AADT | 5,900 vehicles / day |
| Passenger Cars | 5,400 cars / day |
| Trucks | 500 trucks / day |
| VOT | 1.3 MnDOT |
| Person Trips | 7,020 |
| Truck Trips | 500 |
| Value of Passenger Travel Time | $16 / hour |
| Value of Truck Travel Time | $27.3 / hour |
| Car Operating Cost | $0.31 / mile |
| Truck Operating Cost | $0.96 / mile |

Detour Cost Per Day

| | Truck | Car | Total |
|---|---|---|---|
| Operating Costs | $11,520 | $40,176 | $51,696 |
| Time Costs | $9,555 | $78,624 | $88,179 |
| Total | $21,075 | $118,800 | $139,875 |

Figure 15: Detour for Culvert 5648




Source of background image: Google Maps

A discount rate of 2 percent was applied to future damage costs and expenditures per MnDOT recommendations. The analyses began in 2020, the assumed year that construction would be completed, and were run through 2100 (the assumed end of the facility's design life).

For the purposes of this analysis, two sets of depth-damage functions were run for each adaptation option. One set, shown in Figure 16, includes the physical repair costs required to fix the facility along with the social costs for detours and injuries. A second set, shown in Figure 17, considered just the physical repair costs. This second assessment was undertaken to evaluate if the conclusions from the economic analysis would be different if MnDOT considered only direct agency costs.

The consultant team performed a total of 72 model runs (36 with social costs included and 36 without) for Silver Creek. These model runs calculated the differences in expected life cycle repair expenses between the design options given projections of rainfall patterns and flood levels over time. The construction costs of each option were then added in to provide a complete picture of expected outlays likely to be accumulated under each design.

Results of the analysis comparing the expected total life cycle costs (including construction) can be found in Table 6 through Table 11. Figure 18 and Figure 19 display this information graphically.

Figure 16: Depth-Damage Functions for the Culvert 5648 Design Options With Social Costs

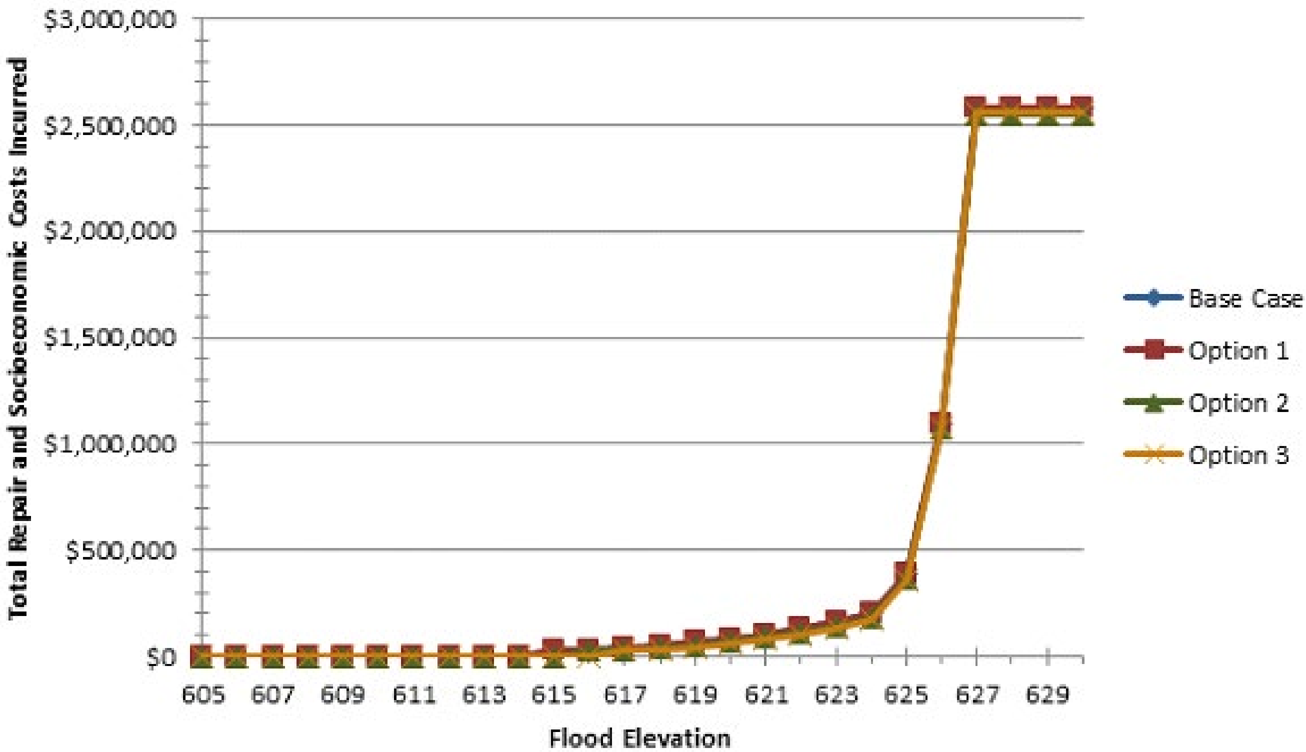



Figure 17: Depth-Damage Functions for the Culvert 5648 Design Options Without Social Costs

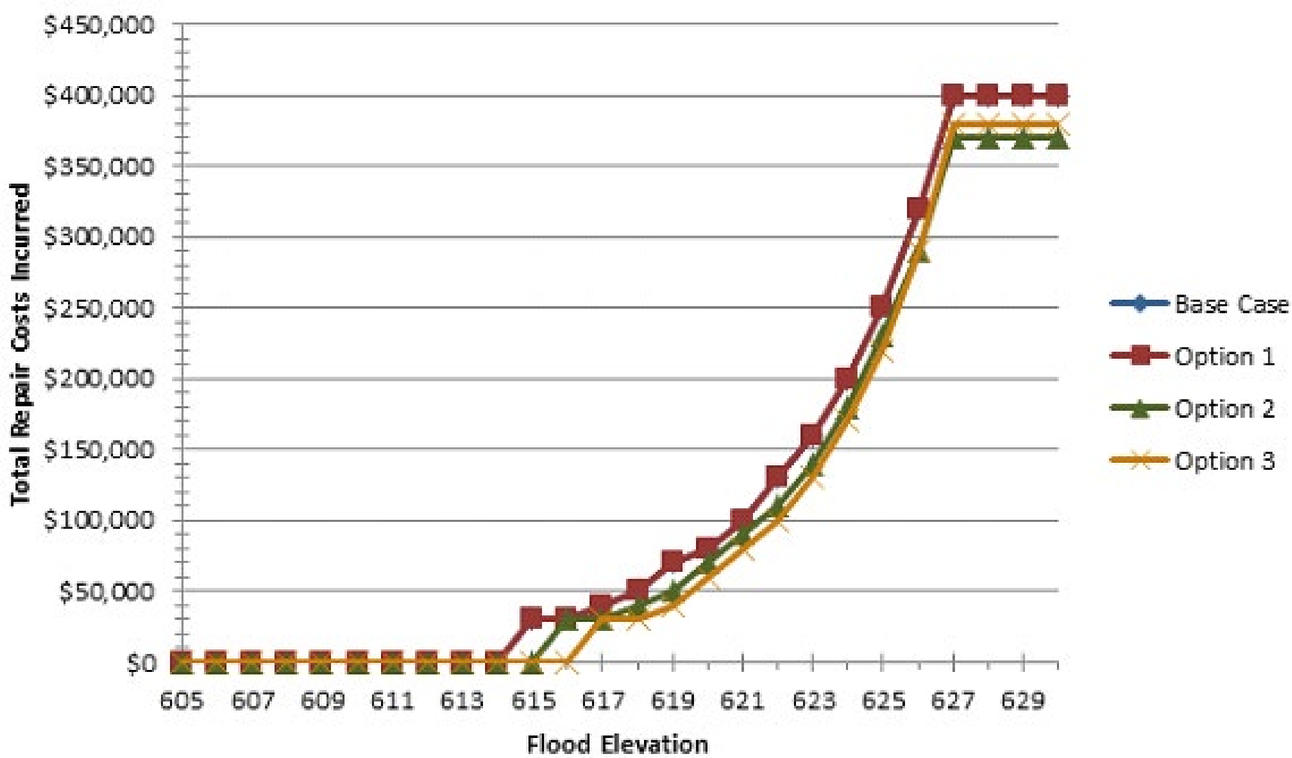


Table 6: Projected Life Cycle Costs for Culvert 5648 Adaptation Option WITHOUT Social Costs, Low Scenario

| | Period 1 2025-2055 | Period 2 2056-2085 | Period 3 2086-2100 | Initial Construction Costs | Total Damage/Repair Costs by 2100 | Total Life Cycle Cost by 2100 |
|---|---|---|---|---|---|---|
| Base Case: Replace in Kind | 48,250 | 21,678 | 6,866 | $643,069 | $76,794 | $719,863 |
| Option 1: Two Cell Culvert | 18,238 | 7,856 | 2,488 | $697,413 | $28,582 | $725,995 |
| Option 2: 52-Foot Bridge | 69,034 | 31,226 | 9,890 | $1,023,476 | $110,150 | $1,133,626 |
| Option 3: 57-Foot Bridge | 25,848 | 11,134 | 3,526 | $1,095,934 | $40,508 | $1,136,442 |

Table 7: Projected Life Cycle Costs for Culvert 5648 Adaptation Options WITHOUT Social Costs, Medium Scenario

| | Period 1 2025-2055 | Period 2 2056-2085 | Period 3 2086-2100 | Initial Construction Costs | Total Damage/Repair Costs by 2100 | Total Life Cycle Cost by 2100 |
|---|---|---|---|---|---|---|
| Base Case: Replace in Kind | 50,328 | 24,861 | 12,693 | $643,069 | $87,882 | $730,951 |
| Option 1: Two Cell Culvert | 18,238 | 9,049 | 4,882 | $697,413 | $32,169 | $729,582 |
| Option 2: 52-Foot Bridge | 72,494 | 55,098 | 20,600 | $1,023,476 | $148,192 | $1,171,668 |
| Option 3: 57-Foot Bridge | 25,848 | 11,134 | 3,811 | $1,095,934 | $40,793 | $1,136,727 |

Table 8: Projected Life Cycle Costs for Culvert 5648 Adaptation Options WITHOUT Social Costs, High Scenario

| | Period 1 2025-2055 | Period 2 2056-2085 | Period 3 2086-2100 | Initial Construction Costs | Total Damage/Repair Costs by 2100 | Total Life Cycle Cost by 2100 |
|---|---|---|---|---|---|---|
| Base Case: Replace in Kind | 89,574 | 46,937 | 19,528 | $643,069 | $156,039 | $799,108 |
| Option 1: Two Cell Culvert | 21,008 | 24,861 | 9,292 | $697,413 | $55,161 | $752,574 |
| Option 2: 52-Foot Bridge | 58,645 | 26,751 | 26,740 | $1,023,476 | $112,136 | $1,135,612 |
| Option 3: 57-Foot Bridge | 27,932 | 23,958 | 12,156 | $1,095,934 | $64,046 | $1,159,980 |

Table 9: Projected Life Cycle Costs for Culvert 5648 Adaptation Options WITH Social Costs, Low Scenario

| | Period 1 2025-2055 | Period 2 2056-2085 | Period 3 2086-2100 | Initial Construction Costs | Total Damage/Repair Costs by 2100 | Total Life Cycle Cost by 2100 |
|---|---|---|---|---|---|---|
| Base Case: Replace in Kind | 120,262 | 52,703 | 16,693 | $643,069 | $189,658 | $832,727 |
| Option 1: Two Cell Culvert | 18,226 | 7,851 | 2,487 | $697,413 | $28,564 | $725,977 |
| Option 2: 52-Foot Bridge | 69,148 | 31,269 | 9,904 | $1,023,476 | $110,321 | $1,133,797 |
| Option 3: 57-Foot Bridge | 25,839 | 11,130 | 3,525 | $1,095,934 | $40,494 | $1,136,428 |

Table 10: Projected Life Cycle Costs for Culvert 5648 Adaptation Options WITH Social Costs, Medium Scenario

| | Period 1 2025-2055 | Period 2 2056-2085 | Period 3 2086-2100 | Initial Construction Costs | Total Damage/Repair Costs by 2100 | Total Life Cycle Cost by 2100 |
|---|---|---|---|---|---|---|
| Base Case: Replace in Kind | 120,262 | 52,703 | 16,693 | $643,069 | $189,658 | $832,727 |
| Option 1: Two Cell Culvert | 18,226 | 7,851 | 2,487 | $697,413 | $28,564 | $725,977 |
| Option 2: 52-Foot Bridge | 69,148 | 31,269 | 9,904 | $1,023,476 | $110,321 | $1,133,797 |
| Option 3: 57-Foot Bridge | 25,839 | 11,130 | 3,525 | $1,095,934 | $40,494 | $1,136,428 |

Table 11: Projected Life Cycle Costs for Culvert 5648 Adaptation Options WITH Social Costs, High Scenario

| | Period 1 2025-2055 | Period 2 2056-2085 | Period 3 2086-2100 | Initial Construction Costs | Total Damage/Repair Costs by 2100 | Total Life Cycle Cost by 2100 |
|---|---|---|---|---|---|---|
| Base Case: Replace in Kind | 290,776 | 125,251 | 46,990 | $643,069 | $463,017 | $1,106,086 |
| Option 1: Two Cell Culvert | 20,990 | 111,568 | 36,756 | $697,413 | $169,314 | $866,727 |
| Option 2: 52-Foot Bridge | 58,740 | 26,785 | 41,520 | $1,023,476 | $127,045 | $1,150,521 |
| Option 3: 57-Foot Bridge | 27,913 | 23,937 | 39,611 | $1,095,934 | $91,461 | $1,187,395 |

Note: Options with the best life cycle cost-effectiveness are highlighted in green.

Figure 18: Cost Effectiveness of Culvert 5648 Adaptation Options Without Social Costs

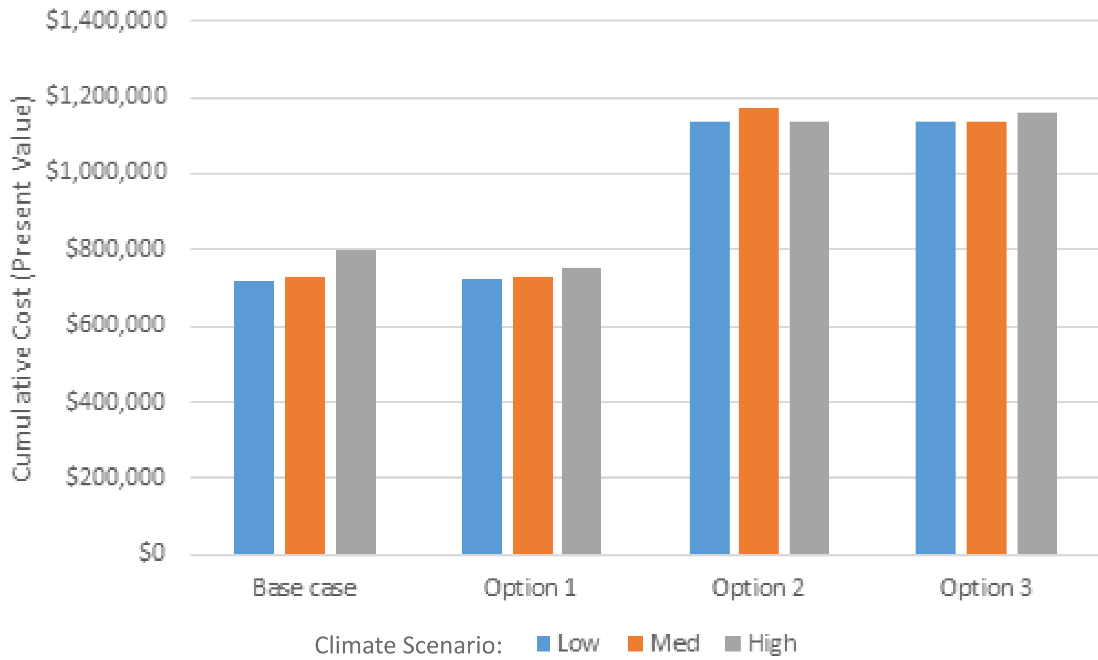
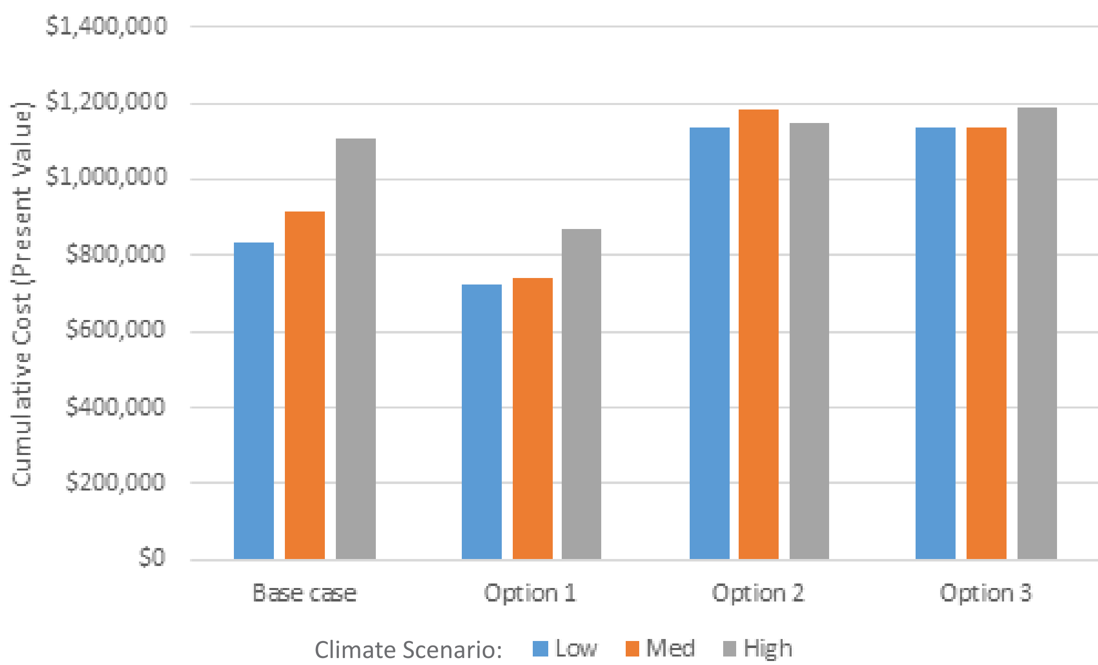



Figure 19: Cost Effectiveness of Culvert 5648 Adaptation Options With Social Costs



Key findings of the analysis include:

- If social costs of detours and injuries are included, Option 1, the expanded two cell culvert, is the most cost effective design in all rainfall increase scenarios (low, medium, and high).
- If the social costs of detours and injuries are not included, replacement-in-kind of the exiting culvert (with modifications for fish passage) is the lowest cost option if the low rainfall scenario were to occur. If the medium and higher scenarios of rainfall increase were to occur, Option 1 is the most cost effective option.

Thus, different conclusions are arrived at depending whether one considers social costs. It is recommend that social costs be included in the analysis which points to Option 1 being the preferred option under the range of climate scenarios tested. That said, although the economic analysis can point the way to the most cost-effective option, decision-makers should consider other social or political criteria not included in the modeling before deciding on a course of action. These considerations are offered in the next step.

## Step 9 – Evaluate Additional Decision-making Considerations

Potential additional decision-making considerations that are of concern for the Silver Creek site would include fish passage design requirements, maintenance of traffic, and on-going maintenance needs of the selected alternative. The pilot study project did not fully delve into all of these issues but specific points of consideration could include whether a culvert option can provide both a sustainable platform for channel bed sediments and meet the low flow velocity and depth requirements for fish passage. Finally, from a long-term maintenance standpoint, the selection of a bridge option is going to encumber the district with an additional structure in need of regular inspections, while a culvert option will have its own maintenance needs that may be more or less of a concern.

Each of these factors, along with other possible factors related to sustainability, permitting, project feasibility and practicality, ongoing maintenance needs, capital funds availability, and project risk should be considered along with the cost-effectiveness results, to select a design the provides the greatest value to MnDOT and the community.

## Step 10 – Select a Course of Action

Based upon the results of Step 8, Option 1 would be recommended for the site. However, there are known additional decision-making considerations for this site that include fish passage requirements. The pilot study was not developed to enough detail to determine the applicability of the culvert structure to the local fish passage requirements, thus a specific recommendation could not be made. Meeting of these additional requirements will directly impact the Department's ability to permit and construct an individual option and may supersede the recommendations of this analysis.

## Step 11 – Plan and Conduct Ongoing Activities

After construction, facility performance should be monitored and recorded in an asset management database. Specific items that should be recorded include frequency of overtopping, duration of closures, whether injuries resulted from the overtopping, and any damage costs. Instances where an adaptive design prevented the incurrence of costs relative to a traditional design should also be noted and a tally maintained of costs avoided; eventually this can be used to determine whether the additional costs incurred for the adaptation were justified. All of this information will aid in future decision-making for this and other assets.

# APPENDIX A | SILVER CREEK COST ESTIMATES

## EXISTING CONDITION | WORST CASE REPAIR COST

| | QTY | Unit | Unit Price | Total |
|---|---|---|---|---|
| Traffic Control | 1 | LS | $7,000 | $7,000 |
| Erosion Control | 1 | LS | $12,000 | $12,000 |
| Rip Rap (Outfall Scour Pool) | 400 | CY | $120 | $48,000 |
| Guard Rail | 120 | LF | $60 | $7,200 |
| Stream Diversion | 1 | LS | $12,000 | $12,000 |
| Storm Clean-up | 1 | LS | $30,000 | $30,000 |
| Excavation | 240 | CY | $30 | $7,200 |
| Structural Backfill | 1200 | CY | $50 | $60,000 |
| Re-Set Culvert 2-cell (14'x14' ea) | 1 | LS | $50,000 | $50,000 |
| Culvert end section | 2 | EA | $10,000 | $20,000 |
| Pavement Restoration | 105 | Tons | $120 | $12,600 |
| Mobilization | 1 | LS | 20% | $53,200 |
| Contingency | 1 | LS | 25% | $79,800 |
| Total | | | | $400,000 |

## OPTION #1 | CONSTRUCTION COST

| | QTY | Unit | Unit Price | Total |
|---|---|---|---|---|
| Traffic Control | 1 | LS | $10,000 | $10,000 |
| Erosion Control | 1 | LS | $25,000 | $25,000 |
| Rip Rap (Outfall Scour Pool) | 400 | CY | $120 | $48,000 |
| Guard Rail | 120 | LF | $60 | $7,200 |
| Stream Diversion | 1 | LS | $25,000 | $25,000 |
| Demolition | 1 | LS | $50,000 | $50,000 |
| Excavation | 1245 | CY | $30 | $37,350 |
| Structural Backfill | 1245 | CY | $50 | $62,250 |
| Culvert 2-cell (16'x14' ea) | 180 | LF | $1,200 | $216,000 |
| Culvert end section | 4 | EA | $10,000 | $40,000 |
| Pavement Restoration | 115 | Tons | $100 | $11,500 |
| Mobilization | 1 | LS | 15% | $79,845 |
| Contingency | 1 | LS | 25% | $153,036 |
| Total | | | | $770,000 |

## OPTION #1 | WORST CASE REPAIR COST

| | QTY | Unit | Unit Price | Total |
|---|---|---|---|---|
| Traffic Control | 1 | LS | $7,000 | $7,000 |
| Erosion Control | 1 | LS | $12,000 | $12,000 |
| Rip Rap (Outfall Scour Pool) | 400 | CY | $120 | $48,000 |
| Guard Rail | 120 | LF | $60 | $7,200 |
| Stream Diversion | 1 | LS | $12,000 | $12,000 |
| Storm Clean-up | 1 | LS | $30,000 | $30,000 |
| Excavation | 249 | CY | $30 | $7,470 |
| Structural Backfill | 1200 | CY | $50 | $60,000 |
| Re-Set Culvert 2-cell (16'x14' ea) | 1 | LS | $50,000 | $50,000 |
| Culvert end section | 2 | EA | $10,000 | $20,000 |
| Pavement Restoration | 105 | Tons | $120 | $12,600 |
| Mobilization | 1 | LS | 20% | $53,254 |
| Contingency | 1 | LS | 25% | $79,881 |
| Total | | | | $400,000 |

## OPTION #1 | DEPTH DAMAGE FUNCTION

| Flood Elevation (Feet) | Physical Damage & Repair Cost | Socioeconomic Costs | | | Property | Total Cost | % Damage | Notes |
|---|---|---|---|---|---|---|---|---|
| | | Detour | | Injury | | | | |
| | | Days in Effect | Cost | | | | | |
| 605 | $0 | 0 | $0 | 0 | $0 | $0 | 0% | |
| 614 | $0 | 0 | $0 | $0 | $0 | $0 | 0% | |
| 615 | $30,000 | 0 | $0 | $0 | $0 | $30,000 | 8% | Embankment erosion starts |
| 616 | $30,000 | 0 | $0 | $0 | $0 | $30,000 | 8% | |
| 617 | $40,000 | 0 | $0 | $0 | $0 | $40,000 | 10% | |
| 618 | $50,000 | 0 | $0 | $0 | $0 | $50,000 | 13% | |
| 619 | $70,000 | 0 | $0 | $0 | $0 | $70,000 | 18% | |
| 620 | $80,000 | 0 | $0 | $0 | $0 | $80,000 | 20% | |
| 621 | $100,000 | 0 | $0 | $0 | $0 | $100,000 | 25% | |
| 622 | $130,000 | 0 | $0 | $0 | $0 | $130,000 | 33% | |
| 623 | $160,000 | 0 | $0 | $0 | $0 | $160,000 | 40% | |
| 624 | $200,000 | 0 | $0 | $0 | $0 | $200,000 | 50% | |
| 625 | $250,000 | 1 | $140,000 | $0 | $0 | $390,000 | 98% | Overtopping |
| 626 | $320,000 | 5 | $700,000 | $80,000 | $0 | $1,100,000 | 275% | |
| 627 | $400,000 | 15 | $2,100,000 | $80,000 | $0 | $2,580,000 | 645% | |

## OPTION #2 | CONSTRUCTION COST

| | QTY | Unit | Unit Price | Total |
|---|---|---|---|---|
| Traffic Control | 1 | LS | $25,000 | $25,000 |
| Erosion Control | 1 | LS | $30,000 | $30,000 |
| Rip Rap (Abutment Protection) | 450 | CY | $120 | $54,000 |
| Guard Rail | 120 | LF | $60 | $7,200 |
| Stream Diversion | 1 | LS | $30,000 | $30,000 |
| Demolition | 1 | LS | $50,000 | $50,000 |
| Excavation | 1390 | CY | $30 | $41,700 |
| Structural Backfill | 1390 | CY | $50 | $69,500 |
| 52 ft Simple Span Bridge | 2600 | SF | $180 | $468,000 |
| Pavement Restoration | 140 | Tons | $100 | $14,000 |
| Mobilization | 1 | LS | 15% | $118,410 |
| Contingency | 1 | LS | 25% | $226,953 |
| Total | | | | $1,130,000 |

## OPTION #2 | WORST CASE REPAIR COST

| | QTY | Unit | Unit Price | Total |
|---|---|---|---|---|
| Traffic Control | 1 | LS | $12,000 | $12,000 |
| Erosion Control | 1 | LS | $15,000 | $15,000 |
| Rip Rap (Abutment Protection) | 450 | CY | $120 | $54,000 |
| Guard Rail | 120 | LF | $60 | $7,200 |
| Stream Diversion | 1 | LS | $15,000 | $15,000 |
| Storm Clean-up | 1 | LS | $50,000 | $50,000 |
| Excavation | 278 | CY | $30 | $8,340 |
| Structural Backfill | 1390 | CY | $50 | $69,500 |
| 52 ft Simple Span Bridge | 0 | SF | $180 | $0 |
| Pavement Restoration | 140 | Tons | $100 | $14,000 |
| Mobilization | 1 | LS | 20% | $49,008 |
| Contingency | 1 | LS | 25% | $73,512 |
| Total | | | | $370,000 |

## OPTION #2 | DEPTH DAMAGE FUNCTION

| Flood Elevation (Feet) | Physical Damage & Repair Cost | Socioeconomic Costs | | | Property | Total Cost | % Damage | Notes |
|---|---|---|---|---|---|---|---|---|
| | | Detour | | Injury | | | | |
| | | Days in Effect | Cost | | | | | |
| 605 | $0 | 0 | $0 | 0 | $0 | $0 | 0% | |
| 614 | $0 | 0 | $0 | $0 | $0 | $0 | 0% | |
| 615 | $0 | 0 | $0 | $0 | $0 | $0 | 0% | |
| 616 | $30,000 | 0 | $0 | $0 | $0 | $30,000 | 8% | Embankment erosion starts |
| 617 | $30,000 | 0 | $0 | $0 | $0 | $30,000 | 8% | |
| 618 | $40,000 | 0 | $0 | $0 | $0 | $40,000 | 11% | |
| 619 | $50,000 | 0 | $0 | $0 | $0 | $50,000 | 14% | |
| 620 | $70,000 | 0 | $0 | $0 | $0 | $70,000 | 19% | |
| 621 | $90,000 | 0 | $0 | $0 | $0 | $90,000 | 24% | |
| 622 | $110,000 | 0 | $0 | $0 | $0 | $110,000 | 30% | |
| 623 | $140,000 | 0 | $0 | $0 | $0 | $140,000 | 38% | |
| 624 | $180,000 | 0 | $0 | $0 | $0 | $180,000 | 49% | |
| 625 | $230,000 | 1 | $140,000 | $0 | $0 | $370,000 | 100% | Overtopping starts |
| 626 | $290,000 | 5 | $700,000 | $80,000 | $0 | $1,070,000 | 289% | |
| 627 | $370,000 | 15 | $2,100,000 | $80,000 | $0 | $2,550,000 | 689% | |

## OPTION #3 | CONSTRUCTION COST

| | QTY | Unit | Unit Price | Total |
|---|---|---|---|---|
| Traffic Control | 1 | LS | $25,000 | $25,000 |
| Erosion Control | 1 | LS | $30,000 | $30,000 |
| Rip Rap (Abutment Protection) | 450 | CY | $120 | $54,000 |
| Guard Rail | 120 | LF | $60 | $7,200 |
| Stream Diversion | 1 | LS | $30,000 | $30,000 |
| Demolition | 1 | LS | $50,000 | $50,000 |
| Excavation | 1440 | CY | $30 | $43,200 |
| Structural Backfill | 1440 | CY | $50 | $72,000 |
| 57 ft Simple Span Bridge | 2850 | SF | $180 | $513,000 |
| Pavement Restoration | 150 | Tons | $100 | $15,000 |
| Mobilization | 1 | LS | 15% | $125,910 |
| Contingency | 1 | LS | 25% | $241,328 |
| Total | | | | $1,210,000 |

## OPTION #3 | WORST CASE REPAIR COST

| | QTY | Unit | Unit Price | Total |
|---|---|---|---|---|
| Traffic Control | 1 | LS | $12,000 | $12,000 |
| Erosion Control | 1 | LS | $15,000 | $15,000 |
| Rip Rap (Abutment Protection) | 450 | CY | $120 | $54,000 |
| Guard Rail | 120 | LF | $60 | $7,200 |
| Stream Diversion | 1 | LS | $15,000 | $15,000 |
| Storm Clean-up | 1 | LS | $50,000 | $50,000 |
| Excavation | 360 | CY | $30 | $10,800 |
| Structural Backfill | 1440 | CY | $50 | $72,000 |
| 57 ft Simple Span Bridge | 0 | SF | $180 | $0 |
| Pavement Restoration | 150 | Tons | $100 | $15,000 |
| Mobilization | 1 | LS | 20% | $50,200 |
| Contingency | 1 | LS | 25% | $75,300 |
| Total | | | | $380,000 |

## OPTION #3 | DEPTH DAMAGE FUNCTION

| Flood Elevation (Feet) | Physical Damage & Repair Cost | Socioeconomic Costs | | | Property | Total Cost | % Damage | Notes |
|---|---|---|---|---|---|---|---|---|
| | | Detour | | Injury | | | | |
| | | Days in Effect | Cost | | | | | |
| 605 | $0 | 0 | $0 | $0 | 0 | $0 | 0% | |
| 614 | $0 | 0 | $0 | $0 | $0 | $0 | 0% | |
| 615 | $0 | 0 | $0 | $0 | $0 | $0 | 0% | |
| 616 | $0 | 0 | $0 | $0 | $0 | $0 | 0% | |
| 617 | $30,000 | 0 | $0 | $0 | $0 | $30,000 | 8% | Embankment erosion starts |
| 618 | $30,000 | 0 | $0 | $0 | $0 | $30,000 | 8% | |
| 619 | $40,000 | 0 | $0 | $0 | $0 | $40,000 | 11% | |
| 620 | $60,000 | 0 | $0 | $0 | $0 | $60,000 | 16% | |
| 621 | $80,000 | 0 | $0 | $0 | $0 | $80,000 | 21% | |
| 622 | $100,000 | 0 | $0 | $0 | $0 | $100,000 | 26% | |
| 623 | $130,000 | 0 | $0 | $0 | $0 | $130,000 | 34% | |
| 624 | $170,000 | 0 | $0 | $0 | $0 | $170,000 | 45% | |
| 625 | $220,000 | 1 | $140,000 | $0 | $0 | $360,000 | 95% | Overtopping starts |
| 626 | $290,000 | 5 | $700,000 | $80,000 | $0 | $1,070,000 | 282% | |
| 627 | $380,000 | 15 | $2,100,000 | $80,000 | $0 | $2,560,000 | 674% | |