U.S. Department of Transportation
Federal Highway Administration

TEACR Engineering Assessment

Wildfire and Precipitation Impacts to a Culvert:

US 34 at Canyon Cove Lane, Colorado

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 the impacts of wildfire and precipitation on the performance of a highway stream crossing.

Overview

This case study investigates the impacts of changing environmental conditions, including both wildfire and precipitation, on the performance of a highway stream crossing. Although this case study focuses on the performance of an existing culvert, the approach also applies to performance of a bridge under these circumstances.

To date, the impact of wildfires on transportation infrastructure has not been well documented in the literature. While in some regions, wildfires are anticipated to increase in frequency or severity as conditions change, it is difficult to connect generalizations about increasing fire risk to specific threats to individual

Case Study Snapshot

Purpose: The US 34 study was performed by the research team to investigate the combined impacts of changing precipitation and wildfire risk on the performance of a culvert structure.

Location: US 34 between Estes Park and Loveland, Colorado. Existing culvert crossing at milepost 66.9 at the intersection of US 34 and Canyon Cove Lane.

Approach: The research team performed the study using a HEC-HMS watershed model to stream flow rates under current, future, and wildfire burnout conditions. The HEC-RAS river model was used to model the performance of the US 34 culvert crossings.

Key Findings: (1) Scenarios of future environmental conditions may not present continuously increasing (or decreasing) trends in stressors; (2) the inclusion of wildfire impacts on watershed land cover greatly increases the volume of watershed stream flow runoff from precipitation; (3) sediment and debris flows impact the performance of the system hydraulics through both sediment bulking of peak stream flows and potential aggradation of sediments and debris at the US 34 facility crossing;
(4) the existing culvert is undersized for future conditions and post-fire flood conditions; (5) under the assumption that wildfire probability is low, the recommended adaptation option was to wait and see if a wildfire occurs and then quickly adapt.

Key Lessons: (1) Development of a probability of wildfire occurrence for a given area would add to the robustness of the engineering study and economic analysis; (2) since projected changes in precipitation could be either positive or negative depending on the models and scenarios, a binned approach was necessary so as to not mute the range of results through averaging; (3) The impact of wildfire burns on watershed hydrologic processes and stream runoff can be much more significant than the impact of future changes in precipitation.

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

assets. Wildfire exposure for a given site varies due to a number of factors (e.g., tree cover). Furthermore, there is a geographic disconnect insofar as fire impacts may be felt in locations that were not directly impacted by the fire itself, but where wildfire debris subsequently passes through the area. This analysis attempts to address the interdependent impacts associated with changes in wildfire exposure as well as changes in precipitation and attendant debris flows.[2]

The research team selected a culvert along US 34 in Colorado for this case study. This stretch of highway was severely damaged by floods in 2013 and portions of the temporary repairs to the highway will soon undergo permanent replacements presenting the opportunity for the results of this study to influence project design. This area is also known to have wildfire risk. To assess the impact on culvert performance, this study evaluated the impacts of:

- Wildfire burn on watershed runoff.
- Increased stream flows on the culvert.
- Wildfire-induced debris flows on the culvert.

This study evaluated these impacts through the development of watershed models to determine stream flow rates, river hydraulic models to determine the performance of the culvert, and sediment transport computations to determine the ability of the culvert to convey debris flows. Table 1 presents a summary of the existing culvert performance.

Table 1: Existing US 34 Culvert Performance.

Existing Culvert Configuration	Twin Cell 8-foot by 5-foot Concrete Box Culvert
Existing Culvert Maximum Flow Conveyance	850 cfs[3]
Design Standard	25-Year Storm
Existing Design Storm Flow	838 cfs
Future Climate Simulation 1 Design Storm Flow	721 cfs
Future Climate Simulation 2 Design Storm Flow	943 cfs
Future Climate Simulation 3 Design Storm Flow	1,236 cfs
Will culvert convey existing or future wildfire peak flows?	No
Can culvert convey wildfire debris flows?	No

[2] Culverts are not normally designed with consideration of debris occurring from a wildfire event. Therefore, the results of this analysis must be considered within the context of the fact that the study culvert was not designed for wildfire events, irrespective of future conditions. However, wildfire was combined with precipitation for this analysis as research on the connections between future conditions, wildfire, and ultimate impacts on transportation infrastructure are not well understood.

[3] Cubic feet per second (cfs), is the standard measurement of stream flow rates.

The research team found the following:

- The inclusion of wildfire impacts on watershed land cover greatly increases the projected volume of watershed precipitation-induced stream flow runoff.
- Sediment and debris flows impact the performance of the system hydraulics through both sediment bulking of peak stream flows and potential aggradation of debris sediments at the US 34 facility crossing.
- The existing culvert meets design criteria for present day design storm flows; however, changing climate conditions related to both increased precipitation and post-wildfire conditions will impair the culvert performance. Therefore, adaptation measures for the culvert are needed if the culvert is to fulfill its purpose properly under post-wildfire conditions.
- Under the assumption that a wildfire *will* occur, the most cost-effective adaptation option was found to be designing the replacement culvert to handle wildfire debris flow under a future climate scenario with moderate increases in precipitation (referred to as design Adaptation 3).
- However, the research team believes the probability of wildfire at any one given site is low, although exact probabilities could not be quantified. Because it would be costly to upgrade all culverts in the area on the chance that at least one of them experiences a wildfire event, the research team ended up recommending a different alternative—one that would adapt the culvert only *if* and *when* a fire occurs (called Adaptation X in this case study). The lack of wildfire probability information prevented the team from comparing this alternative with the others using an economic analysis; however, because the probability of wildfire is believed to be low, the research team believes the most prudent course of action would be to wait and see *if* a wildfire occurs, and then adapt.

Table 2 presents a summary of the adaptation options considered for the US 24 stream crossing as part of this study. The options are grouped as “proactive” or “reactive.” The proactive options are cases where the design team is proposing a change to the current day culvert design in anticipation of the future climate. The last two adaptation options, on the other hand, can be considered “reactive.” They take a wait-and-see approach, in which action is taken after a wildfire occurs but (hopefully) before a major precipitation event happens post-fire.

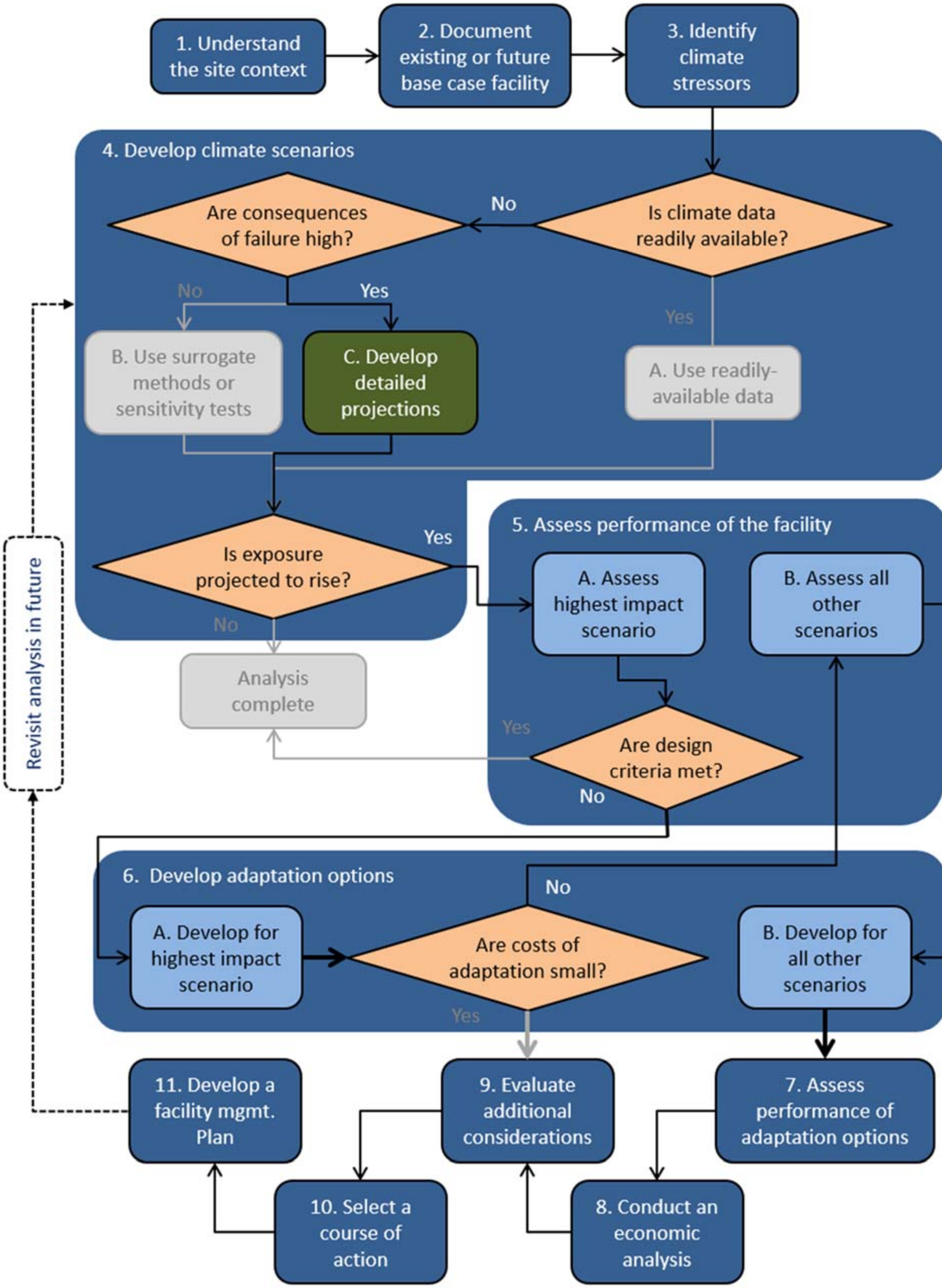
Table 2: Summary of Adaptations Considered in Case Study.

Proactive Adaptations - Present Day Construction			
	Adaptation 1	Adaptation 2	Adaptation 3
Design	50-foot single span bridge	Twin cell 8-foot by 8-foot box culvert	Triple cell 8-foot by 8-foot box culvert with roadway modifications
Design Target	Future Climate Simulation 3 50-year storm with wildfire conditions	Future Climate Simulation 3 25-year storm	Future Climate Simulation 2 50-year storm with wildfire conditions
Can design convey existing or future wildfire peak flows?	Yes	No	Yes, up to projections for Climate Simulation 2
Can design convey debris flows?	Yes	Limited, up to 1,200 cfs	Yes
Present Day Capital Cost	$9.07M	$530,000	$753,600

Reactive Adaptations		
	Adaptation X	Adaptation Y
Design	Post-fire Culvert Adaptation	Post-fire Watershed Treatment
Present Day Construction Features	Twin cell 8-foot by 8-foot box culvert with roadway modifications	Maintenance up-keep of current culvert
Future Construction Features	Expansion of culvert with a third 8-ffot by 8-foot culvert cell	Debris basin, silt fence, log erosion barriers, hydromulch, and check dams
Present Day Capital Cost	$550,000	$0
Future Capital Cost *if* a wildfire occurs	$450,000	$3.26M

This case study is organized according to the Adaptation Decision-making Assessment Process (ADAP). Figure 1 provides an overview of the ADAP steps completed for this analysis.

Figure 1: Overview of ADAP Steps Used for This Analysis.



Contents

Overview ... 1
Details of the Analysis ... 8
Step 1. Understand the Site Context ... 8
Flooding History of US 34 ... 9
History of Wildfires in Colorado and CDOT Response ... 10
Step 2. Document Base Case Facility ... 13
Step 3. Identify Climate Stressors ... 16
Step 4. Develop Climate Scenarios ... 17
Greenhouse Gas Scenarios ... 18
Climate Projections ... 19
Step 5. Assess Asset Performance under the Different Impact Scenarios ... 28
Watershed Hydrology ... 30
Facility Hydraulics ... 52
Findings on Existing Asset Performance ... 60
Step 6. Develop Adaptation Options ... 62
Proactive Adaptation Options (Adaptations 1, 2, and 3) ... 63
Reactive Adaptation Options (Adaptations X and Y) ... 72
Step 7. Assess Performance of Adaptation Options ... 82
Step 8. Conduct Economic Analysis ... 83
Loss of Use Impacts on Estes Park, Colorado ... 84
Property and Infrastructure Damage ... 85
Extended Loss of Tourism ... 85
Monte Carlo Analysis to Identify Preferred Adaptation Option(s) ... 91
Step 9. Evaluate Additional Considerations ... 108
Environmental Drivers ... 108
Political Drivers ... 108
Step 10. Select a Course of Action ... 109
Step 11. Develop a Facility Management Plan ... 110
Lessons Learned ... 111

Appendix 1: Damages 114
Appendix 2: Avoided Damages 116
References 117

Details of the Analysis

Step 1. Understand the Site Context

The culvert selected for study is located on US 34 northwest of Denver, Colorado between Loveland and Estes Park (see Figure 2). For approximately 20 miles, US 34 runs along the Big Thompson River using the Big Thompson Canyon as a means of traversing the rugged forested slopes of the Front Range of the Rocky Mountains. The culvert, situated within the canyon, conveys an unnamed ephemeral[4] stream under US 34 to its point of discharge into the Big Thompson River (see Figure 3). As can be seen in the aerial photo, the culvert is located just east of the intersection of US 34 and a short dead end gravel road called Canyon Cove Lane.

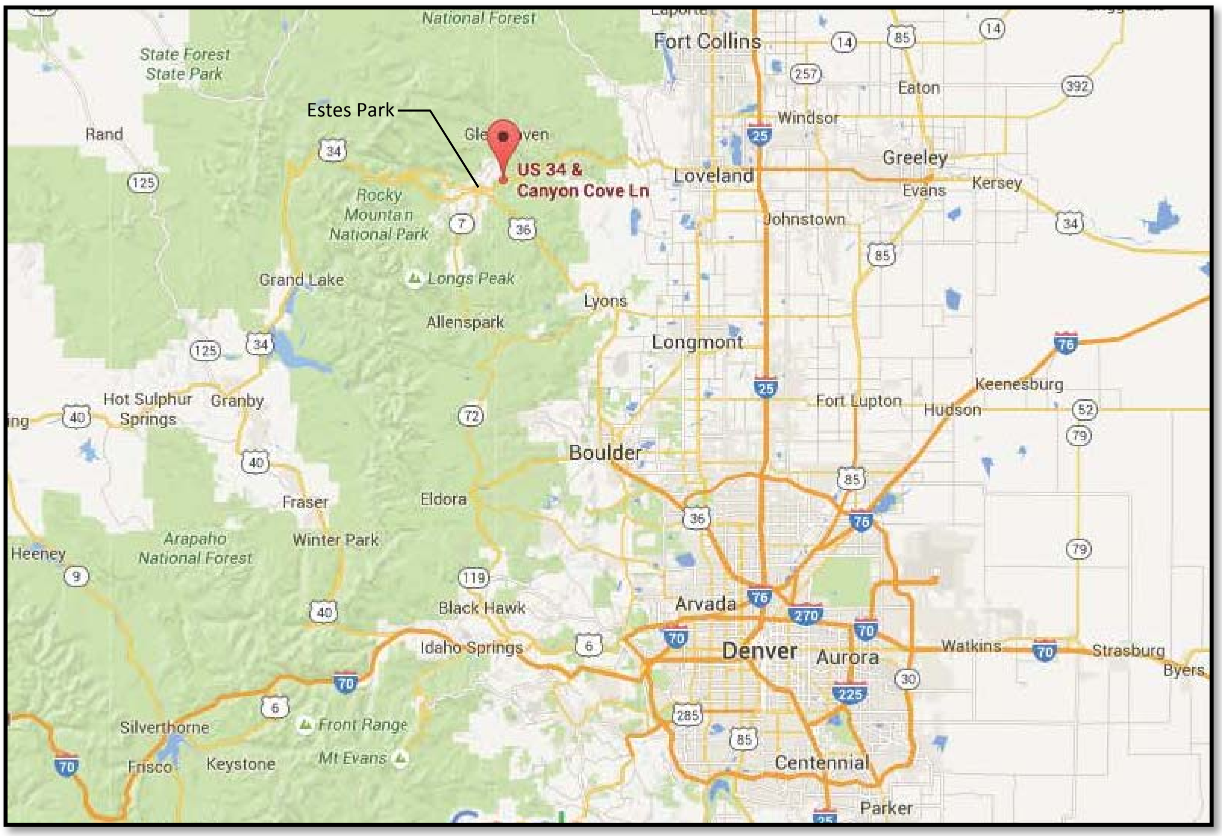


Figure 2: Asset Location.[5]

[4] Ephemeral streams are those that do not have a sustained surface water flow and normally only convey surface flows during precipitation events.

[5] Image source: Google Maps (as modified).

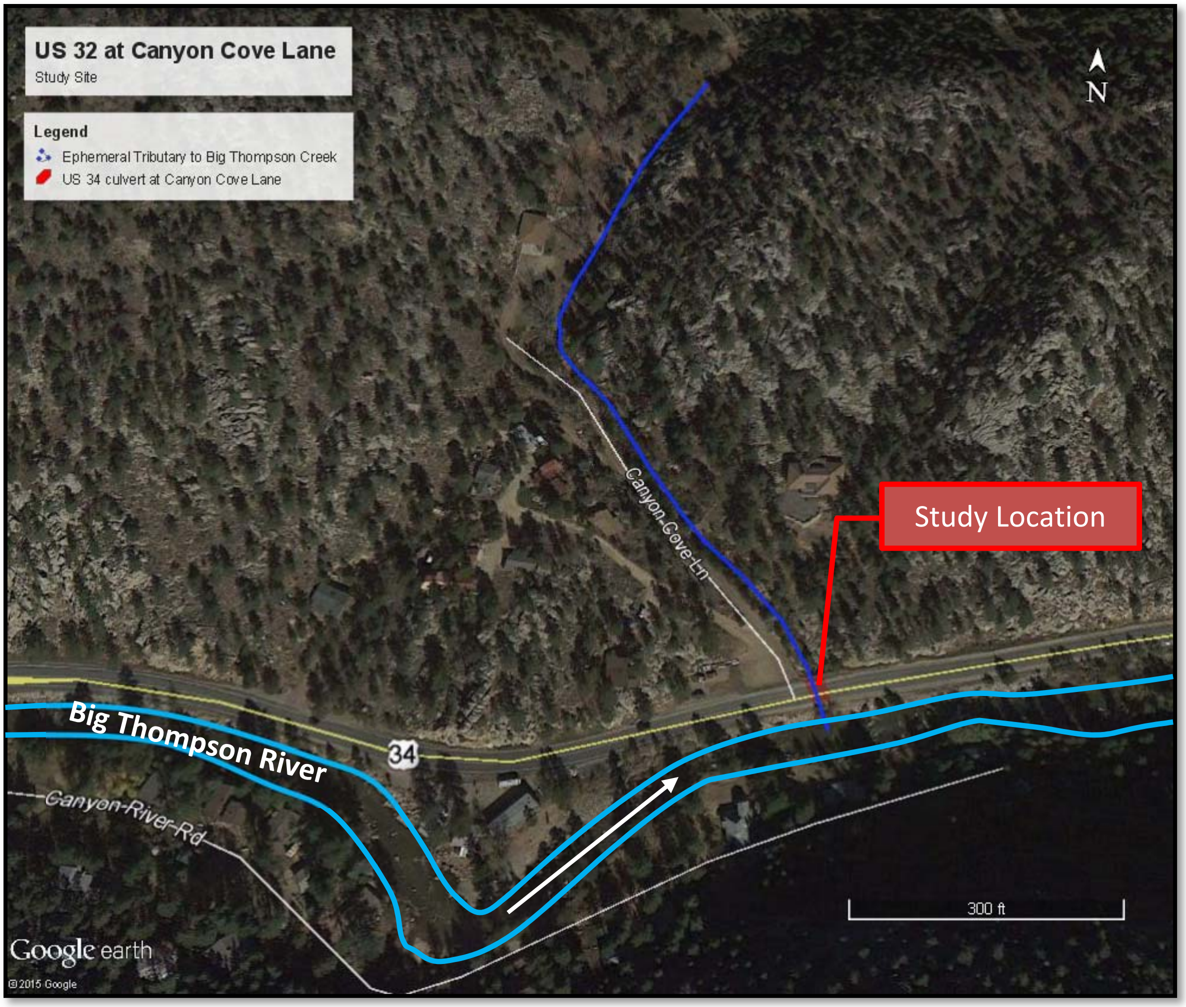


Figure 3: Aerial Photo of the US 34 Culvert Crossing at Canyon Cove Lane.[6]

US 34 is one of only four routes leading into the town of Estes Park and Rocky Mountain National Park[7] and is the primary route connecting these locations to points east such as the Front Range cities of Loveland, Greeley, and Fort Collins. There is also a number of private residences along US 34 in the Big Thompson Canyon whose access is entirely dependent on US 34: thus, loss of service to the roadway due to a culvert failure would cause significant hardship on surrounding communities.

Flooding History of US 34

US 34 has been subjected to flood related closures in this area in the past. In July 1976, a severe flash flood event destroyed significant portions of US 34 through Big Thompson Canyon. The 1976 flood event was caused by up to 14 inches of precipitation over a four-hour period in the

[6] Image source: Google Earth (as modified).
[7] There are only three routes in the winter months when US 34 west of Estes Park is typically closed due to heavy snows.

mountains around Estes Park. The 1976 flood reached an estimated peak discharge of 31,200 cubic feet per second,[8] which remains the highest known discharge for this portion of the river. The July thunderstorm that caused the flood had a peak precipitation rate of 7.5 inches in an hour, with 12 to 14 inches of rain falling mostly within a four to six hour timeframe. By comparison, the 100-year 6-hour storm is currently 4.5-inches of rain for this area. The Unites States Geological Survey (USGS) estimated flood recurrence intervals for the storm to be far in excess of the 100-year flood[9]. Radiocarbon dating of ancient flood deposits indicated that a flood of this size had not occurred in the Big Thompson Canyon for several thousand years.[10] Consequently, this devastating flood destroyed most of the infrastructure within the canyon, including nearly all of US 34. Most bridge and culvert structures along US 34 were replaced during the reconstruction efforts after the 1976 flooding including the culvert that is the subject of this study.

In September 2013, severe flooding again caused substantial damage to this stretch of highway, closing it for several months. The 2013 flooding was caused by a multi-day precipitation event with total precipitation volumes reaching up to 26 inches. The 2013 flooding peaked at an estimated 19,000 cubic foot per second discharge in the Big Thompson River.[11] The 2013 flood peak was equivalent to a 100-year storm[12] for the Big Thompson River. In order to get the road re-opened as quickly as possible, the Colorado Department of Transportation (CDOT) performed temporary emergency repairs, but those repairs were not meant to be permanent and were not built to the design standards used for permanent roadways. In spring 2016, CDOT began a two-year effort to reconstruct part of the road, including possibly the study culvert, to bring the entire roadway up to acceptable standards for a permanent roadway.

History of Wildfires in Colorado and CDOT Response

The occurrence and impact of wildfire in Colorado and other western states has been notably increasing since the 1960s. Data from the Colorado Forest Service (Figure 4) show that Colorado wildfires averaged less than 500 events per year in the 1960’s with less than 100,000 acres in total burned during that decade. Those numbers have increased to over 2,000 events per year with more than 1 million acres burned from 2000 to 2010. Many factors may have contributed to this increasing trend, including forest management practices that encourage the maintenance of high fire risk underbrush, pest infestations that weaken and denude many pine

[8] The Denver Post, 2012.
[9] Jarrett and Costa, 2006.
[10] Jarrett and Costa, 1988.
[11] U.S. Geologic Service, National Water Information System: Web Interface. Peak Streamflow for Colorado: USGS Gage 06741510 Big Thompson River at Loveland, CO.
[12] FEMA, 2013.

forests, and increasing periods of drought. It is reasonable to expect that wildfire risk will increase if these factors persist and are magnified by changing climate conditions.

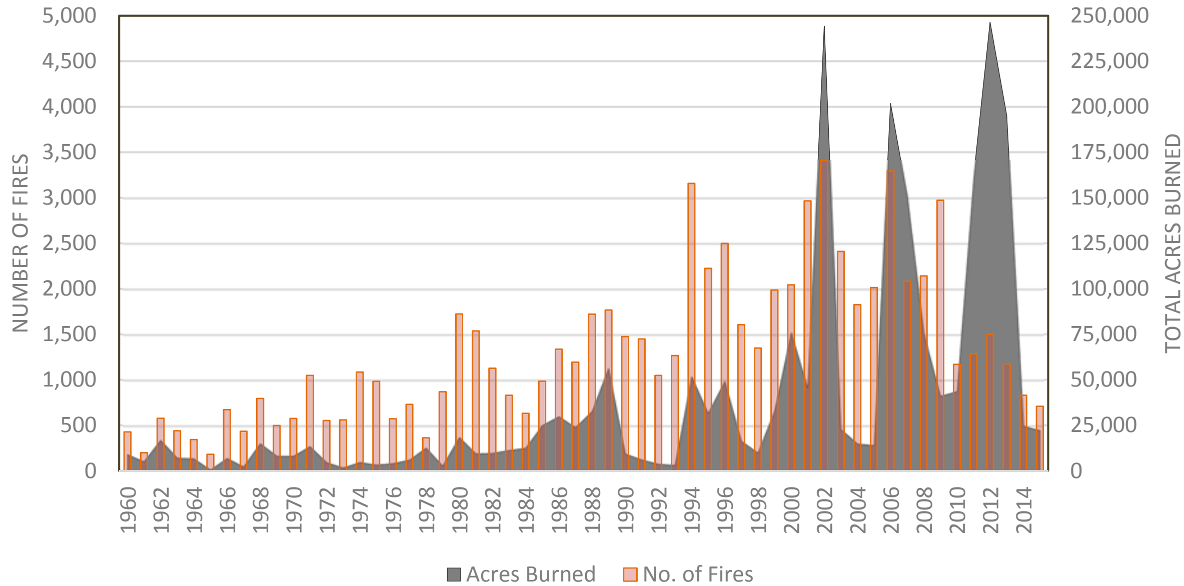


Figure 4: Trends in Colorado Wildfires (1960 - 2015).[13]

The research team studied two recent Colorado wildfires while collecting background information for this study. The fires both occurred in June 2012 and are amongst the most destructive fires in the history of the state. The following sections discuss the fires (High Park Fire and Waldo Canyon Fire) and CDOT's response and experiences with post-fire management.

High Park Fire (2012) and State Route 14 [14]

A lightning strike ignited the High Park Fire on June 9, 2012 in a forested area on private land. The fire burned for 23 days before containment on July 1, 2012. In total, the fire burned more than 87,000 acres, 259 homes, and caused one death.[15] As of 2016, the High Park Fire is the third largest fire in the recorded history of the state, after the 2002 Hayman Fire and 2013 West Fork Fire Complex.

Colorado State Route 14 is located through the northern extents of the High Park Fire, with 9 miles of road having forest burn on the southern side and approximately 11 mile of road having burn on both the north and south sides (20 total miles of road impacted). The wildfire burn significantly affected the watersheds tributary to multiple drainage structures for SR 14.

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[13] Data provided by the Colorado Forest Service.

[14] Background information provided via personal communications between the research team and CDOT (September 2016), unless otherwise noted.

[15] Fire statistics provided by The National Wildfire Coordinating Group Incident Information System are available at: www.inciweb.nwcg.gov.

In the immediate aftermath of the High Park Fire, CDOT mobilized corridor-wide maintenance activities and began the development and implementation of post-fire mitigation techniques along SR 14. Mitigation techniques considered along SR 14 included debris catchments (small-scale debris basins) and upsized culvert crossings. Construction of the improvements started in September 2013. The design methodology utilized by CDOT in the SR 14 culvert sizing pivoted off of the NRCS High Park Fire report. CDOT selected the 10-year post-fire design storm as the design standard for each of these structures, in consideration of the limited window of watershed impairment due to the wildfire burn. In the post-fire mitigation along SR 14, CDOT chose to implement only mitigation techniques that could be used within their current right-of-way. Land acquisition costs, acquisition timelines, and the inability to utilize property condemnation for upland treatments influenced this decision.

Waldo Canyon Fire (2012) and US 24 [16]

The Waldo Canyon Fire, of unknown cause, started on June 23, 2012 in the Pike National Forest. The fire burned for 18 days before containment on July 10, 2012. In total, the Waldo Canyon Fire burned 18,000 acres, 346 homes, and caused two deaths[17]. As of 2016, the Waldo Canyon Fire is one of the most destructive fires[18] ever in Colorado, second only to the 2013 Black Forest Fire.

The Waldo Canyon Fire burned up to the Colorado Springs city limits on fire's eastern limits and US 24 / Fountain Creek / Manitou Springs along the fire's southern limits. During the fire, CDOTs emergency response focused on facilitating resident evacuations via US 24 and I-25 and maintaining US 24 for fire fighters and other emergency responders.

Figure 5: Post-wildfire debris flows on US 24 near Waldo Canyon (2013). Photograph courtesy of the Colorado Department of Transportation.

In the immediate aftermath of the fire, CDOT ran continuous maintenance operations on US 24 and other roadways impacted by the fire while concurrently preparing plans for longer-term improvements to mitigate the increased environmental risks caused by the fire. CDOT performed the continuous maintenance operations to maintain roadway operation

[16] Background information provided via personal communications between the research team and CDOT (September 2016), unless otherwise noted.

[17] Fire statistics provided by The National Wildfire Coordinating Group Incident Information System are available at: www.inciweb.nwcg.gov.

[18] Based upon insurance claims.

through debris clean-up and facilitate rapid road closures in the event of precipitation / flooding from the time of the fire through 2014, until construction of long-term improvements were completed. During the continuous maintenance period, seven different storm events caused debris flow to clog the culverts and flood the roadways. CDOT staff noted that debris flows and maintenance needs increased each successive year after the fire, leading up to the installation of the long-term improvements. CDOT developed a corridor response plan as part of the continuous maintenance operations to outline maintenance responsibilities and emergency actions. The corridor response plan included installation of gates for emergency closure of US 24 and installation flood monitoring gauges / cameras in Waldo and Williams Canyons.

CDOT ultimately constructed three debris basins and replaced a 72-inch culvert under US 24 with a larger box culvert structure. As with the High Park Fire activities, the 10-year post-fire design storm was defined as the design standard for each of these structures. CDOT constructed the debris basins upstream of the US 24 culvert crossings of Sand Gulch, Fern Gulch, and Wellington Gulch. In the case of the Waldo Canyon post-fire mitigation, CDOT elected to expand usage of debris basins rather than culvert enlargement due to concerns about flooding in Manitou Springs. In the immediate aftermath of the fire, post-fire inflated stream flows and debris threatened the US 24 corridor and on multiple occasions clogged the culverts resulting in debris build up on the US 24 roadway. However, the undersized culverts at US 24 had the effect of decreasing the flooding impacts in Manitou Springs as much of the debris deposited on US 24 and did not progress downstream to threatening the village. Enlargement of US 24 culverts to mitigate flood impacts on the roadway corridor would have exacerbated the post-fire flood impacts in the town. CDOT performed proactive coordination with the surrounding communities to identify and address concerns related to post-fire flooding impacts, resulting in the selected debris basin designs with only a single culvert enlargement.

CDOT's capital costs for the post-fire mitigation improvements for the Waldo Canyon Fire totaled just under $13M. The capital cost was partially mitigated by reduced maintenance needs along US 24 upon completion of the debris basins and the culvert upsizing. Since completion of construction in 2013 through late 2016, the debris basins have on average required five to seven maintenance clean-outs each year, while the downstream culverts have not required any maintenance clean-outs. Prior to construction of the debris basins, CDOT staff estimated that culvert maintenance clean-outs were necessary on a near monthly basis.

Step 2. Document Base Case Facility

The current US 34 culvert at Canyon Cove Lane was constructed in the late 1970s during reconstruction after the 1976 Big Thompson River flood. The culvert has twin cells, each of which are 40 feet long and eight-foot wide by five-foot high cast-in-place reinforced concrete boxes. As per CDOT design requirements, the design storm for a two-lane rural road like US 34 with a 50-year discharge less than 4,000 cubic feet per second is the 25-year storm. The design storm shifts to the 50-year event for 50-year discharges greater than 4,000 cubic feet per second. In addition, the Colorado Water Control Board has documented a 100-year storm design standard for cross-culverts, particularly for roadways that are the lone egress route from residential properties. The research team utilized the CDOT design standard in the analysis of the facility performance, but also considered the Water Control Board's guidance in making final recommendations.

The existing US 34 culvert appears to be in good structural condition, with no major issues noted by the research team during the site visit. There is some sediment deposition within both box cells as shown in Figure 6. Concrete endwalls[19] with 45° wingwalls[20] are located at the entrance and exit to the culvert boxes. The survey data for the site showed the roadway cover[21] over the top of the culvert opening to be approximately two feet. As noted in Step 1, the culvert is located immediately upstream of the watershed's outlet into the Big Thompson River. At the outlet of the culvert, the stream channel largely loses definition and is part of the riprap streambank slope for the Big Thompson. CDOT provided topographic survey data for the current culvert crossing.

[19] An endwall is a wall perpendicular to the stream that protects the culvert inlet/outlet from erosion.
[20] Wingwalls are walls extending outward from the endwalls directing water into (or out of) the culvert boxes and protecting against erosion.
[21] Cover is measured from the top of the culvert barrel to the edge of the roadway pavement.

Figure 6: Sediment Deposition Inside the US 34 Culvert, October 2015 (left) and View of Culvert Inlet Showing Wingwall (right). Photograph provided courtesy of FHWA.

US 34 at the culvert crossing is a two lane asphalt roadway. The road has 12-foot travel lanes with three-foot wide paved shoulders along each travel lane. The road is situated on an embankment about 15-feet above the low flow water surface of the Big Thompson River to the south (see Figure 7). The embankment is armored with large diameter riprap[22] protection. The riprap rock is estimated to have a mean diameter of 24 inches. The research team estimated that the armored embankment has a constant slope of 38° above normal grade. Detailed geotechnical data on the construction of the roadway embankment were not available at the time of this study; however, based on the available materials for embankment construction in the area and its relatively steep slope, the research team assumed that the roadway embankment was constructed using compacted rock fill with an estimated mean rock diameter of two inches.

[22] Riprap is a layer of large stone used to protect underlying materials from erosion.

Figure 7: Armored Embankment along the Big Thompson River at the Culvert Outlet. Photograph provided courtesy of FHWA.

Step 3. Identify Climate Stressors

Climate Stressors

- Change in wildfire potential
- Change in frequency and intensity of extreme precipitation events

All culverts are sensitive to changes in precipitation. In some locations, including the one being studied, wildfire poses an additional second-order threat to culverts. This is because, after a fire occurs, (1) the reduction in vegetation in the immediate aftermath can be destabilizing to the soils; (2) the fire can change the soils capacity to infiltrate water, resulting in increased runoff; and (3) there is often substantial debris left behind from burnt vegetation. The latter is important because, when it rains, the runoff will move more debris through the culvert and some of that debris could settle in the culvert itself, partially blocking it. Then, when significant rain events happen in the future, the culvert may no longer be of sufficient size to pass the flow of water and debris, resulting in roadway overtopping and culvert failure.

Climate change may increase the intensity of precipitation resulting in greater depths of rain over any given time period. It may also increase wildfire potential[23] in a number of ways. For example, the moisture state of potential fuel sources, daily weather conditions (e.g. hot and dry conditions), and other factors influence fire potential. In addition, changes in temperatures and precipitation could create conditions conducive to pests or diseases that damage or kill trees, making them more susceptible to fire.

Considering both the implications of fire and precipitation on culvert performance, the research team investigated changes in the following specific climate stressors:

- Change in wildfire potential. While the research team was unable to consider all factors affecting wildfire,[24] the research team did consider the increase in fire potential, which is a measure of the change that a fire of a certain severity will occur. Specifically, the team considered changes in the Keetch-Byram Drought Index (KBDI), which is widely used as an indicator of conditions conducive to wildfires, and which takes into account fuel and soil moisture levels, as well as other weather conditions (such as hot temperatures) that could contribute to wildfire conditions. Changes in wildfire potential were used to qualitatively inform potential changes in the occurrence of wildfire-driven debris flow and the associated economic consequences.
- Changes in the magnitude of the two-year, five-year, 10-year, 25-year, 50-year, 100-year, and 500- year 24-hour return period precipitation events. Changes in these precipitation events affect water levels and debris flows through the culvert.

Step 4. Develop Climate Scenarios

For this effort, the research team developed projected changes in seven daily precipitation recurrence intervals and wildfire potential. Future projections were developed for 30-year intervals centered around 2045, 2065, and 2085 and compared to a baseline centered around 1995. This section begins with an overview of the greenhouse gas scenarios selected for study then provides details on the climate projections developed.

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[23] Wildfire potential refers not to frequency of wildfire events, but the likelihood that a fire of a certain magnitude will occur in a given area. Fire potential takes into account characteristics like fuel moisture levels, weather conditions, and potential fire behavior (e.g. how the fire will spread and the intensity of the burn).

[24] Consideration of changes in pest and disease incidence, changes in lightning strikes, and other factors associated with future conditions could also be included; however, they introduce significant layers of uncertainty and were beyond the resources of this project.

Environmental Scenarios

The scenarios considered in this study include projections based on three plausible trajectories of future greenhouse gas (GHG) concentrations, referred to as representative concentration pathways (RCPs). The RCPs describe how global society may evolve in its use of fossil fuels, technology, population growth etc. and the resulting emissions and the total GHG concentration levels in the atmosphere. The three scenarios used here include:

- RCP 4.5, with a radiative forcing[25] of approximately 4.5 watts per square meter by about 2100 indicating a low to moderate increase in the total greenhouse gas concentration levels in the atmosphere.
- RCP 6.0, with a radiative forcing of six watts per square meter by about 2100 indicating a moderate increase in the total GHG concentration levels in the atmosphere.
- RCP 8.5, with a radiative forcing of 8.5 watts per square meter by about 2100 indicating a high or unabated increase in the total GHG concentration levels in the atmosphere.

Climate Data Overview

Level of Detail: Developed detailed projections

Data Source: U.S. Bureau of Reclamation (2013) which provides peer-reviewed statistically downscaled data of the World Climate Research Programme's Coupled Model Intercomparison Project 5

Scenarios: RCP 4.5, RCP 6.0, RCP 8.5

Is exposure projected to change in the future? Yes, precipitation depths are expected to increase under at least one of the return periods calculated for each of the three scenarios developed and conditions are expected to become more favorable for wildfires under all scenarios.

Figure 8 presents the equivalent carbon dioxide[26] concentrations of different RCPs. As shown in the graph, RCP 4.5 annual GHG emissions rise quickly but then stabilize with time. After about 2060, RCP 6.0 GHG emissions exceed RCP 4.5 GHG emissions and then stabilize. Finally, RCP 8.5 GHG emissions rise steadily at a greater rate compared to the other RCPs and do not stabilize at the end of the century. It is important to note that global radiative forcing does not reflect local changes in precipitation—i.e. more global radiative forcing does not necessarily consistently indicate more or less precipitation for a given area.

[25] Radiative forcing causes a change in the energy balance leading to a net warming or cooling of climate. For example, a change in the concentration of carbon dioxide or the output of the sun can cause a radiative forcing (IPCC 2014 Working Group III).

[26] Carbon dioxide equivalent is a measure used to compare the emissions of various greenhouse gases based upon their global warming potential.

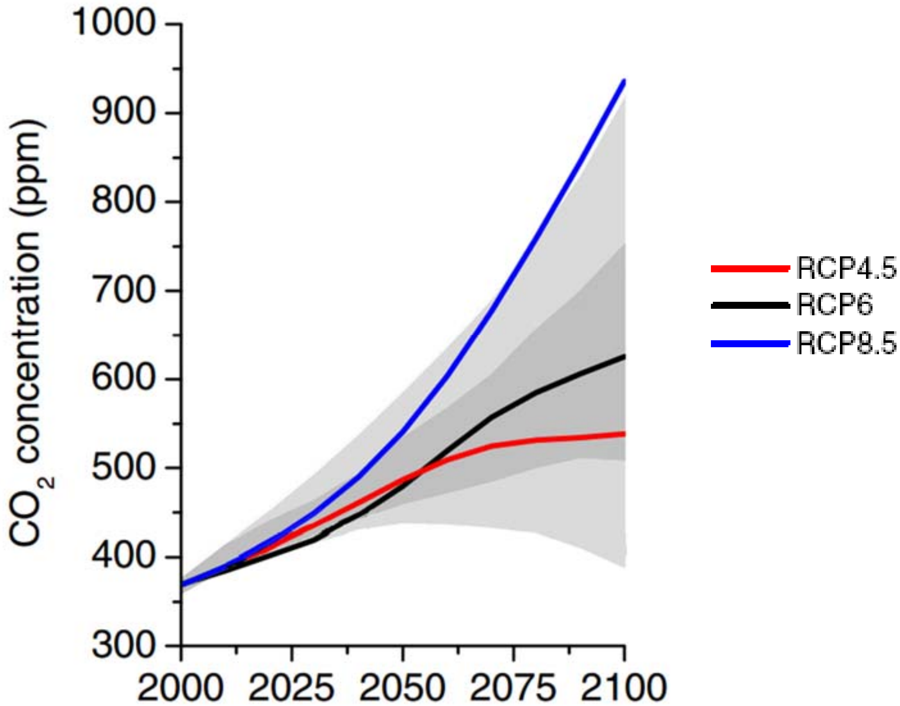

Figure 8: Equivalent Carbon Dioxide (CO_2) Emission and Radiative Forcing Trajectories of Different Representative Concentration Pathways.[27,28]

Climate Projections

For the future climate projections, the publically available statistically downscaled[29] data provided by the U.S. Bureau of Reclamation (USBR) were used (USBR 2013). The USBR's website provides downscaled data from the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project 5 (CMIP5) that were used to inform the Intergovernmental Panel on Climate Change (IPCC) Assessment reports. These simulations, originally available at a spatial resolution around one degree,[30] have been statistically downscaled to 1/8 degree resolution for the United States by USBR. Daily values for minimum temperature, maximum temperature, and precipitation were downloaded for 11 global climate models, four USBR grid cells,[31] and the three RCPs from 1950 to 2099 (see Table 3). This analysis averages across the

[27]Source: Van Vuuren et al., 2011. The Representative Concentration Pathways: An Overview. Climatic Change, 109 (1-2), 5-31.

[28] Light gray represents 98% of the range of Integrated Assessment Modeling (IAM) scenarios; dark gray represents 90% of the range. See Van Vurren et al (2011) for more information.

[29] Statistical downscaling is a technique for improving the spatial resolution of climate projections based on historical climate observations.

[30] The one degree value is approximate because each climate model's spatial resolution varies and may be smaller or larger than one degree.

[31] Four grid cells were chosen based on the center of the study location with latitude of 40.41439° North and longitude of 105.25329° West.

four grid cells for each model/scenario combination. The remainder of this section describes how this information was used to develop the precipitation and wildfire projections.

Table 3: Summary of Global Climate Models and Scenarios Used.

Global Climate Models	Scenarios
▪ bcc-csm1-1 ▪ ccsm4 ▪ gfdl-esm2g ▪ gfdl-esm2m ▪ ipsl-cm5a-lr ▪ ipsl-cm5a-mr ▪ miroc-esm ▪ miroc-esm-chem ▪ miroc5 ▪ mri-cgcm3 ▪ noresm1-m	▪ RCP4.5 ▪ RCP6.0 ▪ RCP8.5

Precipitation Events

This analysis considered how changes in climate may affect the magnitude of the two-year, five-year, 10-year, 25-year, 50-year, 100-year, and 500-year 24-hour precipitation return periods. Although a 24-hour storm was used, given the properties of the study watershed, the research team suspects that a six-hour, or shorter, return period might have been more appropriate. However, there are inherent uncertainties in the statistical frequency analysis of extreme precipitation events and the use of projected climate data, particularly at sub-24 hour durations, to inform these analyses to produce reliable and robust results is an area actively being researched. Because of this, the research team used the 24-hour duration (daily) publicly available downscaled data from the climate models.

To establish a baseline for reference, return periods for the historical period of record based on observations were obtained from the National Oceanographic and Atmospheric Administration's (NOAA) Atlas 14, Volume 8, Version 2.[32] NOAA tested various theoretical distributions and determined that the generalized extreme value distribution (GEV) provides the best fit for developing return periods for this area. Table 4 provides the daily precipitation amounts for each recurrence interval as estimated by NOAA.

[32] NOAA, 2013. NOAA Atlas 14 Volume 8 Version 2.0: Precipitation-Frequency Atlas of the United States.

Table 4: NOAA Atlas 14 Estimated Daily Precipitation (inches) by Recurrence Interval (90 Percent Confidence Level).[33]

	Recurrence Intervals (years)						
	2	5	10	25	50	100	500
NOAA 24-Hr Precip. Depth	1.62	2.00	2.41	3.11	3.75	4.49	6.63

Next, the percent-change in future return periods for each climate simulation (i.e., for a given climate model and RCP scenario) was developed using the following steps:

1. The maximum daily precipitation for a given year was determined for each grid cell from 1980 to 2099.
2. The GEV was fitted to each set of maximum precipitation for each 30-year time period (for the baseline simulation and each future time period) for each grid cell.
3. The return periods were then calculated based on the GEV-fit for each 30-year time period and grid cell.
4. Return periods were then averaged across the four grid cells for each time period.
5. The projected percent change was then calculated by subtracting the baseline value from the future value and dividing by the baseline value (note that the future and baseline values are based on climate simulation data).[34]

When fitting a distribution and then extrapolating to obtain values at the tails (e.g. 100-year, 500-year), at least a 30-year time period is preferred. However, since this study was providing results for the end of century when climate may change more rapidly, the first day of the 30-year period and the last day of the 30-year period could be in two statistically different population sets since climate may have changed over the 30-year period.

This methodology was applied to a total of 33 climate simulations (11 climate models and three RCP scenarios), where each simulation suggested how return period values for the seven return periods may change for the three future time periods. All told, this created a wealth of data. Initially, the climate model ensemble, essentially an average value across the models, was considered for each RCP as may be done for annual temperature or monthly precipitation. However, it quickly become evident that averaging across the climate model results for each time period created significant dampening of potential change (particularly as some models for

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[33] The latitude queried from NOAA Atlas 14 was 40.4144° North and the longitude was 105.2533° West. The estimates are based on observations with an average of 68 years of annual maximum values (the minimum number of years used is 30).

[34] Percent-change, as opposed to absolute change, was used to provide a relative amount of projected change. Percent change is preferred given the related uncertainties when projecting changes in extreme precipitation events.

some time periods might suggest a reduction in magnitude for a given return period while others might suggest an increase). In fact, it was not clear that the averaging would produce a physically plausible scenario. In addition, there was often as much or more variability in the projected changes in return periods across the climate models than across emissions scenarios. Because of this, the analysis did not move forward with an ensemble average. Instead, this analysis chose which climate simulations (i.e., climate model under a given scenario) were representative of the range of plausible futures projected across the ensemble. This scenarios-based approach is commonly-accepted practice when using climate change projections in order to express the plausible range of future climate projections.[35]

The next step was to determine how to work around the issue identified with ensembles and select specific climate simulations that could be used in the engineering analysis. An approach was developed that involved ranking each of the 33 climate model/scenario combinations (hereafter referred to as simulations) according to which showed the most impactful changes in precipitation. The first step in this approach involved specifying the metric to be ranked. The team elected to use the 100-year storm to guide the rankings. Thus for each future time horizon, the climate simulation values for the 100 year return periods were ranked from one (highest precipitation increase value) to 33 (lowest precipitation increase value). This approach provided three sets of rankings for a given climate simulation: for example, a given climate simulation might rank third for the 2045 time period, fourth for the 2065 time period, and 13th

35 A few examples of vulnerability assessments or reports that use (or recommend the use of) scenarios include: U.S. DOT (2014a), U.S. DOT (2014b), FHWA (2017), and DOEE (2015). Furthermore, the issue encountered in this case study with negative and positive precipitation values is described on page 7 in Winkler et al (2012): “Another situation where a multimodel mean may be misleading is when some members of an ensemble project a positive change in a climate variable while others project a negative change. In this case, the multimodel mean of the projected change can approach zero even though all of the ensemble members project a substantial change but of opposite sign. The near-zero ensemble mean may be interpreted as "no change" when an arguably more informative interpretation is that the nature of the change is uncertain. Precipitation projections tend to be highly uncertain and often of opposite sign; thus, simple multimodel means may not be very informative in considering future changes in precipitation.”

for the 2085 time period. An average of these three rankings was then calculated to obtain an aggregated ranking for each climate simulation that could then be compared to the similarly calculated averaged rankings of the other climate simulations. This helped isolate the climate simulations that tended towards more extreme or less extreme precipitation events.

Next, the climate simulations were sorted by their overall ranking and inspected. The climate simulations that represented the 90th, the 50th, and the 10th percentiles across all 33 climate simulations were then selected to arrive at three climate simulations, a manageable number to consider in the engineering analysis. This captured a significant part of the spread across climate simulations without being overly skewed towards one extreme simulation or another. [36] Table 5 shows the precipitation changes projected for the three chosen climate simulations, which are described in the box to the right.

It is important to note that the ranking was done for the asset performance analysis provided in Step 5; hence, it was developed only for precipitation and without consideration of the wildfire hazard that informs the economic analysis. Where multiple hazards threaten an asset, it is possible to develop a ranking based on the combined effects of wildfire and flooding rather than just flooding alone. For example, the 100-year precipitation return period could provide the initial ranking to cluster the climate simulations around each percentile but then one could also consider the associated change in the wildfire hazard to augment the ranking. The combined ranking would then provide an indication of which simulation has the biggest change in precipitation and wildfire hazard.

Selected Climate Simulations

Climate Simulation 1

- Representative of the 10th percentile of climate model runs for daily extreme event precipitation.
- Could be considered the Low Precipitation Scenario, since it shows the largest precipitation decrease of the 3 selected simulations
- Largest KBDI / wildfire risk increase
- RCP 4.5
- Climate model = miroc-esm.1

Climate Simulation 2

- Representative of the 50th percentile of climate model runs for daily extreme event precipitation.
- Could be considered the Moderate Scenario, since it shows the middle value of the 3 selected simulations
- Moderate KBDI / wildfire risk increase
- RCP 6.0
- Climate model = ccsm4.1

Climate Simulation 3

- Represents 90th percentile of climate model runs for daily extreme event precipitation.
- Could be considered the High Scenario, since it shows the largest precipitation *increase* of the 3 selected simulations
- Lowest KBDI / wildfire risk increase
- RCP 4.5
- Climate model = mri-cgcm3.1

[36] One concern with selecting the most/least extreme values is that these projections have not been thoroughly investigated and identified as climate models with a downscaling technique that does the “best job” capturing the conditions that play into the rare but extreme events. This would entail significant effort and was beyond the scope of this study.

Table 5: Change in Daily Precipitation Depths by Return Period for Selected Climate Simulations.

	Climate Simulations (GHG Scenario and Global Climate Model)		
2045	Simulation 1	Simulation 2	Simulation 3
2 Year	4%	-10%	-3%
5 Year	-9%	-11%	1%
10 year	-18%	-10%	5%
25 year	-29%	-9%	11%
50 year	-36%	-7%	15%
100 year	-43% (ranked 31)	-5% (ranked 20)	19% (ranked 8)
500 year	-56%	-1%	29%
2065			
2 Year	8%	-10%	17%
5 Year	-1%	-6%	18%
10 year	-6%	-1%	19%
25 year	-12%	7%	20%
50 year	-16%	14%	21%
100 year	-20% (ranked 26)	21% (ranked 8)	22% (ranked 7)
500 year	-28%	40%	22%
2085			
2 Year	9%	-3%	22%
5 Year	0%	-2%	23%
10 year	-4%	-2%	24%
25 year	-8%	-3%	26%
50 year	-9%	-3%	27%
100 year	-11% (ranked 25)	-4% (ranked 21)	27% (ranked 6)
500 year	-13%	-6%	28%
Mean Rank	**27**	**16**	**7**

See Text Box on page 23 for a description of Simulations 1, 2, and 3.

Wildfire

There are a number of factors that influence the magnitude, intensity, and frequency of wildfire for specific regions in the United States. These factors include the prevalence of disease and pests, weather patterns, presence of ignition sources (e.g., cigarettes or lightning[37]), forest type and density, topography, etc. How wildfire may change in the future is further complicated by how pests and vegetation may be affected and/or changed over time in response to climate as well as other stressors such as land-use change as populations and the built environment

[37] Lightning can be a source for the ignition of wildfires. Lightning can be produced from convective activity such as thunderstorms, which, due to the small scale of storms, can be challenging to simulate in climate models. There are variables that can be developed from climate output such as using Convective Available Potential Energy (CAPE) as a proxy for convective activity; however, this was beyond the resources of this project to project.

evolve. This analysis does not delve into these complex issues, which require more sophisticated modeling and effort.

Because of the complexity behind predicting wildfire occurrence, the research team assumed that the ignition probability will not change in the future and considered changes in fire potential instead. Fire potential "measures the chance that a fire of a certain severity will occur in an area" and can be informed by a number of indices that include fuel moisture levels, weather conditions, and potential fire behavior (e.g. how the fire will spread and the intensity of the burn).[38] The Keetch-Byram Drought Index (KBDI) has been used extensively as an indicator of weather conditions that increase fire potential and, recently, within the climate community, as an indicator of future change in wildfire threat for a given location.[39] This indicator is particularly useful for climate studies as it uses annual precipitation, daily precipitation, and maximum temperature as the climate drivers in estimating future change; variables readily available from climate model data. KBDI is based on a daily water balance model that considers precipitation and soil moisture where the maximum storage capacity is set to eight inches.[40] The drought index ranges from zero (no drought) to 800 (absolutely dry).

The first step in developing the index is to inspect the daily precipitation records and initialize KBDI to zero after periods of excessive precipitation (e.g., many days in a row of high precipitation). Then KBDI is calculated using a daily cumulative index by taking the KBDI value from the previous day and subtracting any net daily precipitation from the index and adding a daily drought factor. Net daily precipitation is calculated as follows:

- If daily precipitation is above 0.2 inches, then the net precipitation is equal to the daily amount minus 0.2 inches (this model assumes reductions in drought will only occur if daily precipitation exceeds 0.2 inches).
- If daily observed precipitation is below 0.2 inches, then the net precipitation is set to zero. An exception is made if consecutive days of cumulative precipitation amounts total 0.2 inches or more, in which case the net precipitation is equal to the accumulated amount over the consecutive rainy days minus 0.2 inches. Each subsequent day of precipitation sets the net daily precipitation to the observed daily precipitation. Note that accumulation stops when daily observed precipitation amounts are recorded at trace or zero.

[38] Liu et al., 2014.
[39] Keetch and Byram, 1968; Liu et al., 2012; Dolling et al., 2005.
[40] The value of eight inches for the saturation of the soils is used as the national standard when developing KBDI values. It is considered a reasonable value to inform forest fire control.

The drought factor is calculated based on daily maximum temperature and mean annual precipitation as follows:

$$DF = \frac{(800 - KBDI_{t-1})(0.968 e^{0.0486 T\max_t} - 8.30) * 0.001}{1 + 10.88 e^{-0.0441 P}}$$

Where, $KBDI_{t-1}$ is the KBDI value of the preceding day, $Tmax_t$ is the daily maximum temperature in Fahrenheit, and P is the mean annual precipitation in inches for that given year. Note that the drought factor is equal to zero if the daily maximum temperature drops below about 50^o Fahrenheit. The value of daily KBDI relates to fire potential classifications (i.e. low through extreme) as shown in Table 6.

Table 6: Relationship Between KBDI and Fire Potential Classifications.[41]

Level	KDBI	Condition	Typical Period
Low	0-200	Soil moisture and large class fuel moistures are high and do not contribute much to fire intensity.	Spring dormant season following winter precipitation.
Moderate	200-400	Lower litter and duff layers are drying and beginning to contribute to fire intensity.	Late spring, early growing season.
High	400-600	Lower little and duff layers actively contribute to fire intensity and will burn actively.	Late summer, early fall.
Extreme	600-800	Intense, deep burning fires with significant downwind spotting can be expected. Live fuels can also be expected to burn actively at these levels.	Often associated with periods of severe drought.

This analysis calculated KBDI for each of the 33 climate model simulations. For each climate simulation, the calculation proceeded as follows:

- The value of KBDI was calculated for each day from 1980 to 2099.
- Next, for each 30-year time period, the number of days when KBDI fell into each fire potential classification from Table 6 was counted up and divided by 30 years (the period lengths used for the three time periods in this study) to obtain an annual average of the number of days that fall within each fire potential classification.[42]
- The difference for each fire potential classification between each future time period and the baseline time period was calculated. For example, a climate simulation may suggest

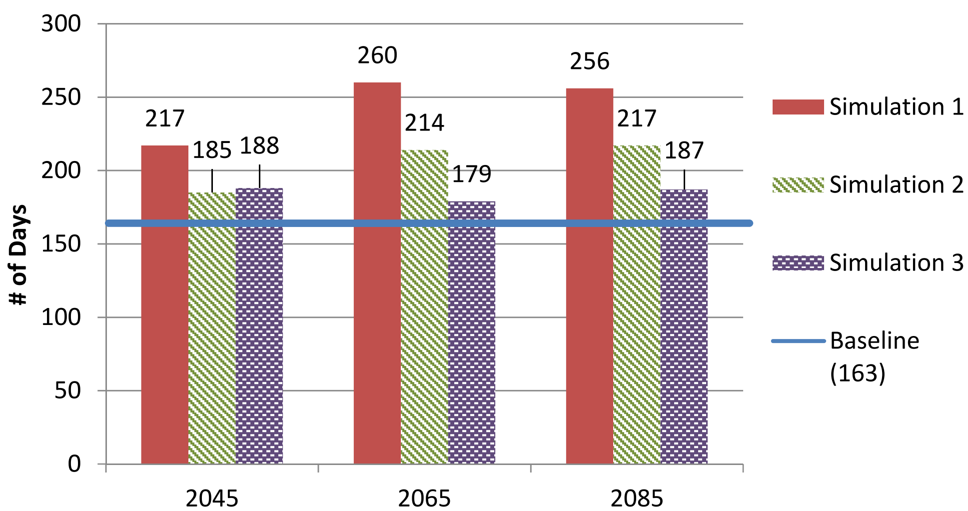
[41]The litter layer consists of organic materials such as needles, leaves, and twigs that lie on the ground and have not yet decomposed. The duff layer consists of moderate to highly decomposed litter and is situated between the litter layer and the soil surface. Table source: Liu et al., 2014.

[42] The simulated change in the annual average KBDI was used, as opposed to monthly average KBDI, to meet the needs of the economic analysis.

that in 2065 there is an increase of 15 days per year that fall within the moderate category compared to 1995 simulated conditions.

Consistent with Liu et al. (2014), ratings of moderate, high, or extreme fire potential were considered to represent the chance a fire could occur if there is a source of ignition.[43] A rating of low assumes there is little chance a fire would occur. KBDI based on daily observations from the US Global Historical Climatology Network (GHCN) Waterdale station[44] suggest about 163 days per year (or 44 percent of the days) currently are classified within moderate to extreme fire potential, suggesting a chance of wildfire. Using the three climate simulations identified in the precipitation events section, Figure 9 provides the number of days per year with a chance of wildfire. The values in parentheses provide the projected change compared to observations. All three simulations suggest an increase in days with a chance of wildfire.[45]

Figure 9: Projected Number of Days per Year with a Chance of Wildfire.



See Text Box on page 23 for a description of Simulations 1, 2, and 3.

[43] Liu et al., 2014.

[44] Station ID 058839. The station is located approximately 13 miles east of the study site, specifically at latitude at 40.4256° North and longitude at -105.2103° West (compared to the study location centered at: 40.41439° North and longitude of 105.25329° West).

[45] The climate ensemble for each scenario suggests an increasing threat of wildfire with future time, particularly notable for the high scenario (RCP8.5). However, as shown in Table 5, individual climate models may not follow the climate model consensus. A number of factors can play a role in whether the chance of wildfire could increase, including changes in the: frequency and intensity of daily precipitation, number of warm to hot days during dry periods, and annual precipitation. In general, wildfire threat increases under hotter and drier conditions; this is the case for the RCP8.5 scenario. However, for example, some climate models under the RCP4.5 scenario do not exhibit significant changes in either drying or warming over time. Therefore, although the models overall suggest an increase in wildfire for the area, specific models do not, which adds a degree of uncertainty with these projections.

Step 5. Assess Asset Performance under the Different Impact Scenarios

In the ADAP process shown in Figure 1, Step 5 is broken into Step 5A (assess performance highest impact scenario) and Step 5B (assess performance under all other scenarios). Similarly, Step 6 is also broken down into Step 6A (develop adaptation options for highest impact scenario) and Step 6B (develop adaptation options for other scenarios). The reason these steps are bifurcated is that it may be possible to streamline the analyses by first looking at the highest impact scenario. For example, if it is determined that the asset would not be damaged under the highest impact scenario, then there is no need to evaluate the asset performance for lower impact scenarios.

In the ADAP process, the highest impact scenarios is evaluated first in order to provide a sensitivity test of the asset performance at the worst combination of climate conditions. The sensitivity test determines if the asset requires adaptation to meet the highest impact scenario or, in the case that performance does not meet the highest impact scenario, if the relative cost of the adaptation for that scenario is significant. If the asset is capable of handling the highest projected impacts under climate change, then further analysis of lower impact climate scenarios is not necessary and the assessment is complete. Likewise, if the analysis shows an adaptation is warranted but its costs are determined to be minimal in Step 6A and if secondary considerations[46] allow, then that adaptation can be selected without further analysis. For example, if a design team were working on the replacement of a roadway cross culvert and determined that the standard culvert design called for a 24-inch pipe, whereas the highest impact scenario would require a 42-inch pipe, the insignificant relative cost difference between the two installations may dictate the selection of the larger pipe, without further analysis of lower impact scenarios. Under this example, the research team considers the increased pipe cost to be insignificant as the costs of performing a detailed engineering alternatives analysis followed by a Monte Carlo economic study would greatly exceed the pipe and installation costs. Conversely, in a case where the highest impact scenario is found to necessitate an expensive adaptation, the ADAP process recommends continued evaluation at lesser impact scenarios under Steps 5B and 6B. In the final economics analysis under Step 7, the highest impact design and the other design alternatives will be evaluated against each other and the best value option determined.

Figure 10 displays the different land cover and climate scenarios considered as part of this study. The non-highlighted paths were analyzed in Step 5A, including the highest impact scenario (level of projected extreme event precipitation depth: Climate Simulation 3 for the

[46] Secondary considerations would include environmental, operations and maintenance, regulatory, or other project considerations that are not necessarily accounted for in the capital cost of an adaptation option.

2085 time period with consideration of a wildfire occurrence), and the orange highlighted paths represent the potential conditions that were considered under Step 5B.

Although the work was conducted in the order of Steps 5A, 6A, 5B, 6B, in this write up, we combine 5A and 5B into a single Step 5; we took a similar approach for Step 6. This approach was taken for improved ease of reading.

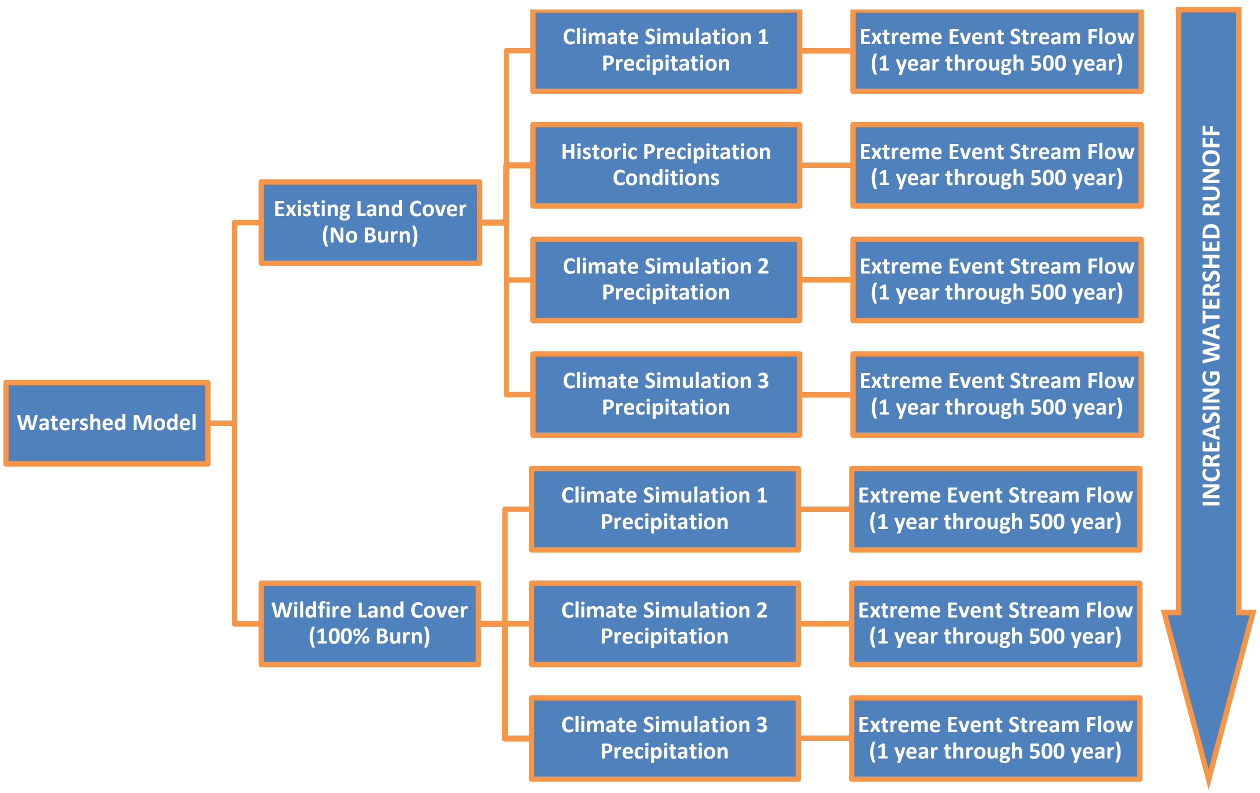


Figure 10: Watershed Land Cover and Precipitation Combinations Studied.

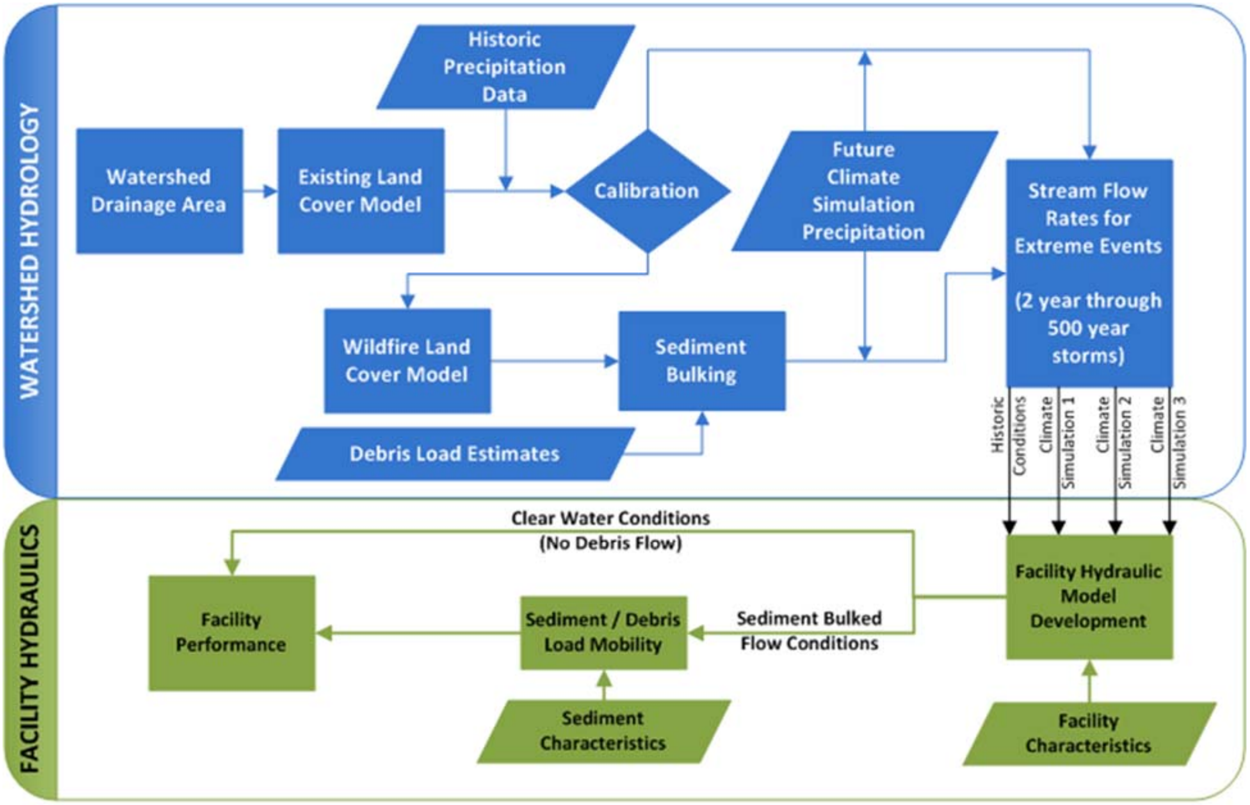


Figure 11: Hydrologic and Hydraulic Engineering Processes.

The general process tying together the engineering analyses performed in this step are presented in the flow chart in Figure 11. As shown in the figure, the engineering analyses for this case study are divided into two primary groups: those focused on watershed hydrology and those focused on facility hydraulics. The watershed hydrology analyses was performed first to determine the stream flow rates based upon watershed and precipitation characteristics. The research team then developed variants of the historical stream flow rates by incorporating wildfire burn effects on the watershed and projected precipitation amounts, described above. The stream flow rates from the watershed hydrology analyses were then utilized as an input in the facility hydraulics analyses. In these analyses, the research team modeled the performance of the culvert to determine if the design standard storm was met.

The remainder of this step is divided into two sections: one covering the watershed hydrology analyses and the other discussing the facility hydraulics analyses. Findings are presented at the end of this step.

Watershed Hydrology

The first phase of the engineering study involved watershed modeling by the research team to determine the stream flow rates at the US 34 crossing. The watershed modeling predicts stream flow rates based upon precipitation volumes, precipitation intensity versus time, watershed size and shape, and watershed land cover conditions. This general process is referred to as hydrologic modeling. Steps of the watershed hydrologic analysis are shown in the flow chart in Figure 12. The general process, as diagramed in the figure, starts with the development of a watershed model for existing land cover conditions using observed precipitation. The research team used this model as the starting point to allow model parameters to be calibrated against historic stream flow data for the site from other stream flow studies.

After calibration of the existing land cover watershed model, the analysis continued with the development of the wildfire land cover model. The wildfire land cover model was developed by the research team as a direct modification of the existing land cover model, where model inputs that represent land cover and stream flow conditions were manipulated by the researchers to represent wildfire burnout conditions. Next, future climate projections for extreme precipitation events (as determined in Step 4) were input into the hydrologic model to determine stream flows.

The remainder of this section walks through the various items in the watershed hydrology flow chart shown in Figure 12. Items covered include defining the watershed drainage area, development of the existing land cover watershed model, model calibration and comparison with other studies, the wildfire land cover watershed model, and incorporation of future precipitation with climate change into the modeling to produce future stream flow rates.

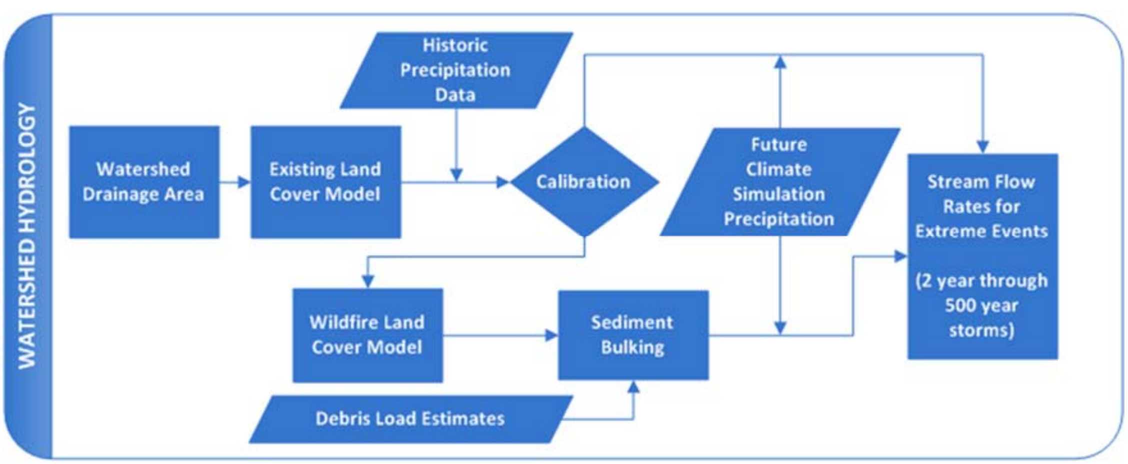


Figure 12: Hydrologic Engineering Process.

Watershed Drainage Area

The study area watershed boundary (see Figure 13), watercourse length,[47] and slope were each mapped out in a Geographic Information System (GIS) software. The watershed boundary was delineated using topography data from the United States Geological Survey (USGS) 10-meter resolution National Elevation Dataset (NED). The watershed delineation performed by the research team determined that the total drainage area contributing to the culvert is 1.59 square miles. The length of the longest watercourse is 2.7 miles with an average slope of 30%.

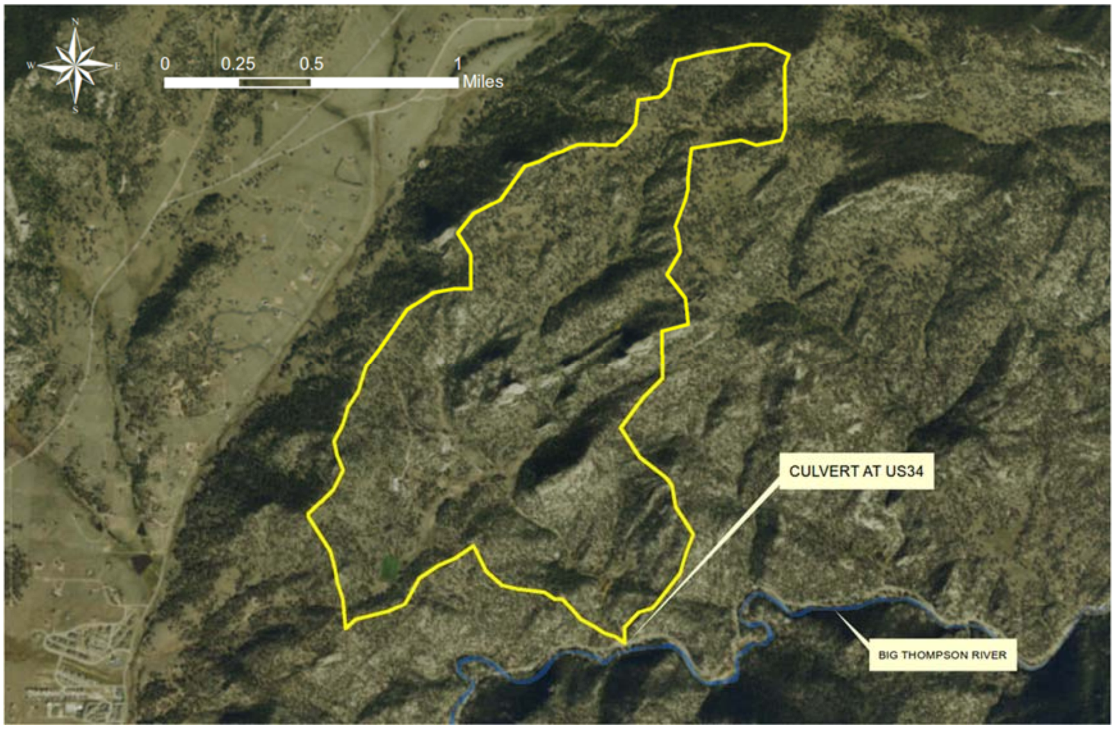


Figure 13: Watershed Delineation for the Study Culvert.[48]

Existing Land Cover Watershed Model

The existing land cover watershed model was developed by the research team to represent current watershed conditions for precipitation, vegetative conditions, soil conditions, and resultant stream flow. The watershed hydrologic modeling was conducted using the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS Version 4.1) computer program.

[47] Watercourse length is measured as the longest possible flow path within the watershed, from the most remote region to the outflow point.
[48] Image source: Google Earth (as modified).

The HMS model of the watershed, as developed by the research team, uses the Soil Conservation Service's (SCS)[49] curve number (CN) method[50] and Type II precipitation distribution.[51] In current practice, there are alternatives to the SCS Type II distribution that may provide improved precipitation distribution patterns for the US 34 corridor, most notably the NOAA Atlas 14 type curves, which NOAA developed from local rain gauge data. Cross-comparison of the SCS Type II curves against the local NOAA Atlas 14 curves has shown substantially higher peak flow rates for the models using the Type II data. These differences are due to a much sharper peak in the Type II curve as compared to the Atlas 14 curves for the US 34 corridor area. However, the Type II curves were utilized in this study as it is the standard method required by CDOT and the Colorado Water Conservation Board[52] for floodplain determinations and provides consistency with the work being performed by the US 34 Flood Recovery Design Team for analysis of the drainage systems. The future climate conditions were also modeled using the SCS Type II curves, due to the issues with statistically downscaled sub-24 hour data discussed in Step 4. In addition, the development of future precipitation distribution curves using projected climate data remains an area actively being researched.

The research team compiled the existing land cover watershed model using a combination of soil and land cover characteristics within the watershed. First, the research team processed soils data from the United States Department of Agriculture's (USDA) Natural Resources Conservation Service's (NRCS) Soil Survey Geographic Database (SSURGO).[53] The team processed the soils data to define soil plots within the watershed as representative Hydrologic Soils Groupings (HSG). HSGs for soils data group areas based on the ability of soil to infiltrate or runoff precipitation. HSG groups range from A to D, with A having the highest ability to infiltrate flows and D having the lowest infiltration rate and highest runoff rate. The HSG mapping in Figure 14 shows the watershed is comprised solely of B and D type soils. The relatively high percentage of D type soils indicates that the watershed will generally have low infiltration and higher runoff rates.

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[49] The SCS was renamed to the Natural Resources Conservation Service (NRCS) in 1994; however, methods developed prior to the name change are still colloquially referenced to the SCS.

[50] The SCS curve number method quantifies the loss of precipitation during the precipitation / runoff cycle to storage, infiltration, plant up-take, etc. The method utilizes a quantitative curve number to represent combinations of land cover and soil types with characteristic rates of loss of precipitation.

[51] The Type II precipitation distribution was developed by SCS in 1973 and published as part of SCS-TP-149. In this publication, the SCS defined several dimensionless precipitation temporal patterns, referred to as type curves. The type curves, in the standard set-up, show the incremental distribution of 24-hour precipitation at 15-minute time increments. The Type II curve is the curve that represents much of the midsection of the United States, including all of Colorado.

[52] Colorado Water Conservation Board, 2006.

[53] Natural Resources Conservation Service – Soils; Online Web Soil Survey. United States Department of Agriculture, available at: http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/geo/.

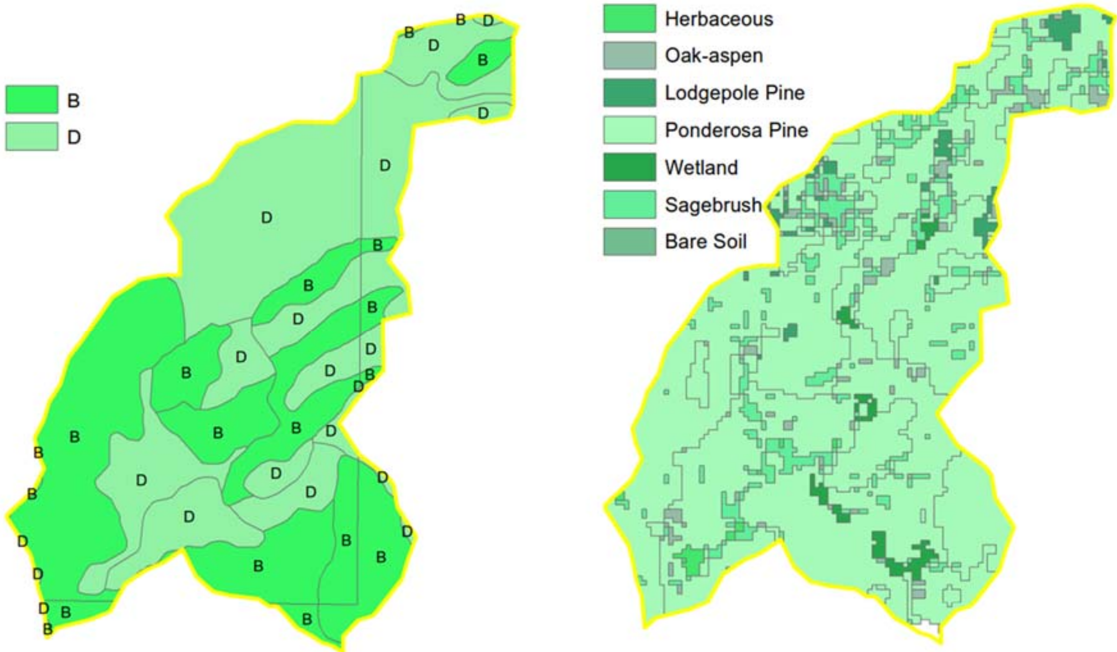

Figure 14: Watershed Hydrologic Soil Groups (left) and Land Cover (right).[54]

The team mapped the existing land cover for the watershed based upon data sets from the Colorado Wildfire Risk Assessment Portal (CO-WRAP).[55] As shown in Figure 14, the watershed studied is a largely undeveloped wooded watershed. The existing land cover consists of 84 percent Ponderosa Pine forest, eight percent sagebrush, three percent aspen forest, two percent of other pine species, two percent of wetland, and one percent of herbaceous vegetation (grasses) and bare soil.

Next, the HSG and land cover mapping was utilized in the SCS CN method to determine precipitation-dependent watershed runoff. Some soils are more absorbent than others are and the types of vegetative land cover can affect both the interception/capture of precipitation and how quickly precipitation runs off. The CN method combines soil type and land cover data into one common quantitative measurement. The CN method is a widely used hydrologic engineering approach that combines the basic precipitation runoff processes including soil infiltration, local ground depression storage, vegetative interception and uptake, transpiration,[56] evaporation, and overland runoff. The CN method was developed by the SCS based on empirical research on several small catchments.

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[54] HSG data source: NRCS; Vegetation cover data source: CO-WRAP.

[55] Colorado Wildfire Risk Assessment Portal, Program Documentation and Webserver. Colorado State Forest Service, available at: www.coloradowildfirerisk.com.

[56] Transpiration is the process of plant root uptake of water to the leaves and subsequent evaporation to the atmosphere.

Curve Numbers for wooded areas can vary based upon the condition of the vegetation in the wooded area. Commonly, CN development studies have classified these conditions as poor, fair, and good. The conditions are intended to be representative of the density of the tree stand within the woods and the condition of undergrowth. Areas with a mature dense tree stand, substantial understory shrub growth, and dense leaf litter will have the highest possible levels of precipitation canopy interception, transpiration, plant uptake, and ground interception, thus resulting in lower relative rates of overland runoff. These types of areas would be categorized as good condition wooded areas. Conversely, areas with lower density tree stands, bare soil, and heavily grazed understory, would have higher rates of overland runoff and be graded as poor condition woods. The wooded areas for the study watershed were determined to be in poor condition by the hydrologic studies performed by the US 34 Flood Recovery Design Team. The research team utilized the results from the Flood Recovery Team to provide consistency between this study and the design work being performed by CDOT.

CN values generally range between 30 and 100 with higher numbers correlating to higher rates of overland runoff. The CN assignment used for each unique set of soil and land cover combinations is shown in Table 7. In this study, the CN of the overall drainage basin was computed by the team as an area weighted value. The resultant overall CN for the existing land cover in the study watershed was calculated to be 82.

The timing of overland runoff within a watershed is another key factor in determining peak discharges at a watershed outlet point. The timing of flows is a function of watershed shape, slope, and flow resistance. Watersheds that have short and rounded shapes will have relatively shorter flow timing thus resulting in overland runoff from multiple areas concentrating at the same time and higher peak flows. By contrast, long skinny watersheds of the same general size will have lower peak flows as the longer flow path timing will cause the distribution of overland flow over a longer time period. The temporal distribution of flow for the study watershed was estimated using the basin lag time (T_{lag}), which is the time from the mid-point of a precipitation event to the mid-point of the corresponding runoff event. In this study, T_{lag} was computed using the NRCS watershed lag equation:

Equation 1

$$T_{lag} = \frac{l^{0.8}(S+1)^{0.7}}{1900Y^{0.5}}$$

Where, S (the maximum potential retention in inches) is:

Equation 2

$$S = \frac{1000}{CN} - 10$$

Table 7: CN Values Used in the Watershed Hydrologic Model.[57]

Land Cover	Cover Condition	Hydrologic Soils Group (HSG)			
		A	B	C	D
Agriculture Grassland Herbaceous	Poor	68	80	87	93
	Fair	49	71	81	89
	Good	39	62	74	85
Aspen Oak Shrubland Oak-aspen	Poor	48	66	74	79
	Fair	35	48	57	63
	Good	30	30	41	48
Mixed Conifer Piñon-Juniper Ponderosa Pine Spruce-Fir Lodgepole Pine	Poor	45	75	85	89
	Fair	36	58	73	80
	Good	30	41	61	71
Shrubland Sagebrush	Poor	48	67	80	85
	Fair	35	51	63	70
	Good	30	35	47	55
Urban Bare soil	n/a	77	86	91	94
Open Water Riparian Wetland	n/a	98	98	98	98

In the above equations, l is the length of the longest watercourse in feet and Y is the average watershed land slope (in percent). The longest watercourse length (14,259 ft.) and average land slope (30 percent) were calculated using the USGS 10-meter elevation data set from the NED. The resultant lag time for the watershed, under current land cover conditions, was computed to be 34 minutes. The resultant lag time was inputted into the HEC-HMS watershed model.

The model specifications discussed above were input into HEC-HMS and the model was run using the NOAA Atlas 14 precipitation estimates based on historical observations. The results of the HEC-HMS watershed hydrologic modeling with existing (no wildfire) land cover conditions are presented in Table 8.

[57] As modified from Table 1 from Yochum, S., 2012. The *source* table was modified by the research team to include cross-references to equivalent land cover designations from the study area data set.

Table 8: Summary of Peak Stream Flows with NOAA Atlas 14 Precipitation and Existing Land Cover.

Return Period (yr.)	Precipitation (NOAA Atlas 14) Inches	Existing Land cover Streamflow Cubic feet per second (cfs)
2	1.62	205
5	2.00	347
10	2.41	519
25	3.11	838
50	3.75	1,150
100	4.49	1,529
500	6.63	2,662

Calibration & Comparison with Other Studies

To calibrate the hydrologic model, the research team compared the results of the HEC-HMS model run using historical precipitation and existing land cover with the modeling efforts undertaken by others. During the calibration process, particular weight was given to the work being performed by US 34 Flood Recovery Team, to provide consistency between this study and the design work being performed on behalf of CDOT.

The calibration process, as performed by the research team, directly compared stream flow discharges for each return period (those shown in Table 8) with the corresponding stream flow rates from alternate sources. The model prepared by the research team was calibrated through adjustments to the watershed cover condition (good versus poor) and the precipitation type curves (SCS Type II versus NOAA Atlas 14) to produce stream flow discharges in line with the appropriate comparison data.

The research team identified three sources of return period based stream flow data for calibration in the development of this study: the Federal Emergency Management Agency (FEMA) Flood Insurance Study (FIS), the US 34 Flood Recovery Program study, and the Colorado regional regression results. No stream flow gauging of the stream had been undertaken by the USGS.

FEMA Flood Insurance Study

The FIS of Larimer County, developed by FEMA, documented the peak flow at the culvert.[58] At 1.63 square miles, the drainage area delineated by the FEMA study is slightly larger than that developed for this study. FEMA peak flows documented in the study are 750, 1,250, 1,650, and

[58] FEMA, 2013.

2,400 cubic feet per second for the 10-year, 50-year, 100-year, and 500-year return periods, respectively. These peak flows were used in the validation of the research team's watershed hydrologic model results, and they match the HEC-HMS modeling results well.

US 34 Flood Recovery Program/CDOT

The US 34 Flood Recovery Team, on behalf of CDOT, prepared a detailed model of Big Thompson River, including several tributaries. The Flood Recovery Team prepared these studies for use in the design of permanent replacement facilities along US 34. The permanent facilities are being designed to replace the temporary facilities constructed in the immediate aftermath of the September 2013 flood event that damaged significant portions of US 34.

The Flood Recovery Team model for the study area is an HEC-HMS watershed model. Peak discharges from the US 34 Flood Recovery Project documented stream flow discharges of 491, 821, and 1,550 cubic feet per second for the 10-year, 50-year, and 100-year return periods, respectively for the study site. [59]

USGS Regional Regression

The regional USGS regression equations for peak flows were the final data source checked by the research team during the validation process and rendered different results. Different regression equations have been specified for different regions of the country. Based on the development mapping for the regional regression equations, the study watershed was mapped as having 95 percent of the drainage area in the Mountain Region and five percent in the Plains Region, thus the area-averaged method was used to calculate the peak flows. Figure 15 shows the boundaries of the Mountain and Plain Regions within Colorado and identifies the project site location. Use of the USGS regression equations gave very low peak flow rates (46.9 cubic feet per second for the 100-year event and 70.1 cubic feet per second for the 500-year event) as compared to the other methods consulted. The research team investigated sole use of both the Mountain Region and Plains Region equations, but did not observe a significantly improved correlation with other available data sets. The US 34 Flood Recovery Team also noted a large deviation between the local regression equations and gauge data along Big Thompson River, from which their models were calibrated. Based on the inconsistency and very low discharges from the USGS equations, the team did not utilize the regional regression equations in the model calibration/validation process for this study.

[59] Jacobs et al., 2014.

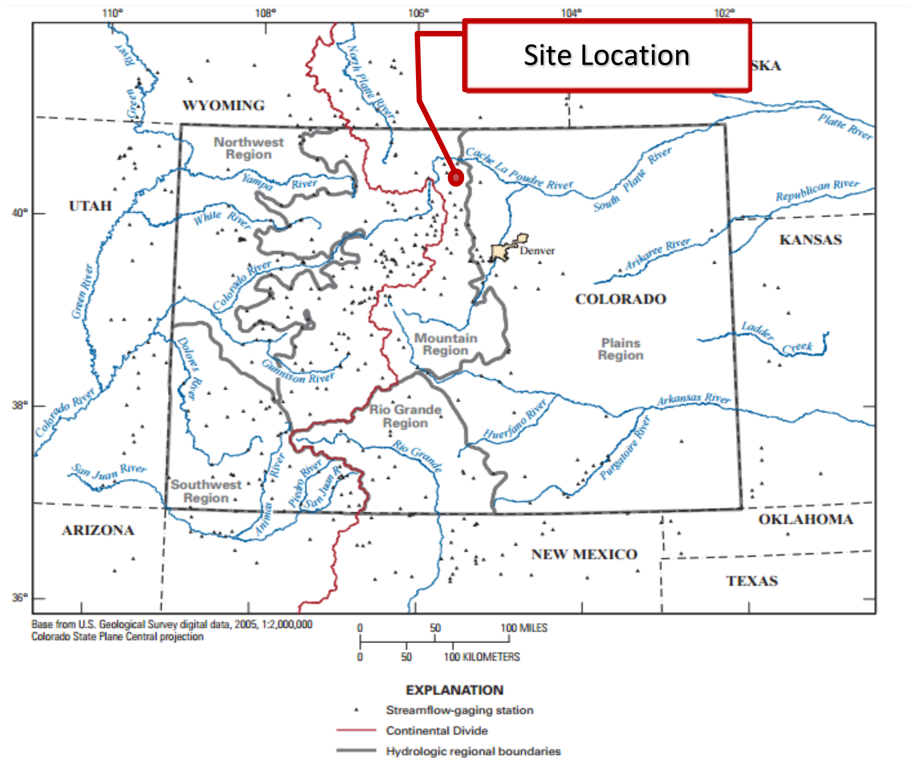

Figure 15: Boundaries of Hydrologic Regions and Locations of Streamflow Gaging Stations in Colorado.[60]

Wildfire Land Cover Watershed Model

Wildfire occurrence in a watershed has been shown to increase both flooding and debris flows in the immediate aftermath of a fire. Increases in flooding are caused by loss of vegetative canopy, loss of leaf litter ground cover/surface storage, and the resistance of burned soils from infiltrating water (hydrophobicity). Hydrophobicity, the soil burn effect, has been shown to persist for at least 22 months[61] in ponderosa and lodgepole pine forests of the Colorado Front Range causing a prolonged risk of increased flooding for years after a fire event. Beyond the impact on soils, the recovery of vegetation and tree stands within the wildfire burn zone is highly variable and largely dependent on the severity of burn to the tree stands. Forests comprised of coniferous trees have a more limited ability to regenerate after fires, however, the trees also have a greater ability to survive fires.[62] Regeneration of forest stands has been shown to take from three to five years for aspen and up to 100-years for piñon pine-juniper forests with severe fire damage. Prior studies have generally assumed that the increased runoff risk in wildfire burn watersheds will be substantial for at least five years. After the initial five-year period, the vegetative cover in the watershed will begin regenerating and the increased

[60] Capesius and Stephens, 2009 (Adapted to show site location).
[61] Huffman et al., 2001.
[62] Moench, 2007.

runoff risk will gradually lessen. The flooding response in the immediate aftermath of wildfires has been measured to magnify the hydrologic process such that a 10-year precipitation could produce a 50-year to 200-year flooding event.[63,64]

The research team incorporated the impacts and increased flooding risk into the study by developing a variant of the existing land cover watershed model. The primary basis for modeling of wildfire effects on the watershed is the process documented in the USDA report on the High Park fire,[65] which provides pre- and post-fire calibrated modeling results. The High Park fire study also utilized HEC-HMS and the CN methodology for prediction of pre- and post-fire runoff conditions. The study noted that soil burn severity is the principle driver for the increasing flow in post-fire runoff predictions.

In this case study, the research team felt it was appropriate to assume a complete burn of the watershed because of its small size (1.59 square miles). The assumption of complete watershed burn is not appropriate for studies of larger watersheds, such as, for example, that of the Big Thompson River. In these cases, the use of wildfire burn models and multiple watershed burn pattern scenarios may be necessary to reasonably reflect the impacts of wildfire burn areas that are only a portion of the study area watershed.

Soil burn severity is measured and mapped in the aftermath of a fire. The common method for mapping the soil burn severity is the Burned Area Reflectance Classification (BARC) which utilizes reflectance data from satellite imagery for aerial mapping. Soil burn severity is scored on a scale of zero to four, with zero indicating a no burn condition, one a low soil burn, and four a high soil burn condition. The research team did not find any literature with methods for predicting soil burn severity in advance of a wildfire. However, CO-WRAP produces data sets on wildfire intensity which CO-WRAP staff and the research team postulated would provide a reasonable predictor of soil burn severity. The wildfire intensity mapping produced by CO-WRAP is scored on a scale of zero to five, with zero indicating a non-burnable condition and five as the highest intensity.

The research team performed a test on the theory that CO-WRAP wildfire intensity was a reasonable predictor of soil burn severity and to develop a correlation between the zero to four soil burn severity scale and the zero to five wildfire intensity scale. The test was performed using the High Park Fire soil burn severity mapping compiled by the USDA and the pre-fire wildfire intensity mapping for the High Park area produced by CO-WRAP. Figure 16 shows the wildfire intensity mapping for the High Park area and Figure 17 shows the soil burn severity as

[63] Condera et al., 2003.
[64] Yochum, 2012.
[65] Yochum, 2012.

mapped by the USDA. Note that Figure 17 has several parallel lines across the data set that represent data gaps that occurred during splicing and processing of the satellite imagery.

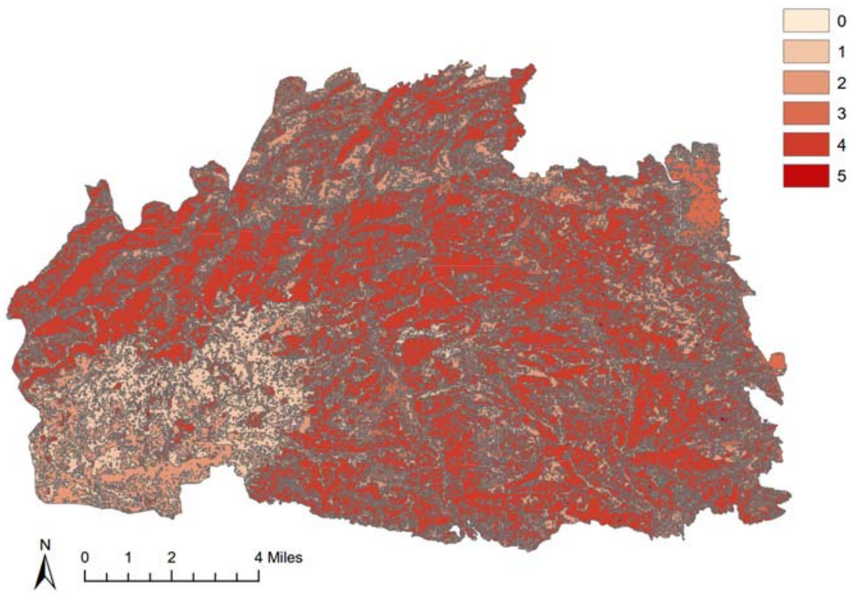

Figure 16: CO-WRAP Wildfire Intensity Mapping for the High Park Area (Pre-Fire Conditions).

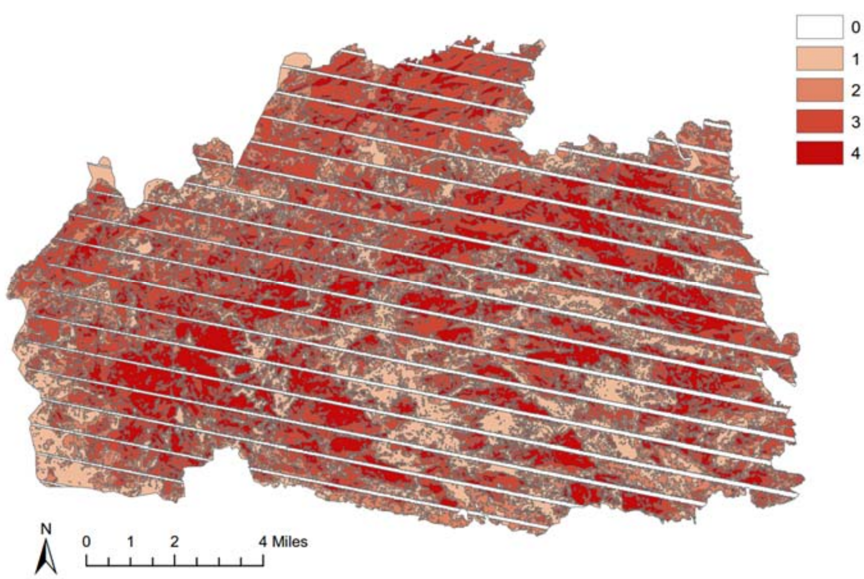

Figure 17: Soil Burn Severity from the High Park Fire Mapped using the BARC Process.

The research team compiled a cross-correlation of the soil burn severity and wildfire intensity mapping for quantitative testing of the data agreement. The data sets were area weighted to allow for larger mapping areas in agreement to have a greater influence on the cross-correlation. The resultant relationships from the cross-correlation are presented in Table 9. This table provides the resultant conversions for the wildfire intensity zero to five scale over to the soil burn severity zero to four scale. Using the conversions documented in Table 9, the cross-correlation was back-checked by the research team by statistically comparing the mapped soil burn severity for the High Park Fire with the predicted soil burn severity. The predicted soil burn severity was determined using the CO-WRAP wildfire intensity mapping, presented in Figure 16, and the conversions presented in Table 9. Figure 18 is a plot of the area weighted mapped soil burn severity versus the area weighted predicted soil burn severity for the High Park Fire area. The plot includes a 45-degree line, which would indicate the perfect fit trend between the data sets. While the data sets do not sit on the 45-degree line, there is a reasonable degree of agreement and a resultant R-squared[66] value of 0.87.

[66] R-squared is a statistical measure of the goodness of fit of the regression line around the data points. Its value ranges from zero to one with zero indicating random data with no fit and one indicating a perfect fit (i.e. all points falling on the line).

Table 9: Conversion table for CO-WRAP Fire Intensity to Soil Burn Severity.

CO-WRAP Fire Intensity and Soil Burn Severity Conversions						
Fire Intensity CO-WRAP	0	1	2	3	4	5
Soil Burn Severity High Park	1	2	2	3	3	4

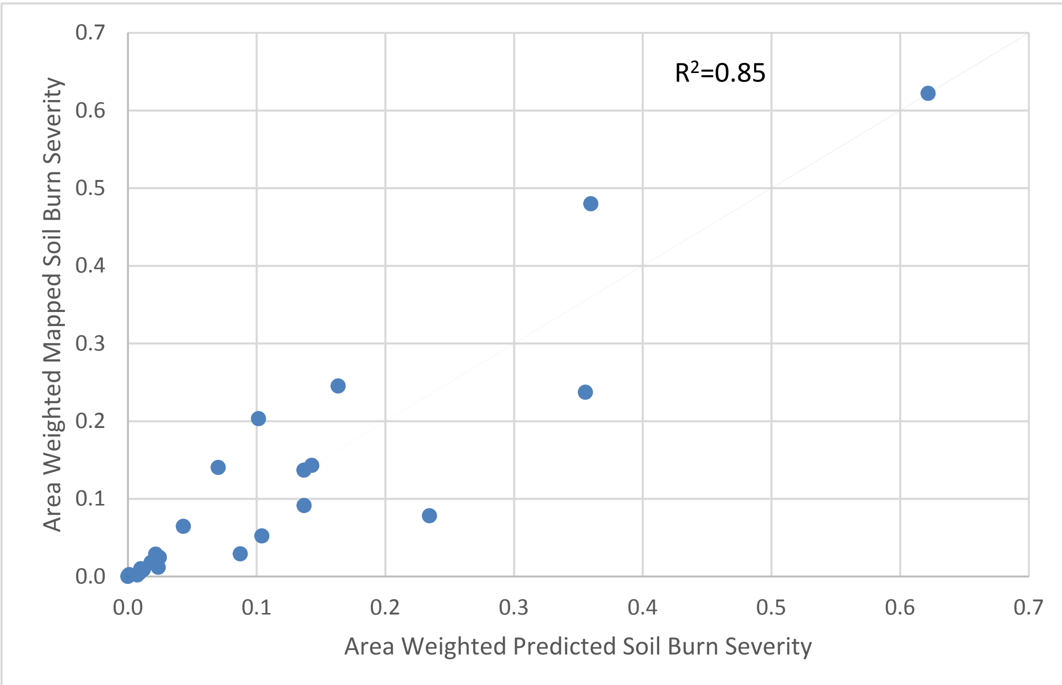

Figure 18: Correlation between Predicted Soil Burn Severity and Mapped Soil Burn Severity Using Area Weighting for the High Park Fire Area.

Considering the statistical agreement of the data sets, a visual comparison of the mapping presented in Figure 16 and Figure 17 shows several notable discrepancies between the data sets. These discrepancies can be noted in the southwestern corner of the map where the CO-WRAP data predict only low levels of fire intensity while the BARC analysis mapped several areas with the highest level of soil burn. Conversely, several areas towards the center of the site were predicted for higher wildfire intensities but mapped with low soil burn severity. There are many potential causes for these discrepancies that would not be captured by this comparative test, including initial soil moisture content, groundwater levels, and sand and gravel content of the soils. The research team recommends that continued research be performed on the correlation of these data sets; however, given the reasonable correlation determined by the statistical analysis, the research team decided that the CO-WRAP wildfire intensity values could serve as a good proxy for soil burn severity.

Next, CO-WRAP fire intensity data were downloaded for the watershed (see Figure 20). Then, using the CO-WRAP data and the conversions in Table 9, the soil burn severity was projected for the study watershed: the result is shown on the map on the right in Figure 20. The conversion was performed across the entire watershed because, as previously noted, this study assumes that 100 percent of the watershed will burn during a single large wildfire event. The research team determined the assumption to be reasonable due to the small size of the subject watershed (1.59 square miles) compared to the size of large Colorado wildfires (since 1999, the Intra-Mountain West has had fifty-seven significant wildfires greater than 100,000 acres [156 square miles] in size[67]). Based on the mapping conversion, less than one percent of the drainage area is projected to have a soil burn severity of four, 83 percent a burn severity of three, 17 percent a severity of two, and less than one percent is projected to have a burn severity of one.

Figure 19: Wildfire burn of a lodgepole / ponderosa pine forest, John Day, OR; August 2015 (Left) and post-wildfire condition of a lodgepole / ponderosa pine forest, John Day, OR (Right). Photographs provided courtesy of the US Forest Service.

Once the soil burn severity was mapped for the study site, new hydrologic inputs for the HEC-HMS watershed model were developed. The most substantial impact of wildfire on the watershed hydrologic process occurs in the ability of flows to infiltrate in the soils or runoff (if they are unable to infiltrate), which in this process is defined by the CN. The NRCS documented relationships between CN, soil burn severity, pre-fire land cover, and HSGs in studies of the

[67] The National Interagency Fire Center database is available at: www.nifc.gov/fireinfo/.

North Fork Fire (2012)[68] and the High Park Fire[69]. The CNs determined from the NRCS studies are presented in Table 10. The table contains four soil burn severity categories and seven vegetation cover categories. The calculated soil burn severity data shown in Figure 20 and the HSGs and land cover from Figure 14 were cross-referenced to map the corresponding CN values for the watershed based on the table. Compiling this information geographically, the wildfire burn projection for the study watershed resulted in an ultimate curve number of 93 compared with only 82 for the non-fire condition. The noted increase in the watershed curve number will result in a substantial increase in overland runoff/stream flow, as significantly less precipitation is infiltrated and intercepted by vegetation.

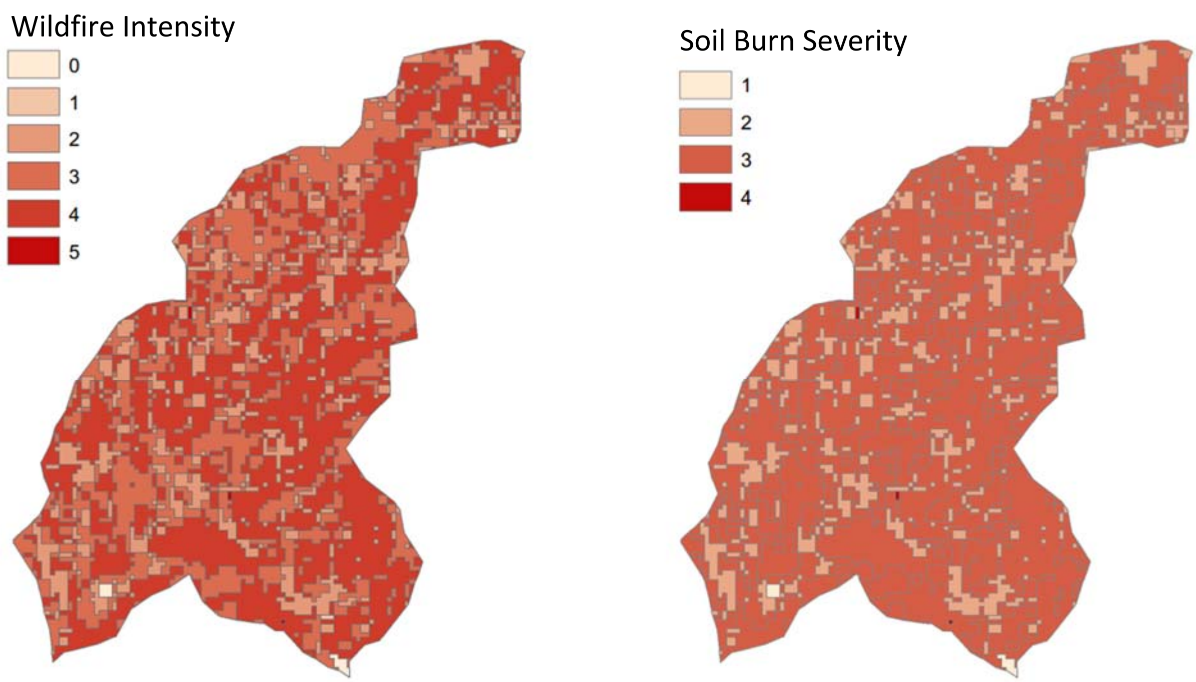

Figure 20: US 34 Study Site Wildfire Intensity from CO-WRAP (left) and Projected Soil Burn Severity (right).

The lag time used in the hydrologic modeling process is also impacted by the wildfire burnout of the watershed. The acceleration of flow timing within a burned watershed can be attributed to the loss of vegetative resistance, which slows runoff. Vegetation slows flows via several mechanisms along the flow path including canopy interception of precipitation, surface roughness of herbaceous and shrub plants slowing sheet flow and shallow concentrated flows, and riparian buffer woody vegetation providing frictional resistance to in-stream flows. These

[68] Unpublished study, referenced by Yochum, 2012.
[69] Yochum, 2012.

effects are captured in the NRCS lag equation through the use of the watershed CN as shown in Equation 1. While the watershed slope and longest flow path are not impacted by the watershed burn, substitution of the burned watershed CN of 93 into the S factor for lag equation reduces the watershed timing to 22 minutes from the pre-fire timing of 34 minutes.

Table 10: Curve Numbers for Wildfire Burn Conditions by Soil Burn Severity, HSG, and Land Cover.[70]

Cover	Condition	A				B				C				D			
		Unburned	Low	Moderate	High	Unburned	Low	Moderate	High	Unburned	Low	Moderate	High	Unburned	Low	Moderate	High
Herbaceous	Poor	68	72	75	80	80	85	87	89	87	88	90	92	93	93	95	98
	Fair	49	55	67	77	71	75	80	86	81	85	88	89	89	90	90	95
	Good	39	50	65	75	62	70	75	85	74	80	81	88	85	88	89	90
Oak-aspen	Poor	48	60	72	80	66	70	75	87	74	80	85	92	79	85	90	95
	Fair	35	45	65	77	48	55	65	86	57	75	75	89	63	70	80	92
	Good	30	40	60	75	30	35	50	85	41	60	65	88	48	55	70	92
Ponderosa Pine	Poor	45	60	72	80	75	80	84	87	85	90	91	92	89	90	92	95
	Fair	36	45	65	77	58	65	75	86	73	80	80	89	80	85	90	92
	Good	30	40	60	75	41	50	60	85	61	65	75	88	71	75	80	92
Sagebrush	Poor	48	60	72	80	67	70	80	87	80	85	90	92	85	90	92	95
	Fair	35	45	65	77	51	60	75	86	63	70	75	89	70	75	85	92
	Good	30	40	60	75	35	40	60	85	47	55	65	88	55	60	70	92
Lodgepole Pine	Poor	45	60	72	80	66	70	75	87	77	83	85	92	83	90	92	95
	Fair	36	45	65	77	60	65	70	86	73	80	80	89	79	85	85	92
	Good	30	40	60	75	55	60	65	85	70	75	75	88	77	80	80	92
Bare Soil	n/a	77	77	77	77	86	86	86	86	91	91	91	91	94	94	94	94
Wetland	n/a	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98

Sediment Bulking

In addition to the direct runoff impacts of peak flows under wildfire burnout conditions, stream flow dynamics are substantially influenced by debris flow contributions to the system. Debris flows in the post-wildfire conditions are hyper-concentrated flows of both alluvial sediments and burned-out woody debris. The concentration of debris in the post-fire flow presents two challenges to stream performance: (1) sediment bulking of peak flows and (2) sediment deposition/channel bed aggradation. The effects of sediment deposition/channel bed aggradation impact the hydraulic performance of the channel and are discussed in the hydraulics section of this study.

[70] Yochum, 2012.

Sediment bulking is the increasing of peak discharges in the channel due to the mixture of both water flow and sediment flow. The watershed hydrologic modeling performed in HEC-HMS only predicts the water flow component of stream flows. Under most conditions, the sediment concentration within stream flows is small enough that the bulking effect on peak flow rates is negligible. However, in post-wildfire watersheds, the sediment concentration is so substantially increased that the bulking effect should be accounted for. As a result, peak discharge results from the HEC-HMS model are amplified to account for the bulking effect caused by sediment.

Figure 21: Debris flows in a post-wildfire river system, John Day, OR; (Left). Sediment deposition / aggradation in a post-wildfire stream, John Day, OR; (Right). Photographs provided courtesy of the US Forest Service.

The increase of the discharge depends on the volume of sediment material that may be discharged from the drainage basin for a given precipitation event. The research team utilized a sediment estimation model for the western United States provided by Cannon and DeGraff.[71] This model states that the sediment volume is a function of drainage basin properties and precipitation depth. Sediment volume (V) is calculated (in cubic meters) according to the following equation:

Equation 3

$$V = e^{(7+0.6(lnA_{30})-0.6(B_{H+M})0.5+0.2D^{0.5}+0.3)}$$

[71] Cannon, and DeGraff, 2008.

Where,

- A_{30} is the area of the basin (in square kilometers) with slopes greater than or equal to 30 percent (0.5 square miles in this case),
- B_{H+M} is the area (in square kilometers) of the basin burned at high and moderate severity (projected to be 1.32 square miles in this case), and
- D is the total precipitation depth (in millimeters).

Modeled sediment volumes as a function of precipitation depth are plotted in Figure 22. The data points in the figure are the NOAA Atlas 14 precipitation depths of the return periods from the two-year to 500-year and all the climate change projected depths discussed in Step 4.

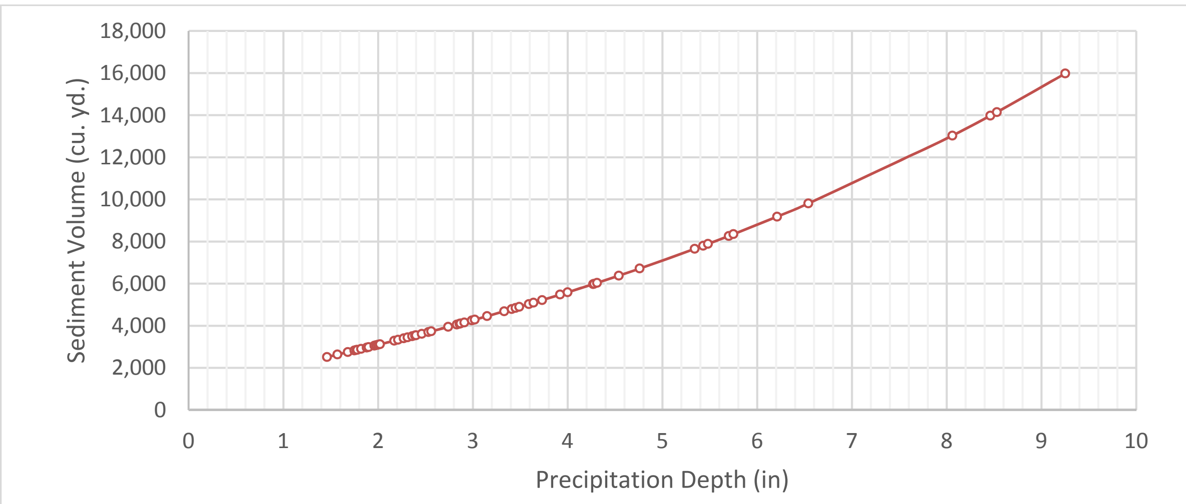

Figure 22: Sediment Volume Versus Precipitation Depth at the Study Site.

Peak discharges of sediment laden flow were calculated by distributing the sediment/debris volume to the clear-water stream flow (i.e. without sediment load) hydrograph[72] to derive bulking factors for various flow rates. Bulking factors are ratios of sediment bulked flows versus pure water flows (clear-water flows). The equations for the bulking factor (BF) and total sediment bulked flow rate (Q_{total}) are as follows:

Equation 4

$$BF = \frac{Q_w + Q_s}{Q_w}$$

[72] A hydrograph is a graphical depiction of flow versus time at a specific point of interest (in this case, the inlet of the culvert).

Equation 5

$$Q_{total} = BF \times Q_w$$

Where,

- Q_s is the sediment flow rate (in cubic feet per second) and
- Q_w is the water flow rate (in cubic feet per second).

Q_s was computed by distributing the sediment volume (as computed with Equation 3) based on the runoff hydrograph distribution. Figure 23 illustrates the outputs of the bulking factor equation. It was created from 56 runoff hydrographs modeled with HEC-HMS covering the full range of precipitation events considered in this study (see the following section on incorporation of the projected precipitation for how these flows were derived).

Combining the results of the sediment load and bulking factor calculations, the sediment load as a function of total discharge (bulked peak discharges) is shown in Figure 24. The total discharge for Figure 24 was computed based upon the peak flow rates from the HEC-HMS modeling (Q_w), the bulking factors shown in Figure 23, and Equation 5.

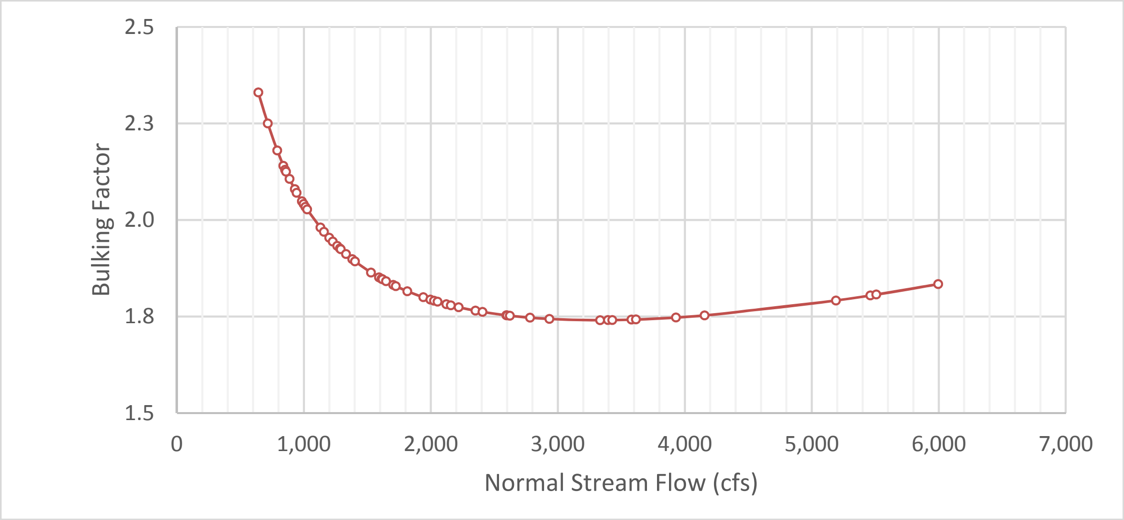

Figure 23: Bulking Factor versus Clear-water (Non-Sediment) Stream Flow at the Study Site.

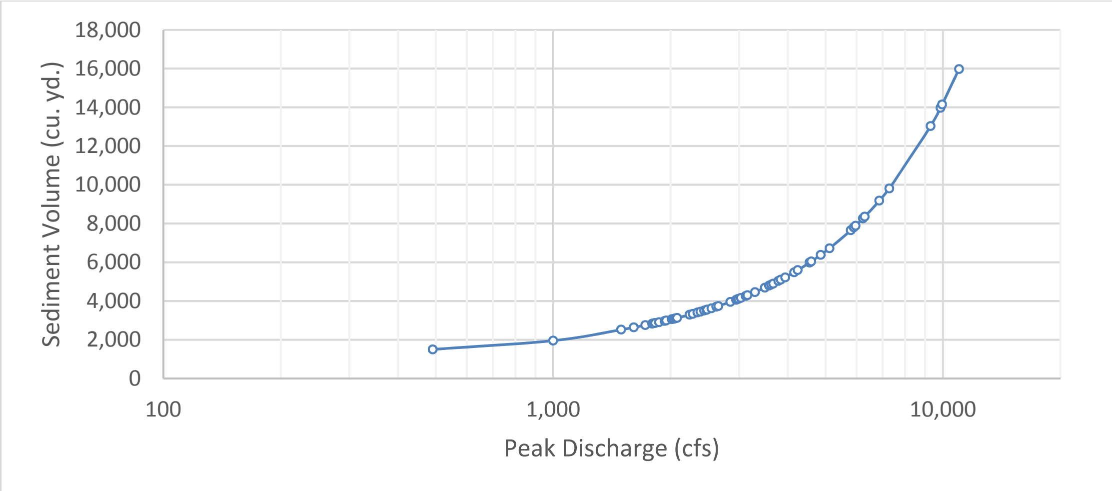

Figure 24: Estimated Sediment Volume as a Function of Peak Discharges.

Incorporation of Projected Precipitation

Inclusion of the future precipitation into this study involved substitution of the NOAA Atlas 14 precipitation depths with the projected precipitation depths into the model. While the precipitation distribution of storm events at the sub-24 hour level are generally expected to change into the future (the southwestern United States is expected to have shorter, more intense rainfalls), there is lower confidence in using climate model projections of sub-24 hour scale precipitation for statistical frequency analysis of extreme precipitation events, particularly when the analysis has its own degree of inherent uncertainties. As noted above, this limitation includes attempting to produce projected precipitation distributions for use with the 24-hour precipitation depths from the climate models. As such, the research team in this study continued to utilize the SCS Type II precipitation distribution for all future storm events.

Using the procedures discussed previously, peak discharges for the existing land cover conditions and wildfire burn conditions were determined for projected precipitation scenarios. The results are presented in Table 11 and results for the highest impact scenario are plotted in Figure 25.

Table 11: Summary of Projected Stream Flows for each future Climate Simulation and wildfire condition.[73]

Return Period (yr)	Land Cover Condition						
	Existing Land Cover				Wildfire Burn with Sediment Bulking		
	Precipitation Scenario						
	Historic (NOAA Atlas 14) (cfs)	Climate Simulation 1 (cfs)	Climate Simulation 2 (cfs)	Climate Simulation 3 (cfs)	Climate Simulation 1 (cfs)	Climate Simulation 2 (cfs)	Climate Simulation 3 (cfs)
	Current Year	**Year of Future Condition: 2045**					
2	205	152	188	226	1494	1,610	1,724
5	347	263	278	355	1826	1,868	2,079
10	519	339	417	571	2037	2,238	2,623
25	838*	433	707	1,002	2,281	2,946	3,626
50	1,150	514	1,021	1,436	2,483	3,670	4,594
100	1,529	585	1,415	1,975	2,655	4,548	5,801
500	2,662	744	2,614	3,682	3,033	7,283	9,954
	Current Year	**Year of Future Condition: 2065**					
2	205	152	252	308	1,494	1,795	1,951
5	347	300	339	497	1,932	2,037	2,441
10	519	459	510	726	2,345	2,473	2,990
25	838*	666	943*	1,140	2,849	3,493	3,938
50	1,150	857	1,420	1,555	3,295	4,560*	4,859
100	1,529	1,070	2,022	2,049	3,781	5,909	5,970
500	2,662	1,669	3,430	4,096	5,115	9,296	10,995
	Current Year	**Year of Future Condition: 2085**					
2	205	188	259	339	1,610	1,816	2,037
5	347	332	347	540	2,016	2,058	2548
10	519	476	497	782	2,387	2,441	3,120
25	838*	721*	796	1,236*	2,979*	3,153	4,151
50	1,150	982	1,095	1,669	3,582	3,837	5,115*
100	1,529	1,277	1,436	2,165	4,241	4,594	6,237
500	2,662	2,192	2,437	3,645	6,298	6,867	9,855

[73] * denotes discharge that meets the overtopping storm design standard (25-year or 50-year) for each land cover and climate simulation. A single value for each land cover and climate simulation combination is flagged, representing the maximum value for each combination.

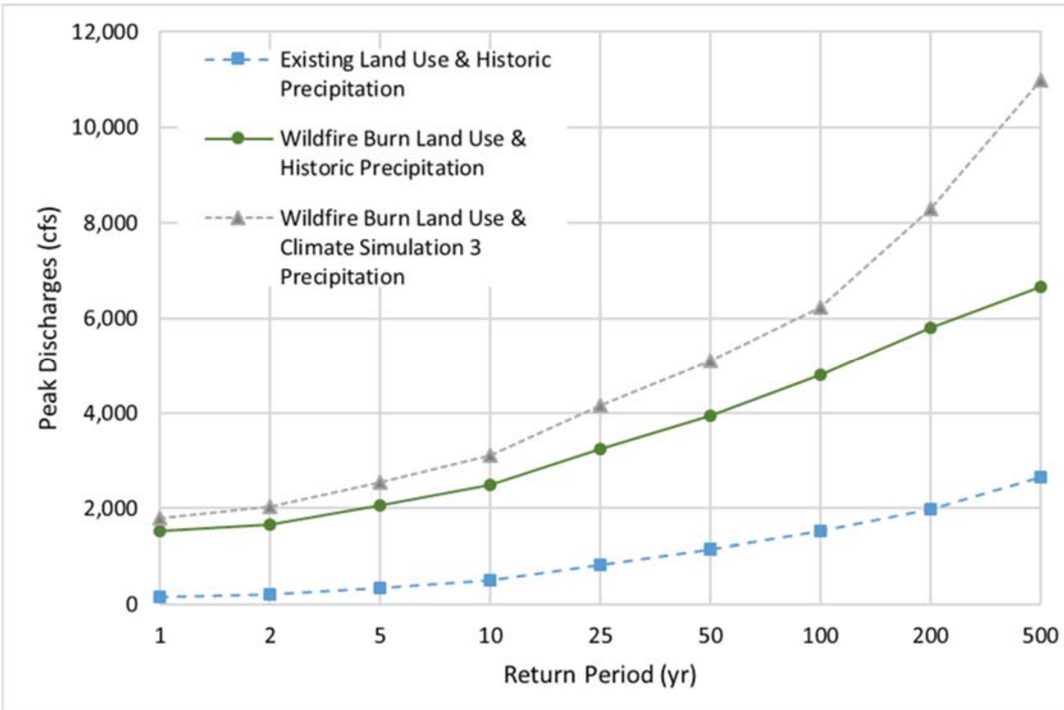

Figure 25: Peak Discharges under the highest impact scenario.

Facility Hydraulics

Once flow rates for the stream system tributary to the US 34 culvert were determined through the watershed hydrology process, the hydraulic performance of the culvert was assessed against CDOT hydraulic structure design standards. Figure 26 depicts the general engineering process that was utilized by the research team for the facility hydraulics study. The process uses the stream flow rate outputs from the watershed hydrology study to determine the performance of the US 34 culvert facility while also incorporating the system performance under wildfire/debris flow conditions.

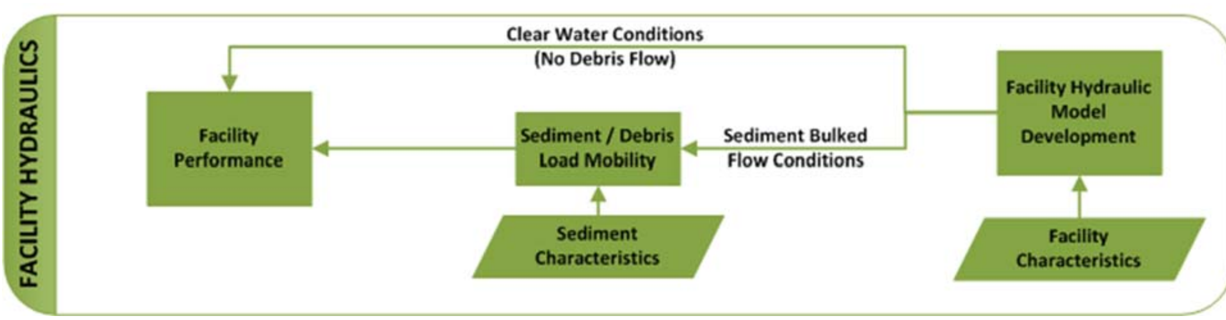

Figure 26: Hydraulic Engineering Process.

The hydraulics evaluation started with the development of a standard riverine hydraulics model for determining system performance under clear water conditions. Clear water conditions for the purpose of this study are considered typical stream flow conditions without enhanced sediment loading from wildfire burn. These conditions may include natural levels of suspended sediment[74] and bed load sediment[75] transport, but do not include debris flow transport typical of wildfire burned watersheds. Clear water conditions are the standard condition for evaluation of hydraulic structure crossings. In order to evaluate the impacts of wildfire debris loading on the performance of the facility, the research team included a step in the process to evaluate the mobility of debris sediments at the facility. The sediment/debris load mobility step was applied by the research team to evaluate the characteristics of the sediment and determine the ability of the stream channel and the culvert to move sediment. The combined results of the clear water and sediment/debris load mobility evaluations were utilized by the research team to provide a comprehensive evaluation of facility performance. The remainder of the hydraulic modeling section discusses the development of the hydraulic model and calculation of sediment/debris flow mobility factors.

Facility Hydraulic Model Development

The USACE Hydrologic Engineering Center River Analysis System (HEC-RAS) Version 4.1 was used to model the hydraulic performance of the structure. The use of HEC-RAS for modeling of riverine conditions is a standard practice for hydraulic engineers in the development of designs for highway bridge and culvert crossings. The model is also the standard method for floodplain modeling and mapping performed by FEMA. However, in the case of hyper-concentrated sediment flows, such as post-fire debris flows, the use of HEC-RAS needs to be carefully considered.[76] The basic mechanics behind the computations in HEC-RAS assume that the flowing fluids are acting as Newtonian fluids.[77] A debris flow may not necessarily act following the properties of a Newtonian fluid, depending on the level of sediment concentration. In practice, it is accepted that flows with bulking factors up to two can be modeled as Newtonian flows in HEC-RAS. Since the majority of the flow events documented under this study have a bulking factor of less than two,[78] the use of HEC-RAS was deemed acceptable for this study. Application of other models, such as FLO-2D, that have specific debris flow capabilities should be considered in other applications with hyper-concentrated debris flows that exceed a bulking factor of two.

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[74] Suspended sediment is commonly comprised of clay, silt and sand materials that are well mixed throughout the depth of stream flow and are held entrained by turbulence.

[75] Bed load sediment is commonly comprised of coarse sand, gravel, and cobble materials that are concentrated near the streambed and are transported by flow stresses at the channel bed.

[76] West Consultants, Inc., 2011.

[77] A Newtonian fluid is a fluid where viscosity (internal fluid resistance) does not change with the rate of flow.

[78] The bulking factor the two-year storm event as documented is greater than two, however, the impacts of this event on the infrastructure design are not as integral as other storm events, thus the impacts were considered by the research team to be minimal to the overall design of the structure.

In the HEC-RAS model developed for this case study, 20 cross sections were cut from photogrammetric survey[79] of the Big Thompson River Canyon that were provided by CDOT and the US 34 Flood Recovery Team. The survey data set had a two-foot contour interval. A Manning's 'n' roughness coefficient[80] of 0.045 was used for all the cross section stations of the stream channel and 0.1 was used for floodplain areas outside of the main channel. The US 34 culvert was modeled in the HEC-RAS model using the standard culvert module. Figure 27 shows the stream and culvert profile developed in the model. The stream profile shows three stream flow discharge rates (5,623 cubic feet per second, 1,778 cubic feet per second, and 562 cubic feet per second) and the peak water surface elevation of each flow event along the stream channel.

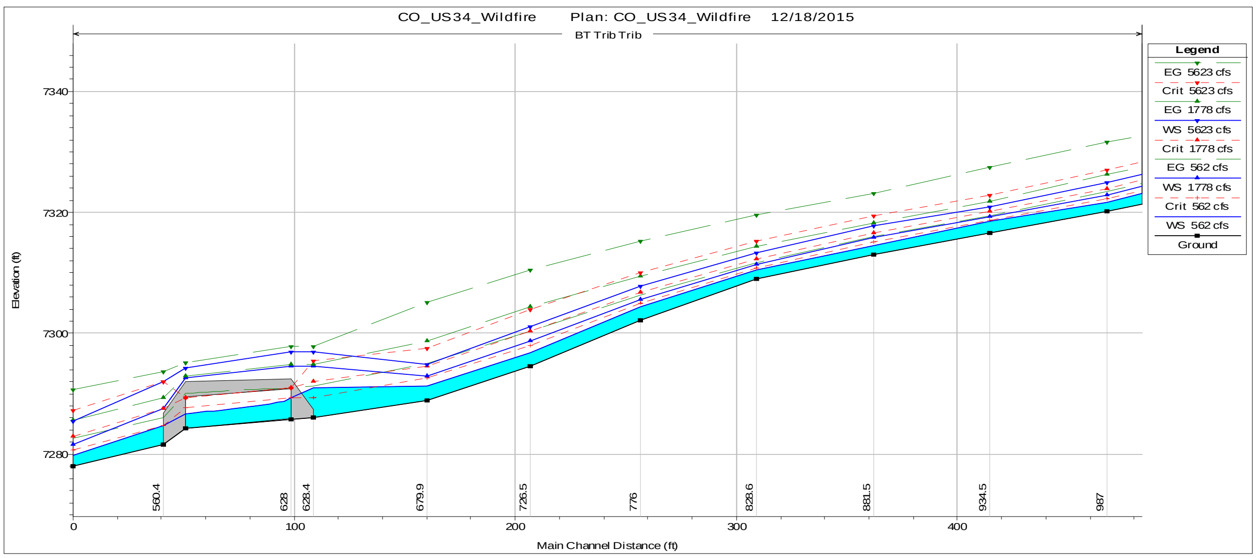

Figure 27: HEC-RAS Modeled Existing Culvert Profile.

Sediment/Debris Flow Mobility

Before the final determination could be made regarding the hydraulic performance of the culvert, the interaction of the debris flows with the structure needed to be determined. Since debris flows have the potential to easily clog small structures such as this culvert and greatly alter the geomorphology of the stream feeding the culvert, the results of a hydraulics analysis would not be meaningful without inclusion of sediment effects.

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[79] Photogrammetric survey involves the development of topographic mapping based on remote sensing and high-speed imaging, typically collected by low flying aircraft.

[80] Manning's 'n' is a numeric coefficient that is used in conjunction with the Manning's equation to quantify the velocity of open channel flow. The 'n' coefficient represents the loss of energy incurred on open channel flow by frictional resistance, turbulence, and minor obstructions. The 'n' value for main channels typically ranges from 0.010 for smooth surfaces up to 0.10 for rough channel conditions. Values for floodplains typically range from 0.060 up to 0.30 (or higher) for natural systems.

Sediment flows in the stream channel fall into three general categories: wash load, suspended load, and bed load. Wash load and suspended load are well-mixed and suspended components of flows that add turbidity to flows, but that are not substantial contributors to the total volume of sediment transport in many cases. Wash load and suspended load typically consist of clay, silt, and fine sand materials being supported throughout the depth of flow. Deposition of these materials will only occur in very low turbulence locations (such as behind dams) and is not an expected contributing factor to the debris flow impacts at the culvert. Bed load, conversely, is the transport of coarser sediment materials near the channel bed. These materials transport via rolling, sliding, and saltation[81] along the stream bed. The transport and deposition of bed load will impact the long-term shape of stream channel beds. In the case of this study, the entire debris flow is being treated as bed load, as the debris flow is expected to consist primarily of coarse sediments.

The movement of sediment in the stream channel as it approaches the US 34 crossing can be broken down into two governing principles: the rate at which sediment can move in the channel (sediment transport) and the ability of the stream channel to move sediment at the given flow conditions (sediment competency). Bedload sediment transport is a complex hydraulic topic that has been the focus of numerous research studies over the past 60 years. While there exist dozens of bedload equations that could be considered applicable for the range of flows and slopes of the tributary channel being studied, the analysis of a debris flow is outside of the development range of these equations. Debris flow originating in a wildfire burn watershed is a hyper-concentrated pulse of sediment flow that is anticipated to act more like a gravity flow, such as a mudslide, than as typical bedload sediment transport. Based on this reasoning, the research team did not attempt to model the debris flow as bedload transport. However, research studies on debris flow performed by Major,[82] Gabet,[83] and Florsheim[84] have shown that the guiding equations for sediment competency translate into situations of debris flows. In particular, the Florsheim study cited the use of the Shields relationship and the DuBoys equation (both discussed below) for modeling of sediment competency in debris flows.

Application of the sediment competency relationship equates to a comparison of the shear stress[85] produced by the stream channel at various flow rates (referred to as the channel

[81] Saltation is the movement of coarse sediment particles in a bouncing type motion along a stream bed.
[82] Major, 1997.
[83] Gabet, 2003.
[84] Florsheim et al., 1991.
[85] Shear stress is a measure of the force of a moving fluid acting at the flow boundary or an object in the flow path (such as debris). The force of shear stress is generated by the frictional interface between the fluid and the boundary or object's surface.

boundary shear stress) versus the critical shear stress[86] required to move the bed load sediment size. In this comparison, deposition will occur at the culvert when the upstream channel is capable of transporting but, at the culvert, the critical shear stress of the bed load sediments is greater than the channel boundary shear stress. Conversely, the channel will maintain competency and convey bed load sediment if the channel boundary shear stress does not drop below the critical shear stress of the bed load sediments. The approaches used for calculating the critical shear stress for bed load transport and the channel boundary shear stress are discussed in the sub-sections below.

Critical Shear Stress for Bed Load Transport

The critical shear stress for the bed load sediments (τ_c) is calculated using the Shields equation:

$$\tau_c = \tau_*(\rho_s - \rho_w)D_{50}$$

Where:

- τ_* is the dimensionless shear stress (known as Shields stress),
- ρ_s is the density of sediment,
- ρ_w is the density of water, and
- D_{50} is the median particle size of the bed load material.

The Shields stress is a non-dimensional factor that has been determined through laboratory flume testing of various coarse sediments against various flow conditions. Following the recommendations of the Florsheim study, the Shields stress was set to 0.06 for the debris flow.

The D_{50} of the bed load material was determined by information collected during the site visit. During the visit, the research team performed a visual assessment of the stream channel and identified depositional features that were judged to be representative of bed load sediments. In this case, the depositional feature chosen as representation of bed load was a sediment accumulation at the upstream end of the US 34 culvert. While the specific gradation properties of the debris flow are unknown, the process of the debris flow production will include erosion of hillslope and near channel areas which are the source of the bed load sediments. The assessed bed load features were determined by the research team to provide the best possible estimate of the debris flow sediment properties, as it is based upon the available sediments and soils in the watershed. The sediment size distribution was analyzed using the FHWA Hydraulic Toolbox[87] Gradation Calculator. Three pictures of the bed-load sediment were taken during the field visit (see Figure 28 for an example). The Gradation Calculator was then used to processes

[86] Critical shear stress is the shear stress force value required to move an object or coarse channel bed particle. The critical shear stress value is the force at the incipient point between movement and non-movement of the particle.
[87] Federal Highway Administration, FHWA Hydraulic Toolbox, Version 4.20. U.S. Department of Transportation, Federal Highway Administration, Bridges & Structures Division.

the images and individually measure the bed sediments in the pictures, compile the varied bed load sediments, and calculate the gradation. Analysis results appear in Figure 29 and Table 12.

Figure 28: Photo of Channel Bed Sediment.[88] Photograph provided courtesy of FHWA.

Using the Shields equation and the field determined D_{50} of 1.52 inches, the critical shear stress for the bed load sediments was calculated to be 0.76 pounds per square foot. Thus, for flow conditions that produce channel boundary shear stress values above 0.76 pounds per square foot, movement of the debris flow sediments will occur. Table 13 is a summary of the factors used in the Shields equation analysis for determining the critical shear stress for bed load transport.

[88] Note the $20 bill shown for size reference.

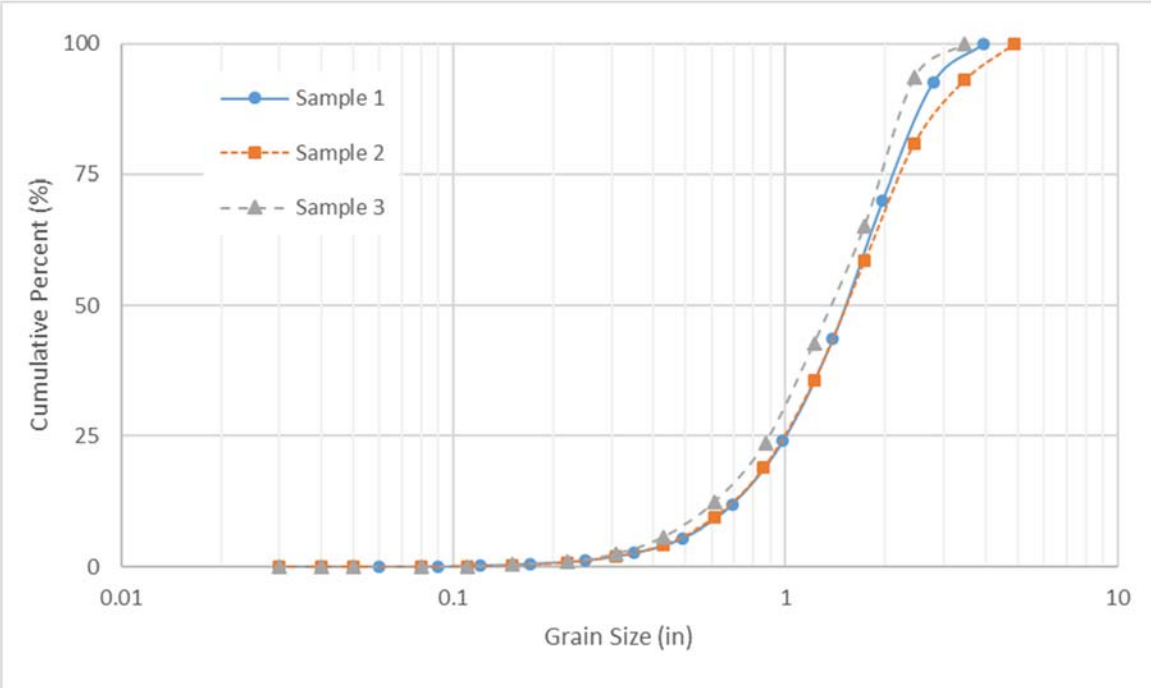

Figure 29: Plot of Channel Bed Gradation.

Table 12: Summary of Gradation Analysis.

Diameter[89]	D_5	D_{15}	D_{50}	D_{85}	D_{100}
Size (in)	0.47	0.77	1.52	2.50	3.93

Table 13: Critical Shear Stress Analysis Parameters and Results.

t_c (lb./ft^2)	τ^*	Specific Gravity[90]	ρ_s (lb./ft^3)	ρ_w (lb./ft^3)	D_{50} (ft.)
0.76	0.060	2.65	162.24	62.40	0.13

[89] Diameter measurements are quantified as D_x where the x subscript is a reference to the cumulative percentage of material that is smaller than the noted measurement for a non-uniform graded material. For example, a D_5 of 0.47 inches indicates that five percent of the soil sample has a diameter smaller than 0.47 inches.

[90] Specific Gravity is the ratio of the density of the rock / sediment materials to the density of water.

Channel Boundary Shear Stress

Channel boundary shear stress is the force generated by stream flows on the streambed and bed load sediments. The channel boundary shear stress (t) is calculated using the DuBoys equation:

$$t = \gamma RS$$

Where:

- γ is the specific weight[91] of water (62.34 pounds per cubic foot),
- R is the hydraulic radius,[92] and
- S is the friction slope[93] (also known as the energy grade slope).

The hydraulic radius and channel friction slope were both determined for a variety of flows based on the hydraulic modeling results. Each value is a direct output from the HEC-RAS modeling exercise.

The results of the channel boundary shear stress calculations are presented on a rating curve in Figure 30. A rating curve is a graphic depiction of the hydraulic performance of a structure: the curve allows for visual representation of important hydraulic properties at a range of flow conditions. Based on the HEC-RAS model runs and the DuBoys equation, a channel boundary shear stress and water surface height rating curve were created for the upstream approach to the culvert structure. As shown in Figure 30, the shear stress (dashed red line) and water surface depth (blue solid line) are calculated as a function of flow rate. The critical shear (0.76 pounds per square foot) and top of culvert headwall positions are shown as horizontal lines that intercept at the critical values. This rating curve presents an overall picture of the sediment competency performance of the drainage structure on a wide range of flow rates. It served as the main tool for evaluating the existing culvert and designing alternatives to meet the three critical evaluation criteria in this study.

Figure 30 reveals a critical deficiency in the use of culverts for the transport of bed load sediments. While a culvert is capable of producing high channel boundary shear stresses for low flows, at intermediate to high flows, the boundary shear stress drops and the ability to transport sediments decreases. The existing US 34 culvert demonstrates this drop in shear

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[91] Specific weight is calculated as the weight per unit volume of a material.

[92] The hydraulic radius is computed as the cross-sectional area of a flow divided by the wetted perimeter (e.g. the perimeter where fluid touches a solid surface not including an open air water surface).

[93] Friction slope is a quantification of the total energy loss (quantified as feet of energy loss) divided by the linear feet of channel over which the energy loss occurs. The friction slope is commonly approximated as the channel bed slope for uniform flow conditions or can be better approximated as the slope of the water surface elevation when information is available.

stress between 180 cubic feet per second and 7,000 cubic feet per second as seen in Figure 30. This drop is occurring as the flow depth begins to exceed the top of the culvert opening and backwater begins to form at the culvert inlet. The backwatering at the culvert entrance greatly decreases the friction slope correspondingly decreasing the channel boundary shear stress in Figure 30 and thus decreasing the ability of the channel to transport the bed load sediments. While the culvert will maintain very high boundary shear stresses inside the pipes under high flow conditions, the decreased boundary shear stress at the entrance will cause the bed load sediments to deposit at the entrance and upstream area. The deposition of sediments at the entrance will begin to block the entrance to the culvert, thus further reducing the inlet capacity of the culvert and furthering the cycle of backwater/decreased boundary shear stress at the culvert entrance. The debris flows to the culvert are of a sufficient volume that the entire entrance to the culvert will readily become blocked causing the culvert to be inaccessible to higher flows that could mobilize the sediment.

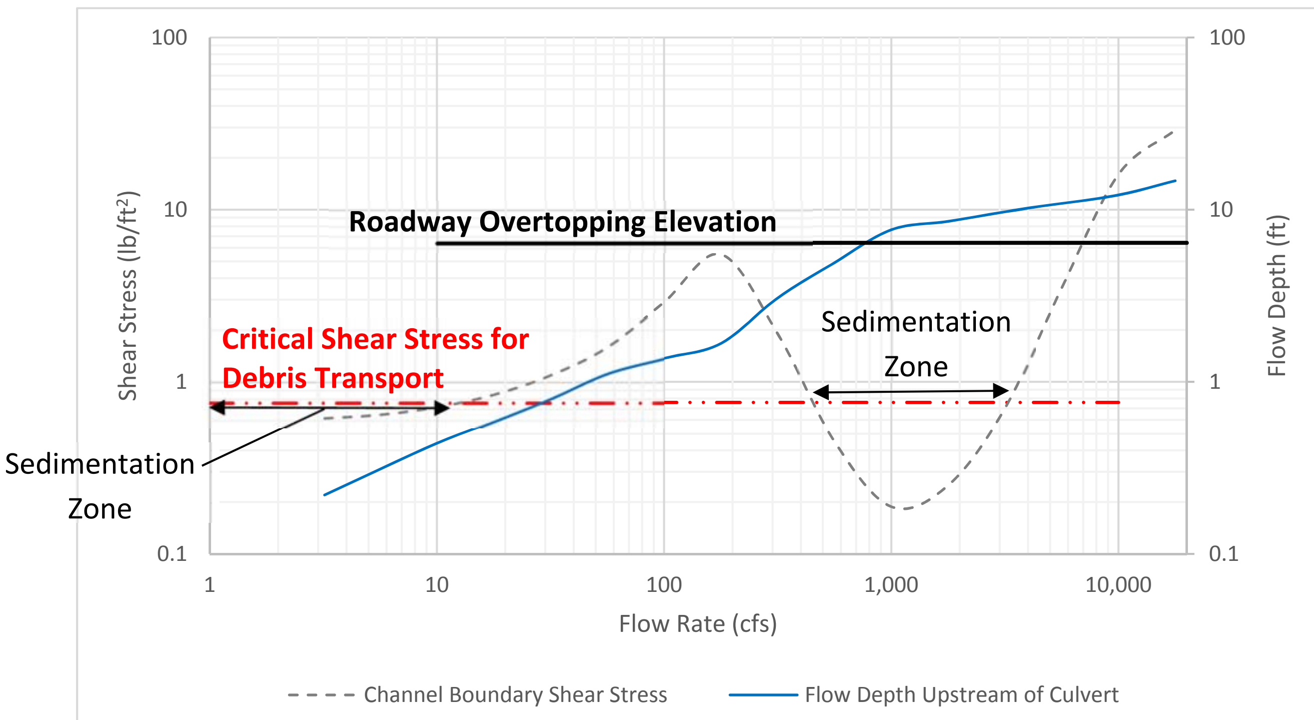

Figure 30: Rating Curve for the Existing Culvert.[94]

Findings on Existing Asset Performance

As mentioned in Step 2, the design standard for this culvert structure is to confine and convey the 25-year or 50-year flow, depending on the 50-year storm being greater than 4,000 cubic

[94]Curves were developed from the HEC-RAS cross-section immediately upstream of the culvert entrance.

feet per second. Currently, the 50-year flow without fire conditions or climate change is 1,150 cubic feet per second, thus the design standard under current conditions is the 25-year storm. As shown in Table 8, the 25-year storm is 838 cubic feet per second. Based on the hydraulic study, the existing culvert is able to convey 850 cubic feet per second before overtopping occurs (shown in Figure 30). Thus, the culvert currently meets the design requirements for the 25-year storm condition.

Review of the range of future precipitation simulations and wildfire burn scenarios shows that the Climate Simulation 1 with current land cover will meet the 25-year storm design standard through the culvert. Climate Simulation 2 fails to meet the 25-year storm design standard in the mid-century timeframe. Under the highest impact scenario, Climate Simulation 3 for precipitation in 2070-2100 with a wildfire burn, the 50-year storm flow rate is 5,115 cubic feet per second. Therefore, following the CDOT design standards, the design standard for the highest impact scenario will be the 50-year storm. At 5,115 cubic feet per second, the existing culvert structure would have substantial overtopping of the structure exceeding the design requirement.

Furthermore, under post-wildfire conditions, when debris flow approaches the US 34 crossing, deposition will occur when flow exceeds 450 cubic feet per second (shown graphically where the shear stress curve dips below critical shear stress curve) due to backwater conditions at the culvert as a result of limited culvert capacity. Based on the topographic data, the total channel volume is around 900 cubic yards between the culvert inlet and the upstream cross-section shown while the sediment volume corresponding to this flow rate is around 1,500 cubic yards. Based on this, the research team concluded that sediment deposition will readily clog the culvert entrance and aggrade the entire approach channel up to the top of the roadway. This will result in future storm flows, and later low flows, being conveyed across the roadway surface, causing damage to the roadway and loss of service. For every other simulation, the existing culvert does not meet the overtopping storm design standard, with or without considering wildfire. As such, the culvert will require adaptation to meet design conditions for the majority of the future Climate Simulations with and without consideration of wildfire.

Step 6. Develop Adaptation Options

The research team investigated five adaptation options in total. The first three can be considered "proactive" adaptation options, as they change the current day culvert design in anticipation of the future climate. The last two adaptation options can be considered "reactive." They take a wait-and-see approach, in which action is taken after a wildfire occurs but (hopefully) before a major precipitation event happens post-fire.

The three proactive adaptation options are:

- Adaptation 1 – Design stream crossing for Wildfire burn land cover and Climate Simulation 3 precipitation.
- Adaptation 2 – Design stream crossing for Existing land cover and Climate Simulation 3 precipitation.
- Adaptation 3 – Design stream crossing for Wildfire burn land cover and Climate Simulation 2 precipitation.

The two reactive adaptation options are:

- Adaptation X: Use culvert design for Adaptation 2 and retrofit culvert for Adaptation 3 design *if* a wildfire occurs.
- Adaptation Y: Build debris-flow containment features *if* a wildfire occurs.

The proactive adaptation options, collectively, represent designs that could address the range of projected future climate conditions. That is, some adaptation options would be better suited if the less extreme climate futures are realized, whereas others may be better options if more extreme climate futures are realized. Normally, a Monte Carlo analysis could use information on the probability of future scenarios occurring to help identify the most cost-effective adaptation option.

Adaptation Option for Highest Impact Scenario

- Replacement of existing twin cell eight foot by five foot concrete culvert with a 50-foot single span bridge.
- Includes raising the roadway elevation by 4-feet.
- Replacement costs are estimated at $9M
- Costs of adaptation option are significant

However, in this case study, there was a major limitation to effectively evaluating the cost effectiveness of these alternatives in Step 8, and making an informed recommendation in Step 10: the research team lacked sufficient information to estimate the probability of a wildfire. Rather, the research team had to assume that these events *would* happen, and then assess cost-effectiveness based on that assumption. Moreover, although it is difficult to estimate precise probability, the research team's research indicates that the risk of wildfire occurring at a given culvert is low over its expected lifetime. Thus, the assumption that an event would occur could cause an overstatement of the cost-effectiveness of the alternatives. Since it is difficult to make an informed recommendation about the most appropriate course of action without wildfire probabilities needed to accurately assessment cost effectiveness, the research team also explored two additional alternatives:

- Adaptation X – Use culvert design for Adaptation 2 and retrofit culvert for Adaptation 3 design *if* a wildfire occurs.
- Adaptation Y – Build debris-flow containment features *if* a wildfire occurs.

Adaptations X and Y represent practices in use today, and do not expressly account for impacts from changes in climate. In contrast to Adaptations 1 through 3, culverts are not proactively adapted; rather, if a wildfire does in fact occur, *then* adaptive measures are taken to reduce vulnerability during a rain event. Because wildfire probability information is not available, it was not possible to perform an economic analysis based on the likelihood that Adaptations X and Y would actually be implemented. Thus, the research team did not complete Steps 7 through 9 for Adaptations X and Y.

Proactive Adaptation Options (Adaptations 1, 2, and 3)

These three adaptation options represent proactive measures that adapt culverts in advance of wildfire and major precipitation events occurring.

Adaptation 1: Design Stream Crossing for Wildfire Land Cover and Climate Simulation 3 Precipitation

Designing of an adaptation option for the highest impact scenario requires upsizing of the structure to meet two key criteria:

1. Sizing the waterway opening to convey the 50-year flow, meeting CDOT design standards.
2. Sizing the waterway opening to maintain a channel boundary stress above the critical shear stress for the bed load sediments, thus maintaining sediment competency through the structure and minimizing the potential for debris/sediment accumulation.

There are several ways to design a stream crossing to meet these criteria, such as using larger culvert cells, more culvert cells, or raising the roadway. For the purposes of this case study, the research team modeled a 50-ft single span bridge for Adaptation 1, since it was the design best suited for the climate scenarios under consideration. With this Adaptation, the US 34 roadway will also need to be raised an average of four feet above the current roadway elevation. Construction of this alternative would require reconstruction of a significant length of US 34 in addition to removal of the current culvert and construction of the new, 50-ft bridge.

Figure 31 shows the hydraulic performance curves for this adaptation option. Based upon the HEC-RAS model results for Adaptation 1, this structure is sized to convey 8,000 cubic foot per second flows, well above the 5,115 cubic feet per second flow of the highest impact scenario. The structure will have a 14-foot clearance above the current stream bed. Bed shear stresses under this option will initially fall below the threshold for transport of bed load; however, the structure has been sized to allow for sufficient capacity for deposition at the low flow rates. At higher flows, the structure does not have the same backwater issues as the culvert and allows for continuously increasing transport of the bed load sediments. The bridge structure was designed by the research team with a higher performance flow rate (8,000 cubic feet per second) than the design storm (5,115 cubic feet per second), because the bed load sediment transport conditions governed the structure sizing.

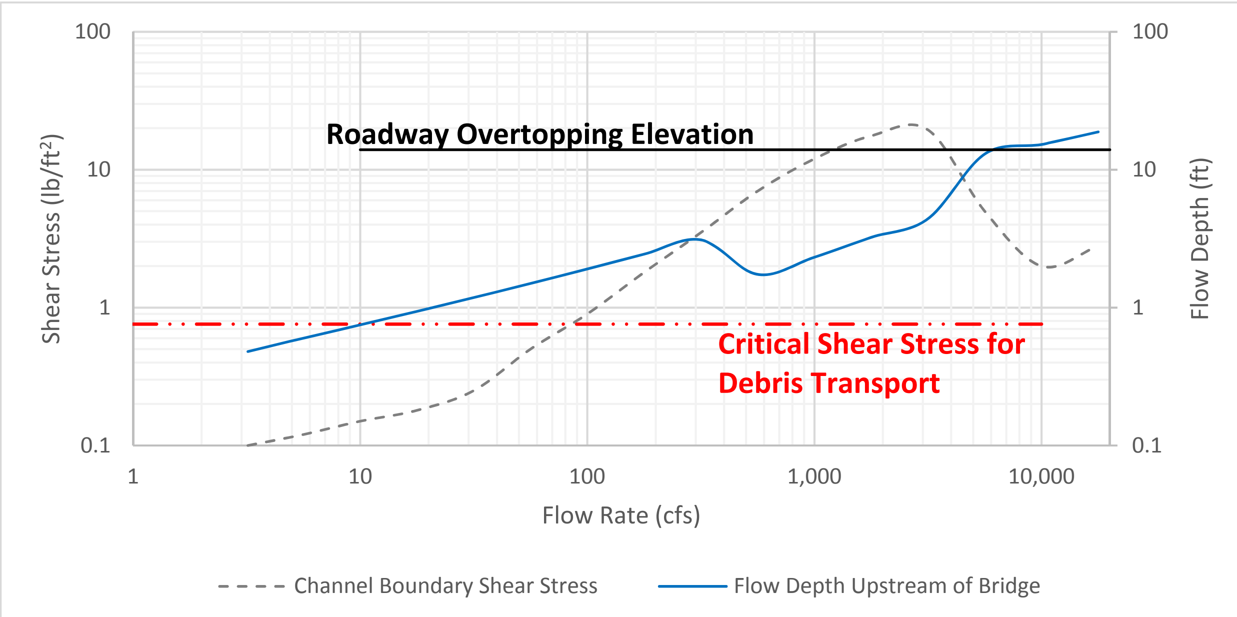

Figure 31: Rating Curve for Adaptation 1.

The research team prepared a planning level construction cost estimate for construction of Adaptation 1. The cost estimates for Adaptation 1 are presented in Table 14. The planning level cost estimate for the adaptation option was prepared using the material and incidental costs provided to the research team by the US 34 Flood Recovery Team and CDOT. The cost estimate includes both construction costs and facility engineering design costs. As shown in Table 14, the design for meeting the highest impact scenario for the study site includes very substantial capital costs. The costs are judged by the research team to be significant as the capital costs (>$9 million) greatly exceed the cost of performing a detailed engineering assessment and economic analysis (<$100,000).

Table 14: Construction Cost Estimate for Adaptation 1.

Item	Quantity	Measurement Unit	Cost
Embankment Fill	33,330	CY	$ 400,000
Excavation	560	CY	$ 24,300
Riprap to protect embankment slopes	111	CY	$ 11,000
Riprap to protect structures (bridges or culverts)	222	CY	$ 21,000
Aggregate Base Course	3,100	CY	$ 93,000
Hot Mix Asphalt	5,100	TONS	$ 411,000
50' Reinforced Concrete Slab Bridge with Wingwalls (including foundations on bedrock)	1	EACH	$ 380,000
Remove & Recycle Ex. Concrete Culvert	1	EACH	$ 20,000
Retaining Walls	2,500	LF	$ 1,875,000
Mobilization Costs			$ 440,000
Traffic Control & Striping			$ 390,000
Erosion and Sediment Control			$ 97,000
Miscellaneous - Force Account			$ 416,000
Minor Contract Revisions			$ 460,000
30% Contingency			$ 1,500,000
Design and Construction Engineering			$ 2,534,000
		Total Project Cost	**$ 9,072,300**

The pros and cons of Adaptation 1 are discussed below in terms of structure performance, construction cost, and practicalities.

Pros for Adaptation 1 include:

- The bridge meets the 50-year design storm for all possible future conditions.
- The potential for sediment deposition at the structure is greatly mitigated by the up-sizing of the facility and maintaining a relatively high channel boundary shear stress.
- While not analyzed in detail due to a lack of supporting information, larger woody debris[95] may present an issue at hydraulic crossings depending on the severity of the watershed burn. Larger bridge crossings will be more resilient to clogging from such debris.

[95] Large woody debris consists of large diameter tree branches or small tree trunks of sufficient size to clog the stream channel. The length of the wood will be greater than half of the channel width and of sufficient stoutness to provide a rigid blockage to water and debris flow forces.

Cons for Adaptation 1 include:

- The cost of this adaptation option is very high. Construction costs for the bridge alone are estimated at $2.2 million for a reinforced concrete slab single span bridge. Additional costs for reconstruction of US 34 at the higher elevation required for use of the bridge are estimated at an additional $6.8 million but could vary substantially based on the need for rock cuts on the canyon walls or placement of retaining walls along Big Thompson River. Total construction costs for the alternative are estimated at approximately $9 million.
- Construction of this option will necessitate the full closure of US 34 through Big Thompson canyon for a substantial period of time. Since US 34 is a key connection to Estes Park and Rocky Mountain National Park, the socioeconomic impacts of a long closure will be significant. The research team estimated the construction period for this alternative to be six months.
- Use of a bridge instead of a culvert will create added maintenance and upkeep requirements for CDOT. The new structure will require significantly more frequent inspections and maintenance on the abutment protection as compared to a culvert.
- Biannual structural inspections of the bridge option will be required. The biannual inspection costs are estimated at $4,000 per inspection cycle.
- The research team anticipates that the deck of the bridge will require replacement one time over the life cycle of the structure, as a routine maintenance and upkeep activity. The cost of the deck replacement is estimated at $300,000.

Adaptation 2: Design Stream Crossing for Existing Land Cover and Climate Simulation 3 Precipitation

Adaptation 2 was designed to meet the 25-year storm overtopping condition under Climate Simulation 3 precipitation conditions. Since this adaptation is not being designed for a wildfire condition, the detailed sediment bulking and sediment competency components of the other culvert studies were not included in the base design considerations. However, CDOT design standards do call for a 10 percent sediment bulking factor to be included in standard culvert designs, which was included in the sizing of this alternative. The design flow rate for Adaptation 2 is thus the Climate Simulation 3 25-year peak design storm of 1,236 cubic feet per second plus the 10 percent sediment bulking factor, or 1,360 cubic feet per second. The Adaptation 2 design selected by the research team includes replacement of the twin six foot by eight foot culverts with the next larger standard box culvert size (twin eight foot by eight foot) with modifications to the culvert inverts and roadway cover. Adaptation 2 as designed by the research team will accommodate flows of 1,680 cubic feet per second, which exceeds the targeted design standard. However, the additional culvert performance is due to minor design modifications that do not carry a significant capital cost, thus the team did not include further investigations to lower design performance.

The design for this adaptation option includes lowering the existing culvert bottom elevation by one foot, raising the roadway surface by one foot, and installation of twin barrel eight foot by eight foot culverts. The inlet to this culvert option will have a chute style concrete apron to allow for rapid inflow into the culvert. The performance rating curve for Adaptation 2 is shown in Figure 32. This culvert design has a capacity of 1,680 cubic feet per second before overtopping of US 34 occurs.

The capital costs of this alternative have been estimated at $283,000 for replacement of the culvert barrels and $247,000 for the associated roadway work for a total estimated cost of $530,000. Table 15 provides a complete breakdown of the cost estimate for this alternative.

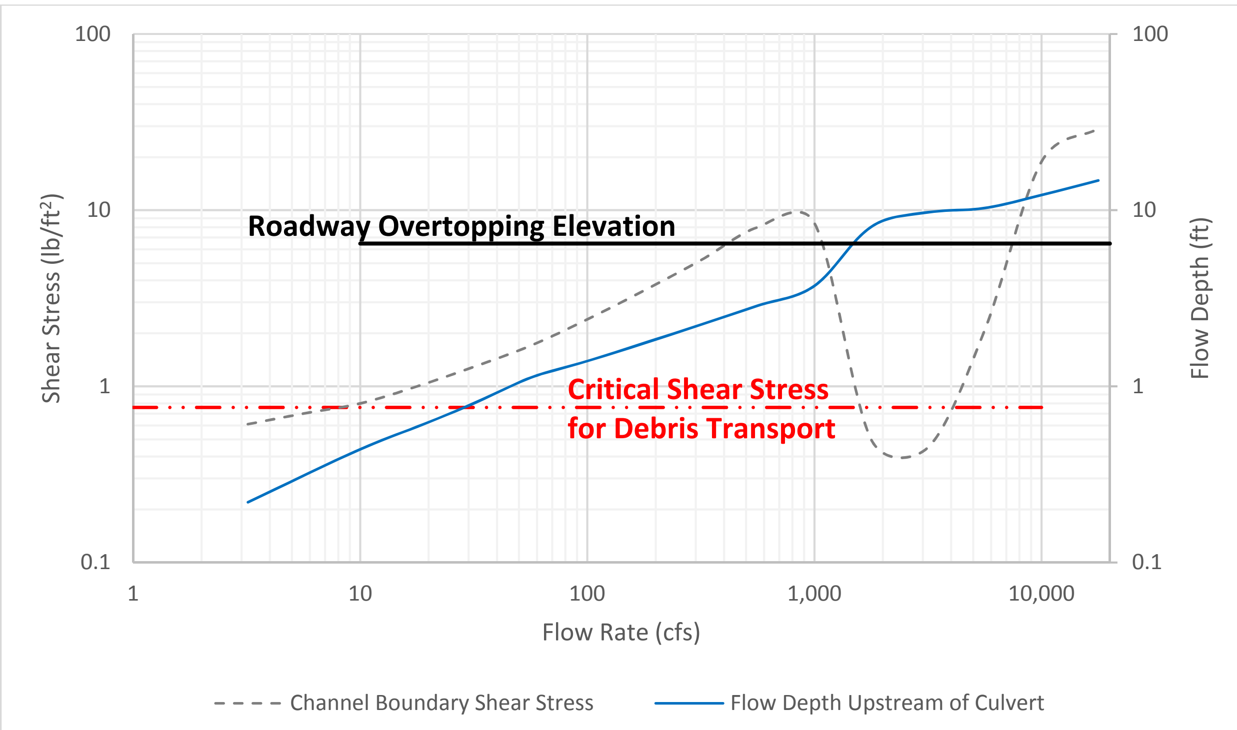

Figure 32: Rating Curve for Adaptation 2.

Pros for Adaptation 2 include:

- It has the lowest capital cost of the three alternatives considered.
- The design meets the design standard under current flow conditions.
- The design meets flows under all of the Climate Simulations with existing land cover.
- The construction period will be relatively short compared to other options. The research team estimated the construction period for this alternative to be one month.
- Construction of the culverts and roadway raising should be capable of being sequenced such that a full closure of the roadway is not necessary. Traffic may be maintained with a single lane closure and a temporary traffic signal to maintain traffic flow. Maintaining

traffic on US 34 will minimize the socioeconomic impact of the project on Estes Park and Rocky Mountain National Park.

- As a small culvert (less than 20-foot total span), the culvert will not require a biannual inspection.
- Long-term maintenance and upkeep for a small culvert installation is the lowest of the options considered, thus the lowest life-cycle costs for CDOT.

Table 15: Construction Cost Estimate for Adaptation 2.

Item	Quantity	Unit	Cost
Embankment Fill	89	CY	$ 1,000
Excavation	444	CY	$ 20,000
Rip Rap to protect structures (bridges or culverts)	83	CY	$ 8,000
Aggregate Base Course	41	CY	$ 1,200
Hot Mix Asphalt	68	TONS	$ 5,500
40' long twin cell 8' x 8' Reinforced Concrete Box Culvert	1	EACH	$ 133,000
Remove & Recycle Ex. Concrete Culvert	1	EACH	$ 20,000
Mobilization Costs			$ 25,500
Traffic Control & Striping			$ 22,500
Erosion and Sediment Control			$ 6,300
Miscellaneous - Force Account			$ 24,000
Minor Contract Revisions			$ 27,000
30% Contingency			$ 88,000
Design and Construction Engineering			$ 148,000
		Total Project Cost	**$ 530,000**

Cons for Adaptation 2 include:

- The structure design does not consider impacts of wildfire.
- Backwater conditions at the culvert for flows between 1,750 cubic feet per second and 4,000 cubic feet per second may allow for sediment buildup during larger storm events.
- Overtopping and clogging may happen under post-wildfire burn conditions.

Adaptation 3: Design Stream Crossing for Wildfire Land Cover and Climate Simulation 2 Precipitation

Adaptation 3 was designed to meet peak 50-year storm flows under post-wildfire land cover conditions and Climate Simulation 2. The primary focus of the design is to minimize backwater conditions upstream of the culvert and maintain sediment transport conditions. Adaptation 3 has been designed as an enhancement of Adaptation 2 with the addition of a third eight-foot by eight-foot concrete box culvert barrel. The alternative was designed to accommodate a peak design storm of 4,600 cubic feet per second including sediment bulking.

As seen in Figure 33, with the addition of the third culvert barrel, the channel boundary shear stress performance is greatly improved at higher flow rates. The shear stress performance is improved, as the culvert does not significantly backwater at higher flows. The design modifications for Adaptation 3 include raising the US 34 roadway by an additional 0.5-feet (one foot total) and lowering the culvert invert by two additional feet beyond Adaptation 2 (three feet total). The use of the concrete apron chute with a greater drop off at the inflow to the culvert allows for a rapid increase in sediment transport mobility at low flow, thus no significant deposition is expected at any flows above seven cubic feet per second (sediment carried by this low flow range is insignificant). The design can accommodate flows of 4,600 cubic feet per second before overtopping, which meets the 4,560 cubic feet per second for Climate Simulation 2 50-year storm post-wildfire.

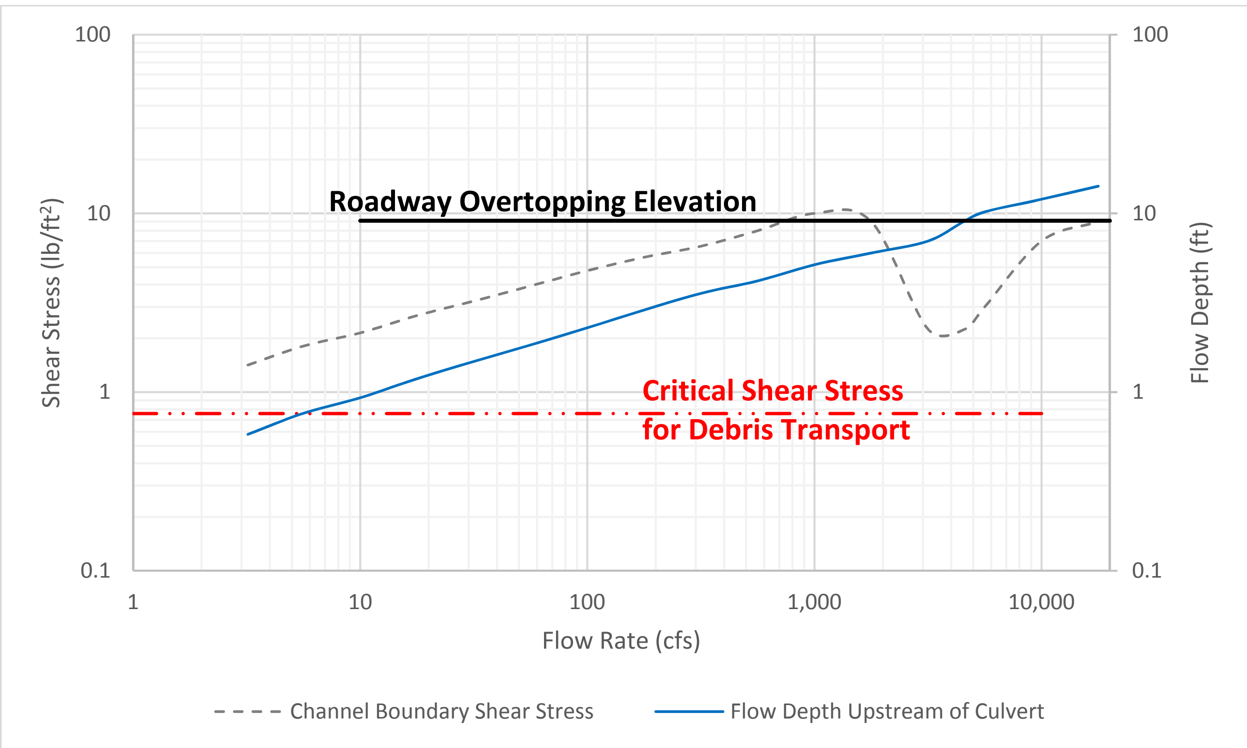

Figure 33: Rating Curve for Adaptation 3.

The capital costs of this alternative have been estimated at $400,000 for replacement of the culvert barrels and $353,000 for the associated roadway work to raise US 34 for a total estimated cost of $753,600. Table 16 provides a full breakdown of the cost estimate for this alternative.

Pros for Adaptation 3 include:

- It has a relatively low capital cost.
- The structure can be constructed as an adaptive modification to Adaptation 2.
- The design is capable of passing watershed wildfire burn and sediment under many conditions.
- The design meets flows for all of the existing Land cover Climate Simulation combinations and for Climate Simulations 1 and 2 with wildfire burn land cover.
- The construction period will be relatively short, comparable to Adaptation 2. The research team estimated the construction period for this adaptation option to be one month.
- Construction of the culverts and roadway raising should be capable of being sequenced such that a full closure of the roadway is not necessary. Traffic may be maintained with a single lane closure and a temporary traffic signal to maintain traffic flow. Maintaining traffic on US 34 will minimize the socioeconomic impact of the project on Estes Park and Rocky Mountain National Park.
- Long-term maintenance and upkeep for a large culvert installation is less than that required for a bridge option, thus life-cycle costs will be lower for CDOT.

Table 16: Construction Cost Estimate for Adaptation 3.

Item	Quantity	Unit	Cost
Embankment Fill	320	CY	$ 4,000
Excavation	711	CY	$ 32,000
Rip Rap to protect structures (bridges or culverts)	139	CY	$ 13,000
Aggregate Base Course	52	CY	$ 1,600
Hot Mix Asphalt	86	TONS	$ 7,000
40' long triple cell 8' x 8' Reinforced Concrete Box Culvert	1	EACH	$ 189,000
Remove & Recycle Ex. Concrete Culvert	1	EACH	$ 20,000
Mobilization Costs			$ 36,000
Traffic Control & Striping			$ 32,000
Erosion and Sediment Control			$ 11,000
Miscellaneous - Force Account			$ 34,500
Minor Contract Revisions			$ 38,000
30% Contingency			$ 125,000
Design and Construction Engineering			$ 210,500
		Total Project Cost	**$ 753,600**

Cons for Adaptation 3 include:

- The structure is not designed for the worst case climate and fire scenario.

- The upstream channel might need to be realigned to accommodate the third culvert inlet.
- The three span culvert option will require a biannual structural inspection. However, as a culvert the inspection is not as intensive as performed for a bridge. Biannual inspection costs are estimated at $2,500 per inspection cycle.

Reactive Adaptation Options (Adaptations X and Y)

Adaptations X and Y represent approaches in line with present day practices. Rather than proactively adapting, DOTs may wait for a wildfire to occur and then adapt it to be able to handle increased flows. These adaptation options may be attractive because the probability of wildfire events is difficult to quantify but is expected to be low; thus, waiting to adapt until a wildfire occurs (if it occurs at all) may make sense in some circumstances.

Although the Step 8 economic analysis can indicate a preferred option among Adaptations 1 through 3, each of them assume that the DOT is willing to proactively upgrade their culverts. In the case of US 34, culverts are already being replaced as part of the ongoing US 34 flood recovery project, so this assumption may be valid. However, this assumption may not hold for other locations; depending on actual probabilities of wildfire, it could be more cost effective to wait until a wildfire occurs and then adapt. Moreover, Adaptations 1 through 3 might not be appropriate for other locations where increases in downstream flooding are a more significant concern, such as CDOT encountered after the Waldo Canyon Fire in Manitou Springs.

Therefore, the research team considered two *reactive* alternatives: 1) Use culvert design for Adaptation 2 and retrofit culvert for Adaptation 3 design *if* a wildfire occurs and 2) Build debris-flow containment features *if* a wildfire occurs.

Adaptation X: Use culvert design for Adaptation 2 and retrofit culvert for Adaptation 3 design if *a wildfire occurs*

Current practices in wildfire adaptation are reactive in nature, where state and federal agencies mobilize after a fire event, starting with Burned Area Emergency Response (BAER) studies to determine the severity of the burn impacts, predict potential storm flows, and determine appropriate infrastructure adaptation actions for impacted areas.

Under Adaptation X, a similar approach would be taken, where the replacement culvert for US 34 considers only climate adaptation for the present day replacement sizing of the US 34 crossing at Canyon Cove Lane (Adaptation 2), with future adaptation in the event of a wildfire (Adaptation 3).

Adaptation 2 is designed to meet the 25-year storm climate change precipitation projections for Climate Simulation 3. The proposed Adaptation 2 design selected by the research team includes placement of twin eight-by-eight-foot box culverts with slight modifications to the roadway cover. Adaptation X would also modify the Adaptation 2 culvert inlet to include the Adaptation 3 chute inlet, which would allow for future adaptation.

In reaction to a future wildfire burn event, the research team proposes that the US 34 crossing be adapted to meet the design example provided as Adaptation 3. Adaptation 3 is designed to meet peak 50-year storm flows under post-wildfire land cover conditions and Climate Simulation 2. This alternative minimizes backwater conditions upstream of the culvert to maintain sediment transport / debris flow conditions in the design of Adaptation 3. Under Adaptation X, in the event of a wildfire, the culvert could then be modified to mirror Adaptation 3 by adding a third eight-by-eight-foot concrete box culvert barrel. The added culvert barrel along with modifications to the roadway cover / road elevation and the modifications to the culvert inlet will allow the design to meet the post-wildfire design conditions.

Under this design approach, the research team considered the potential need for post-fire culvert adaptation in the present day culvert replacement design. Designing the culvert so that it can be modified in the future represents an increase in initial capital costs, but would avoid a full replacement of the culvert if additional adaptation is needed in the future. Thus, the research team estimates the capital costs for initial construction of Adaptation X to be $550,000 in 2017 dollars, which is slightly higher than the $530,000 cost previously assigned to Adaptation 2. If a wildfire occurs and additional adaptation is needed, the capital costs to add the third concrete box culvert barrel would be $450,000.[96] If no wildfire occurs, then that $450,000 would not need to be spent.

If the design team had not included modifications to Adaptation 2 that allowed for future post-fire mitigation, the capital costs for present day replacement (Adaptation 2 / $530,000) and full replacement for the post-fire condition (Adaptation 3 / $750,000) would be $1,280,000 as compared to an estimated adaptation approach cost of $1,000,000 (modified Adaptation 2: $550,000 + Adaptation to Adaptation 3: $450,000).

Pros for Adaptation X include:

- Reactive approaches delay the construction of fire adaptation until after a fire event necessitates their use. This is beneficial as it minimizes capital expenditures on fire adaptation measures in locations where fires do not occur during the design timeframe under consideration.
- The alternative has a relatively low capital cost.
- Construction of Adaptation 3 as an adaptation of Adaptation 2 allows for minimal risk to present day culvert replacement plans.

[96] Costs as provided are 2017 present day costs. Inflation of costs is expected, however, degree of inflation will be dependent on the ultimate date that costs are realized; i.e. occurrence of the future wildfire.

- Right of way acquisition and attendant project delays are unlikely to be necessary.
- Long-term maintenance and upkeep for a large culvert installation is less than that required for construction of a bridge, thus life-cycle costs will be lower for CDOT.

Cons for Adaptation X include:

- The structure is not designed for the worst case climate and fire scenario.
- The upstream channel might need to be realigned to accommodate the third culvert inlet.
- The three span culvert option will require a biannual structural inspection. Biannual inspection costs are estimated at $2,500 per inspection cycle.
- There would be a delay between occurrence of the wildfire and implementation of the proposed mitigation measures. Project delays for the design permitting of the debris basin are expected to last up to 12 months. Lesser delays of four to six months are anticipated for hydromulching,[97] silt fence installation, check dam installation, and log erosion barrier construction.
- Upsizing of the structure will pass all storm flows and debris flows potentially requiring modifications on downstream private properties or other transportation infrastructure crossings.

Adaptation Y: Build debris-flow containment features if *a wildfire occurs*

This adaptation option focuses on containment of debris in uplands areas and attenuation of peak storm flow rates via distributed treatments. The approach is similar to that used by CDOT in response the Waldo Canyon fire and provides an example of a treatment approach for cases where culvert upsizing could produce a negative downstream impact by allowing debris and peak flows to continue downstream unabated, and thus cause problems at downstream culverts. This approach may also be well-suited for areas where multiple culverts would have to be replaced; although this watershed-based approach can be pricey, it becomes more cost-effective when considering the cost of upgrading a large number of culverts.

Adaptation Y could several different forms, including the following treatments:

- debris basin,
- silt fence,
- log erosion barriers,
- hydromulch / seeding, and
- check dams.

[97] Hydromulch and seeding involve the spraying of a mixture of mulch, tackifiers, water, and seed that provide surface coverage over exposed soils and promote the establishment of grasses and other plants.

Each of these treatments was considered following the design guidance in the Burned Area Emergency Response Treatment Catalogue (BAERCat) published by the US Forest Service. The research team considered the topography, site access constraints, projected debris loads, and maintenance needs of each treatment type in the development of this approach.

Adaptation Y assumes each of these treatments would be constructed in order to provide comprehensive watershed-wide adaptation. In the case of the project site watershed, the research team determined that a single treatment approach would be unable to substantially meet the post-fire treatment needs of the watershed and has thus proposed multiple distributed treatments that together are projected to provide a substantive improvement in debris and storm flows at US 34. The following are individual discussions of each component of the holistic watershed treatment.[98]

Debris Basin

A debris basin is used to capture and temporarily store debris, sediment, and storm water from an upstream watershed. The basin can be constructed by excavating a storage area similar to the more common stormwater ponds, but are more effectively placed at natural constrictions in terrain that can be readily dammed with the upstream terrain acting as the storage area. Debris basin differ from standard construction sedimentation ponds as they focus on collection of large debris and course sediments (course gravels, cobbles, and boulders) with short retention times rather than basins with the long retention periods needed for collecting fine sediments (silts and clays). Among the available post-fire watershed treatments, the debris basin is expected to provide the bulk of the mitigation for debris flows and attenuation of peak storm flows from the watershed.

A debris basin is expensive and time consuming to both design and construct, as the basin is required to meet minimum safety standards for small dam construction. A debris basin also requires an access road for regular inspection and maintenance clean-outs, precluding the placement of the basins in remote locations. Construction of debris basin as a post-fire management activity is not common due to high capital and maintenance costs, extensive design and permitting requirements, and space requirements. Use of the basin is reserved for conditions where post-fire debris flows represent a significant threat to human life or property. However, once watersheds have fully healed from a wildfire burn and debris flows have abated, the debris basins can be readily retrofitted into water quality facilities, thus offering long-term benefits past the initial emergency need.

[98] Details related to applicability, material sizing, and unit costs for the debris basin, hydromulching, silt fence, log erosion barrier, and check dams are referenced from the US Forest Service's Burned Area Emergency Treatment Catalogue (2006), unless otherwise noted.

The research team was able to site a debris basin in the study watershed. The identified location of the proposed debris basin is shown in Figure 34. In this location, the debris basin is capable of treating 815 acres of the watershed that is tributary to the US 34 culvert, representing 80-percent of the watershed. Ideally, the basin would be sited to treat the entire watershed; however, steep terrain and limited access in the lower reaches of the stream are not optimal for placement of a basin. In the proposed location, the debris basin has been sized to provide storage for the full 10-year debris flow and storm flow volume. The basin will provide attenuation of peak stream flows up to the 10-year storm level for post-wildfire conditions and will be designed to safely convey the 100-year flows in accordance with Colorado dam safety regulations.

The capital cost of the debris basin is estimated at $1.5 million, not including right-of-way acquisition costs. The research team estimated that maintenance of the basin would occur 10 times a year for the first four years, then gradually decrease to four times a year at year 10.

Hydromulch / seeding

Hydromulch and seeding involved the spraying of a mixture of mulch, tackifiers, water, and seed that provide surface coverage over exposed soils and promote the establishment of grasses and other plants. The BAERCat recommended applications for hydromulch are slopes less than 50-percent, with moderate to high soil burn severity, and no effective soil cover. Rock slopes are not viable candidates for hydromulching as establishment of plant materials is not expected to occur.

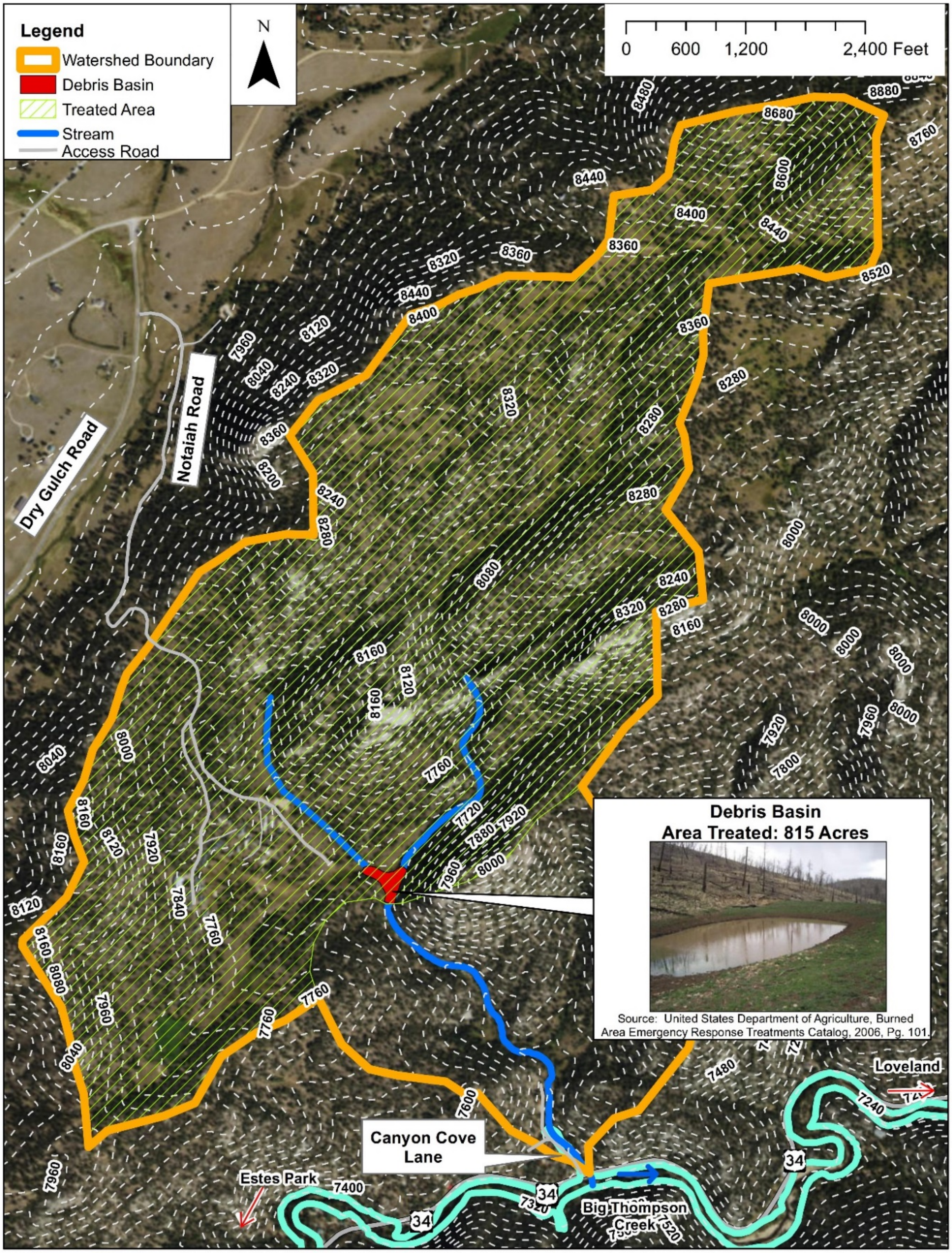

Figure 34: Post-Fire Watershed Treatment - Debris Basin. [99]

[99] Image source: Google Earth (as modified).

Hydromulching can be performed either aerially via aircraft or ground based via hydromulch trucks. Aerial hydromulching is a viable option for remote and difficult access areas of a watershed (see Figure 35). Successful application of aerial hydromulching has been performed from both rotary and fixed wing aircraft (crop dusters). Ground-based hydromulching can occur up to 300 feet from any access road and provides a cheaper option than aerial based methods. The research team is assuming that ground-based treatment of the watershed would be performed for areas within 300 feet of an access road and aerial treatment used otherwise.

Figure 35: Aerial hydromulching after the Cedar Fire, December 2003. Source: US Department of Agriculture "Burned Area Emergency Treatment Catalogue", 2006, pg. 13.

For Adaptation Y, the research team proposes that all non-rocky slopes with grades less than 50-percent within the watershed be treated with either aerial or ground-based hydromulching. The total treatment area within the watershed would be approximately 692 acres with up to 40% performed using ground-based methods. The estimated cost of hydromulching is $1.4 million for the watershed.

Silt Fence

Silt fences are common sediment control measures that use synthetic geotextile cloth erected as barriers along a slope to filter shallow water flows (normally seen as black cloth supported by wood stakes). Silt fences are highly effective sediment trapping devices for small drainage areas (less than 10,000 sf per fence). They rely upon filtering of non-concentrated surface flows with trapped sediments accumulating on the upslope side of the fence. Regular maintenance is necessary for removal of sediments once the upslope accumulation has partially filled the height of the fences. Unlike other BAERCat treatments, silt fence is to be removed once the watershed has healed from burn conditions.

Figure 36 shows proposed locations for silt fence lines in the lower portion of the study watershed. For Adaptation Y, the study team proposes the silt fences to treat 20 acres of the watershed (2% of the total drainage area). The team selected the locations shown based upon construction access, maintenance access, removal access, and appropriate drainage area size and slope.

The study team estimates that 8,500 linear feet of silt fence will be required for the proposed treatment area with an estimated capital cost for installation of $75,000.

Log Erosion Barriers

Log erosion barriers consist of felled logs placed across erosion-prone slopes. The logs are placed in shallow trenches with the upper half protruding above the slope to provide a flow barrier for trapping of sediment / debris. Burned trees on site are used for construction of the log erosion barriers, lessening the need to haul construction materials into difficult access areas. Forestry teams can construct the log erosion barriers using chain saws and hand tools, without the need for heavy construction equipment. US Forest Service experiences with log erosion barriers have shown that proper usage requires adequately embedding the logs into the ground, placement of the logs to avoid concentration of flows, placement of logs in a sufficient density (logs per acre) for the slope and burn severity, placement on slopes less than 60-percent, and placement of soil end berms to improve trapping of water and sediment.

Log erosion barriers should be monitored for effectiveness and remaining sediment trapping capacity. If the barriers reach capacity, additional trees are to be felled and new barriers constructed, as opposed to grading and sediment removal that would be required for silt fences. As the wildfire burn area heals, it is not necessary to remove the log barriers or the accumulated debris, thus negating any added maintenance expenses for the treatment.

For Adaptation Y, the research team proposes placement of log erosion barriers for 153 acres of the lower portion of study watershed that is not tributary to the debris basin. Figure 36 shows the proposed watershed area for treatment with log erosion barriers. Estimated capital costs for installation of the log erosion barriers is $150,000.

Check Dams

Check dams are in-channel sediment trapping structures that slow water velocities in channels and impede the transport of coarse sediments downstream. Check dams capture sediments in the channel as opposed to silt fences and log erosion barriers, which capture sediment on the hillslopes and prevent it from reaching the channel. Check dams can be constructed using rocks, logs, or straw bales. The research team chose rock check dams in the proposed treatments for the study site, as straw and log check dams will only provide effective treatment for relatively small drainage areas with flat slopes and require more frequent maintenance.

The research team proposes placement of rock check dams as a redundant treatment for a 97 acre portion of the lower study watershed. The rock check dams are intended to work in conjunction with log erosion barriers placed in the upper watershed. Multiple rock check dams are intended to be placed in series along the ephemeral stream channel that is fed by this portion of the watershed. Figure 36 shows the alignment of the ephemeral channel that is proposed for retrofitting with rock check dams. Estimated capital costs for installation of the rock check dams is $130,000.

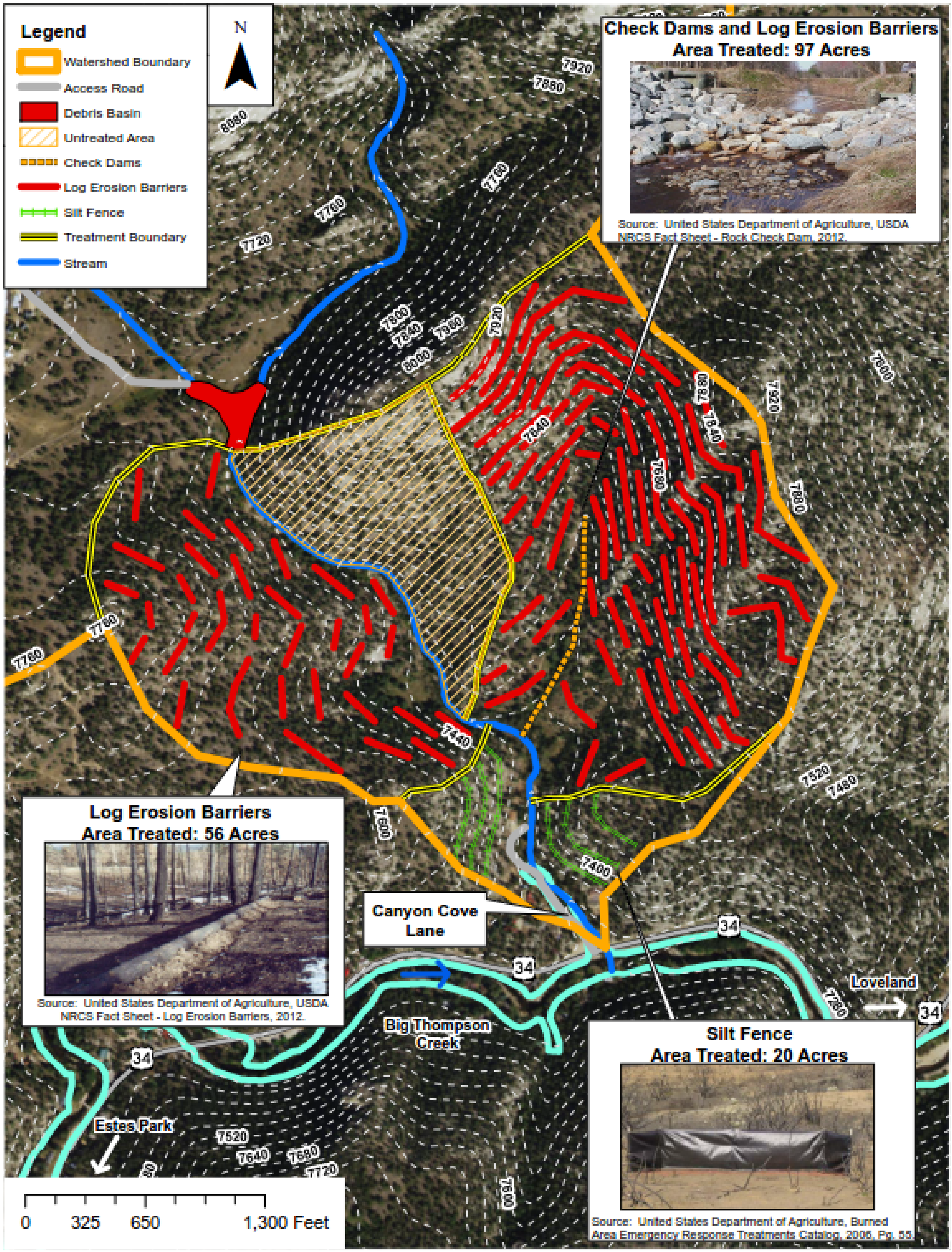

Figure 36: Post-Fire Watershed Approach – Log erosion barrier, Silt Fence, and Check Dam Treatments.[100]

[100] Image source: Google Earth (as modified).

Adaptation Y Conclusion

In total, the distributed measures proposed by the research team will provide treatment for 988 of the 1,018 acres within the study watershed. The total capital costs for the proposed debris basin, hydromulching, rock check dams, silt fence, and log erosion barriers is estimated to be $3.26 million.

As shown in Figure 36, the proposed design does not provide treatment for a 30-acre area of the watershed. This portion of the watershed is below the proposed debris basin and is not a candidate for treatment with other methods due to very steep slopes and exposed rock faces / rocky soils. US Forest Service experiences have documented that steep rocky areas are prone to increased rock slides / sediment and debris flow generation after wildfires, thus the untreated area does represent a continued source of untreated post-fire storm and debris flows. However, since the untreated area represents only 3% of the watershed, the debris load and threat at the US 34 culvert is expected to be minimal.

Pros for Adaptation Y include:

- Reactive approaches delay the construction of fire adaptation until after a fire event necessitates their use. This is beneficial as it minimizes capital expenditures on fire adaptation measures in locations where fires do not occur during the design timeframe under consideration.
- Watershed based approaches treat the source of increased storm flows and debris flows in the watershed, thus minimizing increases in flow in the streams and at the facility.
- Minimizing in-stream flows using watershed approaches provides the ability to protect infrastructure crossings while also providing protection to downstream private development; whereas upsizing of roadway stream crossings will provide increased protection of that structure but potentially cause negative impacts from increased flow and debris downstream.
- Watershed based approaches can provide mitigation for stream flow and debris flow potential impacts for a series of multiple pieces of transportation infrastructure crossing the same river (i.e. the multiple bridge crossings over Big Thompson Creek).
- Debris basins can be retrofitted into water quality facilities after fire impacts have healed, providing long-term benefits after the primary need has abated.

Cons for Adaptation Y include:

- There would be a delay between the occurrence of the wildfire and the implementation of the proposed mitigation measures. Project delays for the design and permitting of the debris basin could last up to 12 months or more. Lesser delays of four to six months are anticipated for hydromulching, silt fence installation, check dam installation, and log erosion barrier construction.

- Right of way acquisition may be required for implementation of several treatments, including debris basins, silt fence, etc. Property acquisition could have significant impacts on project costs.
- The debris basin, rock check dams, and silt fence installations will require continuous maintenance for up to 10 years after construction. Maintenance activities will include regular excavation and clean-out of sediment and debris accumulations, requiring the use of heavy construction equipment.
- A small volume of debris flow is still projected to reach US 34 as the proposed design is not able to provide treatment for 30 acres of the watershed due to site limitations.
- Silt fence, check dams, and debris basins would require removal after fire conditions within the watershed have healed, unless otherwise retrofitted or continuously maintained.
- Maintenance and capital costs may exceed other options for culvert adaptation.

Step 7. Assess Performance of Adaptation Options

This step involves the assessment of the performance of each proposed adaptation option for the US 34 crossing. The research team utilized the engineering design and analysis process described in Step 5 for the design and analysis of each of the adaptation options. Performance rating curves showing the ability of each adaptation option to maintain channel forces for mobility of sediment / debris loads were presented in Step 6. The performance curves also present the overtopping performance of each adaptation option. Table 17 provides a complete summary of the performance of each of the adaptation options under each of the climate simulations and against wildfire burn land cover conditions. The table summary notes whether each adaptation option, including the existing facility, meets the design conditions for each of the conditions considered as part of this study. The design conditions evaluated in the table include the overtopping design standard and the ability of the design to convey sediment/debris flows up to the required design storm.

Adaptations X and Y are not included in Table 17 as the research team did not perform detailed engineering and economic studies on these two adaptation options across the range of climate and wildfire scenarios. Adaptations X and Y represent secondary design options that are not readily weighted against Adaptations 1, 2 and 3 due to the uncertainty in the timing of potential implementation or if implementation will ever need to occur.

Table 17: Summary of Adaptation Option Performance Across All Scenarios.

Facility Design Option	Existing Land Cover: Historic Precipitation Conditions	Existing Land Cover: Climate Simulation 1	Existing Land Cover: Climate Simulation 2	Existing Land Cover: Climate Simulation 3	Wildfire Burn with Sediment Bulking: Climate Simulation 1	Wildfire Burn with Sediment Bulking: Climate Simulation 2	Wildfire Burn with Sediment Bulking: Climate Simulation 3
	Does the design meet the performance standard for the project?						
Existing Facility	Yes	Year of Future Condition: 2045					
		Yes	Yes	No	No	No	No
		Year of Future Condition: 2065					
		Yes	No	No	No	No	No
		Year of Future Condition: 2085					
		Yes	Yes	No	No	No	No
Adaptation #1	Yes	Year of Future Condition: 2045					
		Yes	Yes	Yes	Yes	Yes	Yes
		Year of Future Condition: 2065					
		Yes	Yes	Yes	Yes	Yes	Yes
		Year of Future Condition: 2085					
		Yes	Yes	Yes	Yes	Yes	Yes
Adaptation #2	Yes	Year of Future Condition: 2045					
		Yes	Yes	Yes	No	No	No
		Year of Future Condition: 2065					
		Yes	Yes	Yes	No	No	No
		Year of Future Condition: 2085					
		Yes	Yes	Yes	No	No	No
Adaptation #3	Yes	Year of Future Condition: 2045					
		Yes	Yes	Yes	Yes	Yes	Yes
		Year of Future Condition: 2065					
		Yes	Yes	Yes	Yes	Yes	No
		Year of Future Condition: 2085					
		Yes	Yes	Yes	Yes	Yes	No

Step 8. Conduct Economic Analysis

There are two components to the economic analysis conducted for this case study. First, the research team evaluated some of the potential economic impacts that would arise from a disruption in road access. To focus this analysis, the research team considered the economic impact to Estes Park, Colorado if US 34 were out of service due to storm damage. Estes Park is a tourism-dependent community that sits at the gateway of Rocky Mountain National Park. US 34 is a major route that connects Estes Park to the city of Loveland to the East. Importantly, rain events that disrupt use of US 34 can also disrupt use of the other major routes into Estes Park that connect the town to the cities of Longmont, Boulder, and Denver. Such an event occurred in 2013, temporarily leaving Estes Park accessible only via a highway to the west, where no significant population centers are located. Therefore, this closure introduced a significant detour for traffic traveling between Estes Park and the major nearby cities to the east. This analysis also identifies additional methodological considerations that future analyses may want to take into account – including other categories of direct costs and modeling considerations for further indirect and induced impacts to the broader economy.

The second part of the economic analysis estimates the benefits and costs of Adaptations 1, 2, and 3 developed under Step 6. Using a Monte Carlo analysis, the research team compares the relative benefits and costs of implementing each adaptation option, to help identify a preferred option.

It is important to note that these two analytical components have very different objectives—to illustrate the economic impacts associated with loss of service to a critical roadway, and to help identify preferred adaptation measures—and therefore two very different approaches were employed.

Loss of Use Impacts on Estes Park, Colorado

Estes Park, Colorado (2013 pop. 6,086) is the eastern gateway to Rocky Mountain National Park (RMNP). The vast majority of park visitors pass through Estes Park, whose economy relies heavily on tourism. The most common industry is accommodation and food services, with 23% of the labor force participating.[101]

US 34 is one of three major routes into the eastern side of Estes Park (see Figure 37); the other two are US 36 and CO 7. On the west side, Estes Park is serviced only by the seasonal US 34 (with US 36 also providing service on the West end for a short distance before combining with US 34). The western road runs through Rocky Mountain National Park, and is closed during the winter months.

[101] City Data, 2013. "Most common industries in 2013." A copy of the report is available at: http://www.city-data.com/city/Estes-Park-Colorado.html.

In September 2013, heavy rains brought severe flooding and damage to the highways servicing Estes Park on the east side. US 34, as well as US 36 and CO 7, was severely damaged, temporarily halting access to Estes Park from the east. Though Estes Park could still be accessed via the west side, the detour to access the large population centers to the east was significant, involving long commutes on US 14 to avoid flooded areas. Loss of east-side access led to severe economic impacts on the tourism industry, upon which the town's economy is based. Furthermore, loss of eastside access made it challenging to move goods into the town, and presented a barrier for residents needing to access the services of nearby cities, such as medical facilities.

This loss-of-service analysis considers the broad economic impacts of losing eastern access to Estes Park only through increased transportation costs to Loveland, CO via US 36 instead of the more direct route. The analysis also estimates the loss of tourism related spending to the community, assuming disrupted access to Rocky Mountain National Park (RMNP). Other costs associated with loss of eastern access to Estes Park are discussed qualitatively.

2013 Flood Impacts

Although this analysis presents the likely impacts associated with a moderate flood event in Estes Park that causes US 34 to be closed, the reality is that a weather event that closes US 34 could produce a more significant disruption – of which Coloradans are well familiar. In 2013, a stalled storm system caused massive flooding when approximately a year's worth of precipitation fell in a five day period. Across the state, it was estimated that there were more than 9 deaths, thousands of homes destroyed, and more than $2 billion of property damage.[102] Not only was US 34 severely damaged and closed, but the other major routes into Estes Park were too.

Property and Infrastructure Damage

In Larimer County, 47 homes were destroyed and another 338 sustained significant damage. Another 45 commercial businesses and building sustained significant damage or were ordered demolished. There was $79 million in damage to county roads and bridges.[103] In addition, 400 homes in the area went more than 45 days without sewer access and flushing toilets.[104]

Extended Loss of Tourism

A 2013 analysis of the flood's impact on Estes Park area tourism estimated that 43% of local employment and 65% of sales and tax revenue are derived from tourism.[105] A mid-tier estimate assuming that the floods would decrease 2014 out-of-state tourism spending by 70% in Estes Park and Rocky Mountain National Park would result in an $8.3 million decrease in state tax revenue and $6.3 million decrease in local tax revenue.

Approach and Findings

A review of literature indicates that there are certain categories of costs that are pertinent to natural disaster studies and loss of infrastructure cost analyses, including:

- Loss of tourism and related businesses.
- Increased travel in order to reach nearest city (Loveland).

[102] Duggan, Kevin. September 9, 2014. "Recovering After Rivers Rage." Coloradoan.
[103] Ibid.
[104] Hughes, Trevor. November 2, 2013. "Colorado Flood Victims Rebuild, Slowly but Surely." USA Today.
[105] Colorado State University. October 2, 2013. "Economic Impacts of Colorado Flooding: Identifying the Dimensions and Estimating the Impacts of Reduced Tourism in Estes Park." Regional Economics Institute.

- Increased Health Service Costs.
- Price Gouging.
- Loss of tax revenue.

This analysis quantified the economic impacts from loss of tourism and increased travel distances. The economic impacts of the other three categories—increased health service costs, price gouging, and loss of taxes—could not be quantified due to lack of data and resource limitations, but are discussed qualitatively under the section on Limitations.

Quantified Costs: Loss of Tourism and Increased Commute Times

Loss of Tourism and Related Business

The largest economic impact associated with the loss of eastern access to Estes Park would be the loss of visitors to RMNP and associated tourism spending in the town. This impact can be accounted for in terms of Decreased Hotel Visitations per day and Decreased Meal and Incidental Spending per day. The magnitude of these impacts depends on daily visitors to RMNP, length of stay, and amount spent. A study by Summit Economics calculated the number of people who uses services in Estes Park during their trip to RMNP, their length of stay, and percent of non-local visitors. The research team used these figures from 2011 and proportionated them based on the increased visitation to RMNP. Loss of access to Estes Park via US 34 is not expected to eliminate tourism to the RMNP during its closure, but it will likely diminish visitations. To provide an estimate of the impact, this analysis selected a lower and upper bound on likely tourism losses to show a range of economic impact. For the purposes of this report, the analysis estimated an upper bound loss of 75% of visitations and lower bound of 25%. Variables and formulas are explained in the table below:

Table 18: Loss of Tourism Cost Estimates (2015 Dollars).

Variable	Parameter Key	Variable Value
Estes Park Visitor Days[106]	**A**	2,431,281.74[107]
Daily Visitor Days	**B** = A/365	6,661
25% Tourism Reduction Visitor Days (Lower)	**C** = B*0.75	4,996
75% Tourism Reduction Visitor Days (Upper)	**D** = B*0.25	1,665
Meals and Incidental (M&I) Spending	**E**	$168[108]
Total Loss of Tourism Cost, per Day	**F =** B*E	**$1,119,055.70**
Lower Bound Tourism Cost (75% reduction)	**G** = C*E	**$839,328**
Upper Bound Tourism Cost (25% reduction)	**H** = D*E	**$279,720**

Based on our calculations, the research team estimated a loss of tourism ranging from $279,720 to $839,328 of lost economic activity per day.

Increased Commute to Loveland

For Estes Park residents needing to travel to the nearest city – Loveland, CO –US 34 provides the most direct route at 30.2 miles and approximately 49 minutes of travel. An alternative route that does not rely on US 34 requires the use of US 36 E and US 287 N. This route is 44.7 miles and approximately 59 minutes of travel.[109] The net increase is 14.5 miles and 10 minutes of travel.[110] The research team calculated the impact of a single person making this trip using the alternate route, including travel time and the GSA rate for mileage reimbursement, which includes fuel and vehicle costs. To gauge the broader community impact of such a detour, the analysis team also estimated the impact associated with 5% to 25% of the Estes Park population taking this alternate route. Again, providing a range of impact acknowledges the uncertainty about the number of individuals impacted, while providing a likely magnitude for discussion purposes. Variables and formulas are explained in the table below:

[106] Estes Park Visitor Days is a variable of the number of days non-local RMNP visitors spent in Estes Park.
[107] Data on this variable are from a 2010 survey of the park (Summit Economics), so this number was inflated for the growth in visitors between 2010 and 2015 (29%). Per the 2010 survey, there were 1,884,331 visitor days in Estes Park and an estimated 2,431,281.74 visitor days in 2015.
[108] Per diem rate as determined by the GSA rate for Larimer County, Colorado. Rates are available at: http://www.gsa.gov/portal/category/100120.
[109] Data gathered by comparing travel distance of two routes in Google Maps.
[110] Data gathered by comparing travel time of two routes in Google Maps.

Table 19: Increased Travel Costs to Loveland (2015).

Variable	Parameter Key	Variable Value
Net Increased Mileage (miles, per trip)	**A**	14.5[111]
Net Increase Travel Time (hours, per trip)	**B**	0.17[112]
Value of Travel Time (per hour)	**C**	$17.67[113]
Value of Vehicle Wear	**D**	$.59/mile[114]
Population of Estes Park	**E**	6,086[115]
Cost of Increased Mileage Per Trip	**F=** A*D	$8.56
Cost of Increased Mileage for 5% of Population	**G=** A*D*(.05*E)	$2,604.81
Cost of Increased Mileage for 25% of Population	**H=** A*D*(.25*E)	$13,024.04
Cost of Increased Vehicle Wear Per Trip	**I** = B*C	$3.00
Cost of Increased Vehicle Wear for 5% of Population	**J=** B*C*(.05*E)	$914.09
Cost of Increased Vehicle Wear for 25% of Population	**K=** B*C*(.25*E)	$4,507.43
Increased Transportation Costs per Trip	**L=** F+I	**$11.56**
Increased Transportation Costs for 5% of Population	**M=** G+J	**$3,517.37**
Increased Transportation Costs for 25% of Population	**N=** H+K	**$17,586.87**

[111] See Figure 37 for mileage difference. 30.2 miles on baseline route and 44.7 miles on alternate route.
[112] See Figures 37 for time difference. 49 minutes on the baseline route and 59 minutes on the alternate route.
[113] Texas A&M Transportation Institute, 2015. "Annual Urban Mobility Scorecard." A copy of the report is available at: http://mobility.tamu.edu/ums/.
[114] Internal Revenue Service, December 10, 2014. "New Standard Mileage Rates for 2015." A copy of the article is available at: https://www.irs.gov/uac/Newsroom/New-Standard-Mileage-Rates-Now-Available%3B-Business-Rate-to-Rise-in-2015.
[115] US Census, 2013. The data are available at: http://www.census.gov/quickfacts/table/LND110210/0825115.

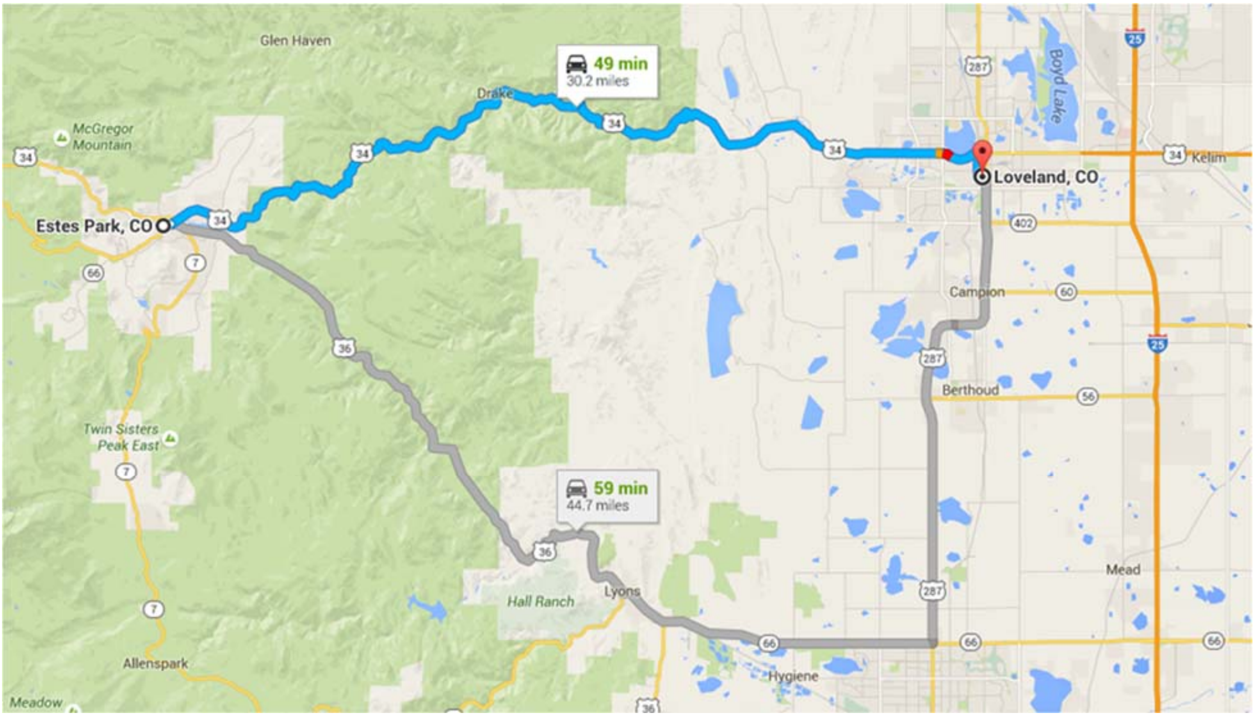

Figure 37: Baseline and Alternate Route to Loveland. Main route to Loveland is presented in blue via US 34. Alternate route to Loveland is presented in gray via US 36E and 287N.[116]

The increased travel to Loveland due to the closure of US 34E could result in $11.56 per person per trip, or a community-wide cost of $3,517.37 if 5% of the Estes Park population were to make one trip, and $17,586.87 if 25% of the Estes Park population were to make one trip.

Qualitative Discussion of Other Costs: Health Services, Price Gouging, Loss of Tax Revenue

Due to data limitations and resource constraints, this analysis only considered direct costs associated with two categories of impact pertinent to the region: loss of tourism and increased commute times; however, natural disaster impacts often involve a variety of other direct costs, discussed below.

Increased Health Service Costs

In order to provide the same level of service during and after a storm that reduces access to Estes Park, Estes Park Medical Center would need to find alternative routes of travel for patients in need of care not immediately available onsite. Examples include helicopter transport for surgical and ICU needs at larger hospital systems, as well as shipping in medications and other supplies. In addition, there could be significant health impacts for patients that are unable to receive the care they need in a timely manner, such as extended illness durations,

[116] Image source: Google Maps (as modified).

lost productivity, and fatalities. In order to appropriately cost these, an analysis would likely need access to some amount of anonymized hospital data to provide a record of what patients are in the community and what services can be provided locally and which require access to a larger health system.

Price Gouging

Colorado currently has no anti-price gouging laws in effect. Previous laws have been proposed, but ultimately vetoed, meaning that so long as a price is clearly stated, it is legal despite the markup during a natural disaster. Examples of price gouging include gasoline prices before Hurricane Ike and Uber Surge Pricing.[117] In order to effectively cost this direct impact, an analysis would likely need to consider pricing changes – either by survey data or local consumer price indices – before and during the natural disaster.

Loss of Tax Revenue

Taxable sales in Estes Park in 2011 totaled $187 million, which generated a total of $5.2 million in tax revenue, approximately 70% of the town's budget. During the government shutdown in 2013—which closed Rocky Mountain National Park—Rocky Mountain National Park lost approximately $10.9 million of potential revenue, which directly contributed to lost revenue for Estes Park as well. [118] An economic loss of this size would mean huge cuts to city services and public programs.

In addition, Visit Estes Park, the tourism agency in Estes Park, is funded by a 2% lodging tax. Without tourists to utilize lodging within the town, the jobs of employees of the agency would be at jeopardy. There could also be a cascade effect to other industries in the town that are reliant on tourism brought into the town via the advertising and promotion done by Visit Estes Park. Anecdotally, a representative from Visit Estes Park noted she had trouble imagining a single industry that would not suffer if tourism were lost altogether.[119]

Modeling Considerations

As mentioned this analysis only considered two categories of direct costs, but lost economic activity and diverted spending affects an economy broadly due to linkages between industries and consumer spending patterns. Software packages have been developed that can model the broader indirect impacts to an economy based on the direct economic shocks. A more robust analysis of a natural disaster or flood event may want to consider using these methods.

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[117] Consumer Protection, 2011. "The Problem with Price Gouging Laws." A copy of the report is available at: http://object.cato.org/sites/cato.org/files/serials/files/regulation/2011/4/regv34n1-1.pdf.

[118] Denver Post. March 3, 2014. "Government shutdown tapped 18.2 percent from Estes Park's sales-tax take." A copy of the article is available at: http://www.denverpost.com/business/ci_25265511/october-shut-down-rocky-mountain-np-cut-estes.

[119] Visit Estes Park Representative by phone. More information is available at http://www.visitestespark.com/.

Conclusions

Taking into account loss of tourism and the impact of detour routes, the total direct economic impact of closure of US 34 is approximately $279,720-$839,328 in lost tourism activity per day and approximately $11.56 per necessary trip to Loveland. Table 2 presents a summary of economic impacts. To put these numbers in perspective, the total annual budgeted expenditures for Estes Park street maintenance in 2016 is $725,540.[120]

Table 20: Economic Impact Summary.

Variable	Economic Impact
Total Loss of Tourism	$279,720-$839,328 per day
Per trip cost to Loveland	$11.56 per trip
Travel to Loveland for 5% of Estes Park residents	$3,517.37
Travel to Loveland for 25% of Estes Park residents	$17,586.87

Monte Carlo Analysis to Identify Preferred Adaptation Option(s)

Economic analyses that account for the probability of different outcomes are critical to project decision-making given the uncertainty of future climate. Similar to economic analyses of transportation, climate adaptation analyses define costs as the costs of constructing and maintaining a given project alternative, while benefits are the reduction in expected lifecycle weather-related damage costs achieved by implementing 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.

There are several ways to conduct economic analyses of climate adaptation options, and there are no established best practices for evaluating and comparing the economic impacts of different adaptation options. This analysis utilized a Monte Carlo analysis to estimate the expected value of the damages that may be experienced by the three proactive adaptation option designs over time under various climate stressor scenarios. The climate stressors considered include (1) the change in frequency and intensity of extreme precipitation events, and (2) the change in wildfire potential. Both of these stressors impact the ability of the adaptation options to effectively pass the flow of water and debris downstream, and thus impact the likely damage associated with a storm event.

This analysis evaluated Adaptations 1 through 3 (described in Step 6).

Based on the Monte Carlo economic analysis and the Keetch-Byram Drought Index (KBDI) results that follow, the preferred course of action is the construction of Adaptation 3—the

[120] The Estes Park 2016 Annual Budget is available at: https://drive.google.com/file/d/0Bxgs0yqHcJzcRFdsbnQzMDBzZ00/view.

culvert optimized for wildfire land cover and Climate Simulation 2. While the results indicate that Adaptation 2 is the cheapest to construct, the estimated damages for that alternative suggest that a wildfire followed by a large storm will result in largescale damages to the structure. Adaptation 1 has been designed to withstand all but the largest storms, and the structure is unlikely to be damaged by high flood waters alone. However, given the significant construction costs, the required closure of US 34 to through-traffic for an extended period of time during the construction phase, and the susceptibility to damages from sediment, Adaptation 1 is not cost effective. According to the analysis, Adaptation 3 presents an adaptation design alternative that provides cost effective hazard mitigation of runoff in periods without a wildfire while also mitigating damages in periods of wildfire.

Methodology

This section presents the approach and results of the economic analysis conducted by the research team to evaluate the various proposed adaptation alternatives. The adaptation options include the following:

- Adaptation 1: Design stream crossing for wildfire land cover and Climate Simulation 3 precipitation.
- Adaptation 2: Design stream crossing for existing land cover and Climate Simulation 3 precipitation.
- Adaptation 3: Design stream crossing for wildfire land cover and Climate Simulation 2 precipitation.

The analysis evaluated the incremental costs and benefits of each adaptation option relative to the no-action alternative (i.e., no action taken to enhance the current culvert).

This analysis is somewhat unique regarding the incorporation of a wildfire climate stressor into the cost-benefit analysis. While many similar studies have estimated the potential damages of extreme precipitation events, this analysis considered the combined conditional implications of both fire and precipitation. Wildfires greatly increase the volume of watershed stream flow runoff from precipitation. After a fire occurs, the following factors impact stream flow runoff: (1) the reduction in vegetation in the immediate aftermath can be destabilizing to the soils; (2) the fire can change the soils capacity to infiltrate water, resulting in increased runoff; and (3) there is often substantial debris left behind from burnt vegetation. The latter is important because, when it rains, the runoff will move more debris through the culvert and some of that debris could settle in the culvert itself, partially blocking it. When significant rain events happen in the future, the culvert may no longer be of sufficient size to pass the flow of water and debris, resulting in roadway overtopping and culvert failure.

Scenario Approach to Incorporate Fire Potential

Basis for Assuming Wildfire Potential Increases

There are slightly over 24 million acres of forest within the mountainous areas of Colorado. Available data on wildfires from 1960 through 2015 have shown an increasing trend in fire occurrence and acreage burned. Data from 2000 through 2015 show approximately 100,000 acres of forest burn per year, correlating to an average of 0.4-percent of the total forest area burning per year over the 2000 through 2015 period. If the 2000-2015 levels continue over the 75-year design life of a new culvert or bridge structure, approximately 30-percent of the forests in Colorado would be projected to burn, which could be interpreted as a 30-percent chance of the forest in the study watershed burning.

The 1960 – 2015 wildfire trends are most commonly attributed to forest management practices that prioritized immediate containment and extinguishing fires rather than controlled burns. These practices have led to unhealthy conditions where dead and dying trees combined with an increase in understory brush have compounded the fuel availability for future fires, resulting in increased fire occurrence, fire intensity, and burn area. The US Forest Service has altered their forest management practices in response to these trends, with current focuses including controlled burns and containment. The expected result of the current forest management practices is a long-term decrease in fires.

However, the KBDI study performed by the research team shows an expected increase in the chance of wildfire occurrence due to climate change and increasing drought conditions.

Using Scenarios instead of Probabilities

Normally, the Monte Carlo analysis would use estimates of probability of wildfire occurrence in the study watershed to fully weigh the economic considerations for infrastructure management. Unfortunately, current models on wildfire probability are prohibitively complicated and require uncommon and site-specific data inputs that the team was unable to quantify for this study. Fire potential—the likelihood that a fire of a certain magnitude will occur in a given area—takes into account characteristics such as moisture levels, weather conditions, and potential fire behavior (e.g., how the fire will spread and the intensity of the burn). However, there is significant uncertainty in how changes in climate and precipitation may affect fire potential. The research team concluded that wildfire probability could not be reasonably estimated for this study due to the complexity of the current models combined with the 1960-2015 historic increasing trends in fire occurrence, expected decreases in fire due to forest management changes, and potential increases in fire due to climate change.

Therefore, the research team took a scenario-based approach to conduct the cost-benefit analysis. This approach assumes that there are eight different scenarios of wildfire occurring or not occurring in the three time periods considered in the analysis. To limit the number of analyses needed, the research team made the simplifying assumption that if a wildfire occurs in a time period, it occurs at the beginning of that time period.[121]

The three periods for the analysis were determined by dividing the total useful life of the adaptation options—from 2016 through 2099—into thirds. This results in three time periods with 28 years each. Period 1 includes 2016 through 2043, period 2 includes 2044 through 2071, and period 3 includes 2072 through 2099. The economic analysis timeframe differs from the engineering timeframe. The engineering timeframe is concerned with the impacts of climate change, which only occur in a measurable fashion after 2030. The economic analysis, however, requires an earlier starting period to fully capture the costs and benefits of the design alternatives.

Table 21 presents the fire occurrence scenarios used in the analysis.

Table 21: Fire Scenarios.

Scenario	Period 1	Period 2	Period 3
1	Fire	Fire	Fire
2	Fire	Fire	No Fire
3	Fire	No Fire	Fire
4	No Fire	Fire	Fire
5	No Fire	No Fire	Fire
6	No Fire	Fire	No Fire
7	Fire	No Fire	No Fire
8	No Fire	No Fire	No Fire

Data

This section presents the primary data used in the economic analysis. These include lifecycle costs, projected stream flows and discharge rates, discharge damage functions, and flood event risk rates.

Lifecycle Costs

Lifecycle costs include the costs incurred to purchase (own), implement, operate, and maintain an asset throughout the usable life of an asset. For the adaptation options that include

[121] The research team developed the scenario approach as a binary decision tree for each time period (fire or no fire) and in the presence of a fire designate that the fire occurs in the first year of that time period for simplicity. A probabilistic approach could be used if better wildfire risk forecasting is available. Separately, an approach that fluctuates the year of the fire within each time period could be used, but this adds an additional layer of complexity to the Monte Carlo analysis and makes the results more difficult to compare without extending the number of iterations performed on the model.

modifying the bridge and culvert, lifecycle costs include construction costs, deck replacement, periodic inspections and maintenance, and loss of function while the initial construction is taking place as well as in the future when maintenance activities render the bridge temporarily unusable.

Table 22 presents the construction and maintenance costs of the adaptation options considered. Please see Step 6 for information on how these costs were estimated.

Table 22: Undiscounted Lifecycle Costs.

Lifecycle Costs	Adaptation 1	Adaptation 2	Adaptation 3
Construction Costs[1]	$9,072,300	$530,000	$753,600
Ongoing Maintenance Cost[2]	$672,000	$0	$420,000
Upgrade Costs[3]	$300,000	$0	$0
Total	**$22,856,718**	**$761,147**	**$1,404,747**

[1] The build-up for the construction costs for each alternative are outlined in Table 14, Table 15, and Table 16 for Adaptations 1, 2, and 3, respectively.
[2] Maintenance costs for Adaptation 1 include two inspections per year and cost $4,000 per inspection. Maintenance costs for Adaptation 3 include 2 inspections per year and cost $2,500 per inspection. Adaptation 2 does not require inspections.
[3] Upgrade costs for Adaptation 1 include the cost of a replacement deck halfway through the lifecycle of the project. Adaptations 2 and 3 do not have additional upgrade costs.

In addition to construction and maintenance costs, there are additional costs due to the partial or total loss of the bridge's function as construction and maintenance activities take place. For example, Adaptation 1 will require the bridge to be closed for approximately 180 days, which means the individuals who travel across the bridge during those days will have to use an alternative route to arrive at their desired destination. This alternate route requires additional mileage to be driven, which yields increased vehicle operating costs, increased cost of travel time, and increased vehicle emission costs due to the increased mileage driven. The research team included these costs in the lifecycle cost estimates. Adaptation 2 and 3 do not require the total closure of the bridge as the construction can be completed in phases allowing one lane to remain open. Thus, these adaptation options do not require additional mileage but will increase travel time as vehicles will idle in the construction zone while waiting to cross the one lane restricted bridge. Table 23 presents the calculation methodology for the loss-of-function cost estimates for the three adaptation options.

Table 23: Loss of Function Cost Estimation.

Variable	Parameter Key	Adaptation 1	Adaptation 2 and 3
Closure Time (days)[1]	A	180	30
Annual Average Daily Traffic (AADT)[2]	B	5,443	5,443
Percent Truck Traffic[2]	C	5%	5%

Variable	Parameter Key	Adaptation 1	Adaptation 2 and 3
Number of Trucks	D = B x C	294	294
Number of Non-Trucks	E = B – D	5149	5149
Extra Mileage During Closure (per vehicle)[3]	F	14.9	0.0
Truck Total Extra Mileage Driven (miles)	G = A x D x F	788,508	0
Non-Truck Total Extra Mileage Driven (miles)	H = A x B x F	13,809,618	0
Truck Operating Cost per Mile ($/mile)[4]	I	$1.17	$1.17
Non-Truck Operating Cost per Mile ($/mile)[5]	J	$0.60	$0.60
Total Extra Operating Cost ($)	**K = (G x I) + (H x J)**	**$9,199,600**	**$0**
Extra Time per Person (minutes/person)[3]	L	12	5
Total Extra Time (minutes)	M = A x B x L	11,756,880	816,450
Percent Personal Travel (%)[6]	N	87%	87%
Percent Business Travel (%)[6]	O	13%	13%
Value of Personal Travel ($/hour)[6]	P	$15.45	$15.45
Value of Business Travel ($/hour)[6]	Q	$25.24	$25.24
Value of Travel ($)	**R = (M / 60) x (N x P + O x Q)**	**$3,276,739**	**$227,551**
Non-Truck Emissions cost per mile ($/minute)[7]	S	$0.02	$0.02
Truck Emissions cost per mile ($/mile)[7]	T	$0.07	$0.07
Non-Truck Idling Cost per Minute ($/minute)[8]	U	$0.001	$0.001
Truck Idling Cost per Minute ($/minute)[8]	V	$0.069	$0.069
Total Emissions Cost Extra Mileage ($)[9]	**W = (S x H) + (T x G) + (U x M x (1 - C)) + (V x M x C)**	**$336,079**	**$3,596**
Total Cost of Loss of Function ($)	**X = F + R + W**	**$12,812,418**	**$231,147**

[1] Adaptation 1 will result in a total road closure for 180 days (6 months) while the road elevation is altered and the bridge constructed. Adaptation 2 and 3 will result in a single lane closure, with the bridge remaining open, for 30 days.

[2] Annual average daily traffic (AADT) represents the average number of vehicles that pass between two recording stations. We use AADT data between reference points 66 and 67 on US 34A from the Colorado Department of Transportation, Online transportation Information System. Available online at: http://dtdapps.coloradodot.info/otis/TrafficData.

[3] Google Maps estimates the mileage between Estes Park and Loveland Colorado at 29.7 Miles taking 46 minutes. During a bridge closure traffic would use US 36, 66, and 287 to reach the same destination taking 44.6 miles and 58 minutes. The difference, 14.9 miles and 12 minutes equals the extra mileage traveled and travel time for Adaptation 1. Under Adaptation 2 and 3, the bridge is not fully closed, and therefore there is no additional mileage. We assume traffic has an additional travel time of 5 minutes to incorporate single lane wait times.
[4] Operating cost per mile of a tractor trailer from the American Transportation Research Institute. Available online at: http://www.glostone.com/wp-content/uploads/2012/09/ATRI-Operational-Costs-of-Trucking-2012.pdf.
[5] Operating cost per mile of the average sedan from the American Automobile Association. Available online at: http://newsroom.aaa.com/tag/driving-cost-per-mile/.
[6] Value of travel time, in dollars per person hour from the Department of Transportation. Available online at: https://www.transportation.gov/sites/dot.gov/files/docs/USDOT%20VOT%20Guidance%202014.pdf.
[7] Truck and non-truck air pollution costs in dollars per mile from the Victoria Transport Policy Institute. Available online at: http://www.vtpi.org/tca/tca0510.pdf.
[8] Truck and non-truck idling cost per minute are derived from emissions releases in grams per minute (VOC, CO, NO_x, and $PM^{2.5}$) from the Environmental Protection Agency (available at: http://www3.epa.gov/otaq/consumer/420f08025.pdf) and the cost of these pollutants in cost per ton from the Federal Highway Administration (available at: https://www.fhwa.dot.gov/asset/hersst/pubs/tech/tech14.cfm).
[9] Adaptation 1 does not result in extra idling time and so W = (S x H) + (T x G). For Adaptation 2 and 3, (S x H) + (T x G) equals zero.

Projected Stream Flows and Discharge Rates

As discussed in Step 4 of this report, several climate simulations were developed by the research team to evaluate the adaptation alternatives. These simulations are referred to as Simulations 1, 2, and 3 and are described in the text box on page 23. In the economic analysis, these three simulations were used to estimate the incremental costs and benefits of each adaptation option relative to the no-action alternative.

The three climate simulations were used to model the watershed hydrologic process and determine the projected stream flows (in cubic feet per second) from various flood events under existing land cover conditions as well as after a wildfire for each of the different flood events (see Table 11). These seven flood events (referenced as “daily precipitation recurrence intervals” in Step 4) include 2-, 5-, 10-, 25-, 50-, 100-, and 500-year flood events. The discharge values were then linearly interpolated by the research team to obtain discharge volumes for each type of flood for every year in each of the three time periods.[122]

Discharge-Damage Functions

The adaptation alternatives considered in the analysis contain different components and are affected differently by flood and sediment loads. The research team determined rating curves for each adaptation option dependent on the sheer stress, flow rate, and flood depth (see Figure 30, Figure 31, Figure 32, and Figure 33). The summary of the performance of each adaptation option relative to the climate simulation and the presence of a wildfire is presented in Table 17. In many cases, the designs will suffer damages if the discharge and/or the sediment load is greater than the structure can support. The research team estimated discharge-damage

[122] Interpolation is a methodology that can be used to estimate unknown data points using adjacent/surrounding known values. Linear interpolation is a commonly used form of interpolation that assumes a straight-line relationship between known points.

functions for each adaptation option for discharge levels with and without sediment. These curves can be used to estimate the costs needed to repair the structures in response to different discharge and sediment scenarios. In addition, the research team estimated the time that the roadway would be closed to traffic to complete repairs. The roadway closure times are used to estimate the loss-of-function costs. Table 24 presents example discharge-damage functions. The total cost at each discharge volume is a summation of the engineering repair cost and the estimated loss of function (see Table 23) due to road closures during repair.

Table 24: Example Discharge-Damage Functions.

	Existing Bridge No Sediment			Existing Bridge Sediment	
Outcome	Discharge (cfs)	Total Cost ($)	**Outcome**	Discharge (cfs)	Total Cost ($)
	3.2	$ -		3.2	$ -
	5.6	$ -		5.6	$ 8,150
	10	$ -		10	$ 8,360
	17.8	$ -	**Stop of Minor Deposition**	17.8	$ 8,540
	31.6	$ -		31.6	$ 8,540
	56.2	$ -		56.2	$ 8,540
	100	$ -		100	$ 8,540
	177.8	$ -		177.8	$ 8,540
	316.2	$ -		316.2	$ 8,540
	562.3	$ -	**Start Major Deposition**	395	$ 37,700
Overtopping	802.2	$ -	**Overtopping**	402	$ 37,700
	1000	$ -		476	$ 37,700
Start of shoulder erosion	1171.1	$ 66,390	**Start of shoulder erosion**	549	$ 96,090
	1288.3	$ 67,590		591	$ 97,290
	1778.3	$ 75,290		739	$ 104,990
	2673.1	$ 84,190		1408	$ 113,890
Full Breach	2805.6	$ 1,420,042	**Full Breach**	1532	$ 1,449,742
	3162.3	$ 1,433,342		1899	$ 1,463,042
	5411.2	$ 1,480,042		3629	$ 1,509,742
Movement of Culvert Barrel	5623.4	$ 4,840,306	**Movement of Culvert Barrel**	3829	$ 4,870,006
	10000	$ 4,908,306		6998	$ 4,938,006
	17782.8	$ 5,044,606		17201	$ 5,074,306

Flood Event Risk Rates

The economic analysis examined the effects of discharge and sediment loads from seven precipitation recurrence intervals or flood events. These seven flood events included 2-, 5-, 10-, 25-, 50-, 100-, and 500-year flood events. In the analysis, these recurrence intervals were converted to annual risk (i.e., likelihood) rates by dividing 1 by the recurrence interval (or flood event year). For example, the annual risk rate of a 50-year storm is 1/50, or 2 percent. Table 25 presents the flood event risk rates used in the analysis.

Table 25: Flood Event Risk Rate.

Flood Event / Return Period (Year)	Annual Risk
2	50%
5	20%
10	10%
25	4%
50	2%
100	1%
500	0.2%

The analysis used these risk rates as the probability distributions in the Monte Carlo analysis. The Monte Carlo analysis randomly sampled storm events for each year from the distributions above. It was only feasible for the Monte Carlo to sample one storm in each year, and each storm chosen was assumed to be the worst storm event of that year. Therefore, the cumulative damage estimates from the Monte Carlo analysis could be an underestimation of the actual damages if there are multiple significant storms in a single year.

Evaluating Uncertainty Using 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.

Since there is uncertainty in the timing of when extreme precipitation events of particular intensities will occur, the random storm selection process is repeated thousands of different times—5,000 in this analysis—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 increases precipitation and, therefore, the runoff of various storms, the Monte Carlo analysis will tend to feature more 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 represents the best estimate of the cumulative expected value of the damages for the given asset under the given scenario.

Results

Discount Rates

When projecting 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 was incorporated into the analysis. In so doing, the estimated benefits and costs of the adaptation options were reduced by a discount factor that increases over time given a constant rate and base year. The selection of the discount rate greatly impacts the dollar value of the discounted cumulative expected damage costs. Although the relative results—how the adaptation options rank relative to each other—remain consistent regardless of the rate chosen, the dollar values generally decline with a higher discount rate. That is, the higher the discount rate selected, the lower the dollar value of future dollar values when perceived from the base year. The larger a discount rate, the less value is placed on benefits in the future, and reversely, the closer the discount rate is to 0, the more value is placed on future benefits.

For the purposes of this analysis, discount rates of 7 percent and 3 percent were used to test the sensitivity of the results produced using the Monte Carlo analysis. The U.S. Office of Management and Budget (OMB) and the U.S. Department of Transportation (DOT) instruct agencies to use these discount rates to assess benefits and costs that occur at different points in time. The discount rate of 7 percent represents the opportunity cost of private capital, while the alternative rate of 3 percent represents social time preference, or the value of consumption today versus the value of future consumption. Note that the lower the discount rate used, the higher the discounted value of benefit streams accrued in the future.

Outcome Metrics

Two outcome metrics—net present value (NPV) and benefit cost ratio (BCR)—were used by the research team to evaluate the cost effectiveness of the alternatives. The NPV is the difference between the discounted total benefits and the discounted total costs. A positive NPV indicates that the alternative is cost effective and will pay for itself over time. The greater the NPV, the more efficiently an adaptation option uses funds.

The BCR is a numeric ratio that expresses the discounted total benefits relative to its discounted total costs. A BCR greater than or equal to one indicates that the benefits are at least as high as the costs. Similar to the NPV, the larger the BCR, the greater the BCR, the better the investment.

Scenario-Specific Results

The results of the analysis are presented in Table 26, categorized by wildfire scenario (1 through 8) and sub-categorized by climate simulation (wet, moderate, and dry). Each of the 5,000 iterations performed resulted in a distinct NPV and BCR for each alternative based on the specific storm events simulated in that sequence. Results shown in the table below are the average cumulative avoided damages across all 5,000 iterations. Undiscounted results are presented alongside the results discounted at 3 percent and 7 percent.

Due to uncertainty and the difficulty in predicting wildfire probability we present the complete set of results to allow the reader to make comparisons based on their knowledge of the study area or intuition about future climates. Cross-alternative comparisons within each climate simulation and within each wildfire scenario can be made. For example, one possible comparison in wildfire Scenario 1 is to compare Adaptations 1, 2, and 3 under Climate Simulation 3 (i.e. the high precipitation scenario). The results indicate that Adaptation 1 has a NPV of -$14.42M and a BCR of 0.34 (using 7 percent discounting). Both of these outcome metrics suggest that Adaptation 1 is not cost effective under a wet climate (Climate Simulation 3) and if a wildfire occurs in each of the three time periods. Adaptation 3 would be a better choice as the NPV is above zero at $6.58 million, and the design alternative has a BCR of above 1 at 7.33. Cross-climate scenario but within scenario comparisons (for example comparing Adaptation 1 under Climate Simulation 3 to Adaptation 1 under Climate Simulation 1) are possible, and represent how an adaptation option fairs under different climate simulations. The same is true for comparisons across different adaptation options under different climates within the same wildfire scenario (for example, comparing Adaptation 1 under a Climate Simulation 3 to Adaptation 2 under Climate Simulation 1).

The adaptation options can be compared across wildfire scenarios to see how they vary in cost effectiveness in the presence or absence of additional wildfires; however, the research team makes no claim to ranking scenarios in terms of probability. Thus, the results for scenario 1 should be viewed equally compared to scenario 8.

It is worth noting that none of the adaptation options are cost effective if there are no wildfires in any of the time periods (scenario 8) or in the case of one wildfire in the last period (scenario 5) using 7-percent discounting. This is due to the effect of discounting on the analysis. Given the long time horizon of the project (50 years), wildfires that occur in the third time period do not justify the cost of construction when using a high discount rate. The benefits in terms of avoided damages are reduced in the long term and do not justify the large upfront construction costs.

Table 26: Scenario Results.

Scenario[1]	Adaptation	Climate Simulation[2]	Mean Net Present Value[3] (millions of 2016 dollars)			Mean Benefit Cost Ratio[4]		
			No discount	3%	7%	No discount	3%	7%
Scenario 1 (F,F,F)	1	3	$75.03	$3.87	-$14.42	4.28	1.17	0.34
	2	3	$15.34	$4.64	$1.42	21.15	7.10	2.87
	3	3	$96.16	$24.97	$6.58	69.45	22.87	7.33
	1	2	$63.26	$0.21	-$15.76	3.77	1.01	0.28
	2	2	$8.85	$3.28	$1.07	12.62	5.31	2.41
	3	2	$85.07	$21.45	$5.26	61.56	19.78	6.07
	1	1	$51.89	-$3.87	-$17.13	3.27	0.83	0.22
	2	1	$26.17	$7.24	$1.70	35.39	10.51	3.23
	3	1	$73.86	$17.42	$3.91	53.58	16.25	4.77
Scenario 2 (F,F,N)	1	3	$32.78	-$1.70	-$14.86	2.43	0.92	0.32
	2	3	$9.56	$3.88	$1.36	13.56	6.10	2.79
	3	3	$54.22	$19.44	$6.14	39.60	18.02	6.91
	1	2	$25.70	-$4.77	-$16.16	2.12	0.79	0.26
	2	2	$6.98	$3.02	$1.05	10.17	4.96	2.38
	3	2	$47.38	$16.46	$4.86	34.73	15.41	5.68
	1	1	$15.17	-$8.70	-$17.51	1.66	0.61	0.20
	2	1	$17.82	$5.89	$1.57	24.41	8.74	3.06
	3	1	$37.01	$12.57	$3.53	27.34	12.00	4.40
Scenario 3 (F,N,F)	1	3	$33.98	-$8.42	-$17.23	2.49	0.62	0.22
	2	3	$10.59	$3.30	$1.14	14.91	5.33	2.49
	3	3	$55.24	$12.71	$3.77	40.32	12.13	4.63
	1	2	$25.19	-$11.25	-$18.40	2.10	0.49	0.16
	2	2	$5.87	$2.31	$0.82	8.72	4.03	2.07
	3	2	$46.93	$9.96	$2.62	34.41	9.72	3.52
	1	1	$21.58	-$12.90	-$19.18	1.94	0.42	0.13
	2	1	$11.01	$2.76	$0.69	15.46	4.63	1.91
	3	1	$43.36	$8.33	$1.84	31.86	8.29	2.77
Scenario 4 (N,F,F)	1	3	$60.99	-$4.19	-$18.65	3.67	0.81	0.15
	2	3	$9.95	$1.41	-$0.39	14.08	2.85	0.49
	3	3	$81.98	$16.82	$2.28	59.36	15.73	3.20
	1	2	$53.00	-$5.71	-$18.91	3.32	0.74	0.14
	2	2	$4.20	$0.52	-$0.46	6.52	1.69	0.39
	3	2	$74.64	$15.41	$2.03	54.14	14.49	2.96

Scenario[1]	Adaptation	Climate Simulation[2]	Mean Net Present Value[3] (millions of 2016 dollars)			Mean Benefit Cost Ratio[4]		
			No discount	3%	7%	No discount	3%	7%
	1	1	$44.21	-$8.36	-$19.53	2.93	0.62	0.11
	2	1	$22.80	$5.06	$0.38	30.95	7.65	1.50
	3	1	$65.99	$12.80	$1.42	47.98	12.21	2.37
Scenario 5 (N,N,F)	1	3	$19.93	-$16.48	-$21.46	1.87	0.26	0.02
	2	3	$5.20	$0.06	-$0.67	7.84	1.08	0.11
	3	3	$41.06	$4.56	-$0.53	30.23	4.99	0.49
	1	2	$14.93	-$17.18	-$21.55	1.65	0.23	0.02
	2	2	$1.23	-$0.45	-$0.72	2.61	0.41	0.06
	3	2	$36.50	$3.92	-$0.61	26.99	4.43	0.41
	1	1	$13.90	-$17.38	-$21.59	1.61	0.22	0.02
	2	1	$7.63	$0.59	-$0.62	11.02	1.78	0.18
	3	1	$35.49	$3.72	-$0.65	26.26	4.26	0.38
Scenario 6 (N,F,N)	1	3	$18.73	-$9.76	-$19.09	1.82	0.56	0.13
	2	3	$4.18	$0.64	-$0.45	6.49	1.85	0.41
	3	3	$40.05	$11.29	$1.84	29.51	10.89	2.77
	1	2	$15.44	-$10.69	-$19.31	1.68	0.52	0.12
	2	2	$2.33	$0.26	-$0.49	4.07	1.34	0.36
	3	2	$36.96	$10.41	$1.64	27.31	10.12	2.57
	1	1	$7.49	-$13.19	-$19.91	1.33	0.41	0.09
	2	1	$14.44	$3.72	$0.25	19.97	5.89	1.33
	3	1	$29.14	$7.96	$1.04	21.74	7.97	2.00
Scenario 7 (F,N,N)	1	3	-$8.27	-$13.99	-$17.68	0.64	0.37	0.20
	2	3	$4.81	$2.53	$1.08	7.32	4.33	2.41
	3	3	$13.30	$7.18	$3.33	10.47	7.29	4.20
	1	2	-$12.37	-$16.23	-$18.80	0.46	0.27	0.14
	2	2	$4.01	$2.04	$0.80	6.26	3.68	2.04
	3	2	$9.24	$4.97	$2.22	7.58	5.35	3.13
	1	1	-$15.14	-$17.73	-$19.57	0.34	0.20	0.11
	2	1	$2.65	$1.42	$0.56	4.48	2.87	1.74
	3	1	$6.50	$3.48	$1.46	5.63	4.05	2.40
Scenario 8 (N,N,N)	1	3	-$22.32	-$22.05	-$21.90	0.02	0.01	0.00
	2	3	-$0.57	-$0.70	-$0.73	0.25	0.08	0.03
	3	3	-$0.87	-$0.97	-$0.97	0.38	0.15	0.07
	1	2	-$22.64	-$22.15	-$21.95	0.01	0.00	0.00
	2	2	-$0.64	-$0.72	-$0.74	0.16	0.06	0.03
	3	2	-$1.18	-$1.07	-$1.01	0.16	0.06	0.03
	1	1	-$22.81	-$22.21	-$21.97	0.00	0.00	0.00

Scenario[1]	Adaptation	Climate Simulation[2]	Mean Net Present Value[3] (millions of 2016 dollars)			Mean Benefit Cost Ratio[4]		
			No discount	3%	7%	No discount	3%	7%
	2	1	-$0.73	-$0.75	-$0.76	0.05	0.01	0.01
	3	1	-$1.36	-$1.13	-$1.03	0.03	0.01	0.01

[1] Each scenario is followed by 3 letters in parentheses separated by commas. Each letter represents the presence (F) or absence (N) of a fire in the given period. So (F,N,F) signifies that a fire occurred in the first and third time period, and no fire occurred in the second time period.
[2] Please see page 23 for a description of the climate simulations.
[3] The net present value is the present value (or discounted) benefits minus the present value costs. A value greater than zero indicates that the alternative is cost effective (the benefits are higher than the costs). Each of the 5,000 iterations performed resulted in a distinct net present value for that specific outcome of storm events. Results shown in the above table are the average of all of these net present values.
[4] The benefit cost ratio is the present value (or discounted) benefits divided the present value costs. A value greater than one indicates that the alternative is cost effective (the benefits are higher than the costs). Each of the 5,000 iterations performed resulted in a distinct benefit cost ratio for that specific outcome of storm events. Results shown in the above table are the average of all of these benefit cost ratios.

KBDI-Based Results

While performing the economic analysis, the research team concluded that there was a higher probability of some climate simulations resulting in a certain wildfire scenario compared to others. As discussed early in this report, there are many uncertainties over the probability of a wildfire due to the number of confounding components, such as recent weather, vegetation, ignition source, and a degree of pure chance. The research team approximated the change using the KBDI, which is an indicator of weather conditions that increase fire potential. The research team developed KBDI estimates for the each climate simulation (see Figure 9). These KBDI values are an indication that certain climate simulations are more likely to result in specific wildfire scenarios. For example, the dry climate simulation (Climate Simulation 1) has higher KBDI values, and therefore higher the chance of wildfires, and so scenarios with more projected wildfires are more likely to occur.

To determine which climate simulation results were the most appropriate for each wildfire scenario, the research team interpolated the KBDI values to obtain values for all study years and then obtained the average numbers of days with a chance of wildfire for each time period. This average number of days with a chance of wildfire was then converted into an annual risk by dividing the number of days by 365. Then to calculate a relative probability, the risk percentages were multiplied across each period.[123] This methodology has a number of challenging features. First, the analysis has to assume that the chance of wildfire is the same across the different climate simulations. Secondly, only the relative magnitudes of the

[123] This methodology can be likened to determining the probability of flipping a coin and receiving three heads in a row. The probability of the coin landing on heads is 50% in each of the three flips, and to determine the chance the probability of each flip is multiplied together. The outcome of three heads in a row is therefore 12.5% (50% x 50% x 50%).

probabilities can be discussed, not exact percentages. That is, the analysis can only claim that based on the KBDI—or the risk of wildfire—there is a higher probability that the dry climate (Climate Simulation 1) will result in Scenario 1 compared to a wet or moderate climate (Climate Simulations 2 or 3).

Table 27 presents the results of the economics analysis when factoring in KBDI. These results are a subset of those presented in Table 26, and more probable based on the KBDI analysis. The research team presents the results in Table 8 to focus the attention on this subset of results, but any outcome from the full list of results is possible.

Table 27: KBDI Based Scenario Results.

Scenario[1]	Adaptation	Climate Simulation[2]	Mean Net Present Value (millions of dollars)			Mean Benefit Cost Ratio		
			No discount	3%	7%	No discount	3%	7%
Scenario 1 (F,F,F)	1	1	$51.89	-$3.87	-$17.13	3.27	0.83	0.22
	2	1	$26.17	$7.24	$1.70	35.39	10.51	3.23
	3	1	$73.86	$17.42	$3.91	53.58	16.25	4.77
Scenario 2 (F,F,N)	1	3	$32.78	-$1.70	-$14.86	2.43	0.92	0.32
	2	3	$9.56	$3.88	$1.36	13.56	6.10	2.79
	3	3	$54.22	$19.44	$6.14	39.60	18.02	6.91
Scenario 3 (F,N,F)	1	2	$25.19	-$11.25	-$18.40	2.10	0.49	0.16
	2	2	$5.87	$2.31	$0.82	8.72	4.03	2.07
	3	2	$46.93	$9.96	$2.62	34.41	9.72	3.52
Scenario 4 (N,F,F)	1	1	$44.21	-$8.36	-$19.53	2.93	0.62	0.11
	2	1	$22.80	$5.06	$0.38	30.95	7.65	1.50
	3	1	$65.99	$12.80	$1.42	47.98	12.21	2.37
Scenario 5 (N,N,F)	1	2	$14.93	-$17.18	-$21.55	1.65	0.23	0.02
	2	2	$1.23	-$0.45	-$0.72	2.61	0.41	0.06
	3	2	$36.50	$3.92	-$0.61	26.99	4.43	0.41
Scenario 6 (N,F,N)	1	3	$18.73	-$9.76	-$19.09	1.82	0.56	0.13
	2	3	$4.18	$0.64	-$0.45	6.49	1.85	0.41
	3	3	$40.05	$11.29	$1.84	29.51	10.89	2.77
Scenario 7 (F,N,N)	1	3	-$8.27	-$13.99	-$17.68	0.64	0.37	0.20
	2	3	$4.81	$2.53	$1.08	7.32	4.33	2.41
	3	3	$13.30	$7.18	$3.33	10.47	7.29	4.20
Scenario 8 (N,N,N)	1	3	-$22.32	-$22.05	-$21.90	0.02	0.01	0.00
	2	3	-$0.57	-$0.70	-$0.73	0.25	0.08	0.03
	3	3	-$0.87	-$0.97	-$0.97	0.38	0.15	0.07

[1]Each scenario is followed by 3 letters in parentheses separated by commas. Each letter represents the presence (F) or absence (N) of a fire in the given period. So (F, N, F) signifies that a fire occurred in the first and third time period, and no fire occurred in the second time period.

[2] Please see page 23 for a description of the climate simulations.

Discussion

Due to the difficulties in determining the risk of a wildfire, the results of the Monte Carlo economic analysis are presented in their entirety. The research team attempted to refine the results using an approximation of wildfire probability by using the KBDI (Table 27), but narrowing the results further is difficult with the amount of remaining uncertainty. A direct comparison of the BCRs across the alternatives will highlight which project has the highest dollar return per dollar invested, while a comparison of NPVs will demonstrate the difference in costs and benefits. Importantly, the relative magnitudes of BCRs across alternatives may not translate into the same relative difference in NPVs given the differences in the costs of constructing each alternative. For example, in Scenario 8 the BCRs for Adaptation 3 (0.15 and 0.07 at 3% and 7% respectively) are higher than the BCRs for Adaptation 2 (0.08 and 0.03). However, the NPVs for Adaptation 3 are lower (-$0.97) compared to Adaptation 2 (-$0.70 and -$0.73).

One additional metric examined by the research team is the effectiveness of each adaptation option relative to the total number of scenarios. Table 28 presents the number of scenarios, out of the eight wildfire scenarios identified in the KBDI analysis above, in which the alternative has a positive NPV and a BCR value greater than one. Recall that an adaptation option is cost effective in a wildfire scenario if its NPV is positive and its BCR is greater than 1.

Table 28: Number of Scenarios (Out of 8 Total) Where Adaptation is Cost Effective.

Adaptation	3% Discounting	7% Discounting
1	0	0
2	6	5
3	7	6

Note: Adaptations are ranked out of the 8 wildfire scenarios identified in the KBDI analysis.

The results indicate that Adaptation 3 is the most effective adaptation option across the various scenarios. While Adaptation 1 is designed to withstand rare storm events and suffers the least amount of damage from catastrophic storms, it is less efficient (in terms of the usage of funds) than Adaptation 3 due to the significant construction costs, the loss of function of US 34 during construction, and the damages resulting from sediment in the runoff (See Appendix 1 for damage estimates and Appendix 2 for avoided damage estimates). Adaptation 2 is also appealing because of its low construction cost and its cost effectiveness during small scale flooding. However, the significant damages resulting from the 50-, 100-, and 500-year floods, however, make Adaptation 2 less attractive relative to Adaptation 3. Adaptation 3 is cost effective in 7 of the 8 wildfire scenarios using 3-percent discounting; it is only inefficient if no wildfires occur or only one occurs in the third time period (and a 7-percent discount rate is used).

Conclusion

Based on the Monte Carlo economic analysis and the KBDI results, the preferred course of action is the construction of Adaptation 3—the culvert optimized for wildfire land cover and climate simulation 2. While the results indicate that Adaptation 2 is the cheapest to construct, the estimated damages suggest that a wildfire followed by a large storm will result in largescale damages to the structure. Adaptation 1 is designed to withstand all but the largest storms, and the structure is unlikely to be damaged by high flood waters alone. However, given the significant construction costs, the required closure of US 34 to through-traffic for an extended period of time during the construction phase, and the susceptibility to damages from sediment, Adaptation 1 is not cost effective. According to the analysis, Adaptation 3 presents an adaptation option that, while costly, provides cost effective hazard mitigation of runoff in periods without a wildfire while also mitigating damages in periods of wildfire.

The research team acknowledges that there are several limitations to this economic analysis. The largest limitation of this analysis is the uncertainty of wildfire. While significant research has been performed to study the conditions conducive to wildfire, the challenge encountered by the research team is how to estimate the probability of wildfire occurrence conditional on projected climate conditions. There is uncertainty inherent in projections of future precipitation patterns already. Adding to that uncertainty is projecting the other conditions that are conducive to wildfire, as well as the possibility that lightening or other fire spark will occur. Therefore, the research team was unable to calculate probabilities that a wildfire would occur.

The research team developed the scenario approach to mitigate the impacts of unknowable wildfire probabilities, but probability inputs are needed for the Monte Carlo analysis to point to one specific adaptation option as the best. We have included the entire list of results in Table 26 to show the range of possibilities and narrowed the findings down in Table 8 based on KBDI, but there remains underlying uncertainty. While Table 27 displays the most likely outcomes, any one of the rows in Table 26 is possible. In general, Adaptation 3 presents the best design alternative across both the narrowed and full results, but there are specific instances where other designs would be better. For example, Adaptation 2 has higher NPVs under a moderate climate in Scenario 8

Step 9. Evaluate Additional Considerations

Under this step of the ADAP process, the research team evaluated additional decision-making factors that cannot be adequately captured by the economic analysis of the facility. This includes other factors that reflect environmental and political concerns as described below.

Environmental Drivers

Since US 34 follows along the top stream bank of the Big Thompson River, any adaptation options under consideration that would require raising of the roadway will cause an encroachment into Big Thompson River. Encroachment into the stream would be caused by the slope grading from a higher roadway down to the toe of slope at the stream. Encroachment into Big Thompson River will cause significant impacts to FEMA regulatory floodplains and loss of regulatory waters of the United States with natural trout habitat. These impacts may require design modification such as the inclusion of reinforced concrete retaining walls to keep the slope fill out of Big Thompson River.

Political Drivers

In the aftermath of the 1976 and 2013 flood events, public and political pressure required CDOT to re-open the road on a highly accelerated schedule to provide access along the corridor and to Estes Park. Following the September 15, 2013 washout of US 34, Colorado Governor John Hickenlooper mandated that CDOT would ensure that the roads were passable by December 1st of the same year. These political drivers necessitated the construction of a temporary roadway that would later require a permanent replacement project. The 2013 temporary construction is slated for permanent replacement from 2016 through 2017. The cost of performing a temporary replacement to be followed later by a permanent reconstruction is more costly than other options for resilient construction during the normal replacement cycle for infrastructure. In general, based on discussions between the research team and the US 34 Flood Recovery Team, it is expected that emergency replacement with a permanent structure for this type of infrastructure would be on the order of 1.5 times the standard replacement construction costs. Whereas, the emergency replacement with a temporary structure followed later by a permanent structure would be on the order of two times the standard replacement construction costs.

If similar extensive damage occurred to US 34 again, it can be anticipated that political leadership would require an accelerated approach, due to the importance of the road. The type of accelerated construction would presumably be dependent on the magnitude of damage that occurs during the event. If the damage to US 34 were limited to just the subject structure of this study, it is the research team's expectation that emergency replacement with a permanent structure would occur. While a larger damage event, such as a larger wildfire that burns significant canyon area beyond this one watershed followed by a flood, may again result in accelerated construction with a temporary replacement.

In consideration of accelerated reconstruction, it may be more cost-effective for an asset owner to select a design that provides the highest level of damage avoidance even if the initial capital cost is more expensive, as it could help avoid paying premium costs for emergency repairs. While the economics analysis included consideration for repairs to future damages and cost inflation associated with rapid response and accelerated schedule repairs, it does not consider temporary reconstruction of the damages for the same failure event. The research team recognizes that the decision making process that necessitates the emergency reconstruction of a temporary replacement roadway, followed later with a permanent reconstruction is not a trivial process and is expected to apply only to special cases of large scale damage.

Step 10. Select a Course of Action

This case is unique in that the lack of probability information caused the research team to recommend a course of action not evaluated during the economic analysis in Step 8.

The economic analysis performed in Step 8 concluded that the most economical course of action considering the various wildfire occurrence scenarios is the construction of Adaptation 3—the stream crossing designed for Wildfire land cover and Climate Simulation 2 precipitation. However, this conclusion was not able to fully encapsulate the influence of wildfire probability in determining between a proactive and a reactive treatment approach to wildfire. In consideration of the anticipated low probability of wildfire occurrence in the study watershed, the research team is recommending that a reactive approach be employed in the design of the replacement culvert structure for US 34 at Canyon Cove Lane.

Among the two reactive approaches outlined in this study, the research team is recommending the one that includes using the Adaptation 2 culvert design and retrofitting it to the Adaptation 3 design if a wildfire occurs (Adaptation X). The culvert adaptation approach is recommended over the watershed treatment (Adaptation Y) due to both initial capital costs and long-term maintenance costs of the two approaches. Review of the site context shows that there are no immediate downstream private properties of concern on the Canyon Cove Lane tributary. Once flows from the tributary have combined with Big Thompson Creek, the size of the tributary flows (including the debris flows) are inconsequential compared to the flow rates in Big Thompson Creek, thus the downstream benefits of the watershed approach are not as significant as may be seen in other locations. However, the research team recognizes that significant benefits and risk reduction will be realized by the DOT participating in watershed restoration programs with other stakeholders in the aftermath of a wildfire. In these cases participation with non-profits, private property owners, and other state/federal agencies is the recommended approach over DOT-led comprehensive watershed treatment.

The research team's recommendation considers both the findings of the economic analysis and the low probability of wildfire occurrence. Under Adaptation X, the culvert is to be reconstructed in the present day with a modified version of Adaptation 2. The modifications are to be incorporated into the design to facilitate future adaptation of the culvert to meet the design of Adaptation 3 in the event of a wildfire occurrence. The research team sized Adaptation 2 for the Climate Simulation 3 precipitation without developing detailed studies for lower precipitation climate scenarios. However, the resultant culvert size recommendation for Climate Simulation 3 (Twin 8'x8' box culverts) represents a minor increase over the existing culvert size (twin 6'x8' box culverts), thus following Step 6 of the ADAP process, the costs of adaptation would be considered small and the Adaptation 2 culvert adaptation design is recommended.

Step 11. Develop a Facility Management Plan

Regardless of which system adaptation option is chosen (if any), the climate drivers in the region should not be expected to remain constant as is generally assumed in the traditional engineering design process. Thus, the performance of the facility and regional climate trends should be monitored after the project is constructed (or it is determined that the existing culvert be left in place). The effects of changing climate trends on the culvert site should be revisited and periodically assessed to determine if the culvert's design standards are being exceeded. Such monitoring and periodic assessment can help indicate if it might be necessary to implement additional improvements, change design guidelines, and/or alter operation and maintenance practices.

The recommended adaptation option, Adaptation X, is defined by the team as a reactive practice with future improvements to the stream crossing proposed in the event of a wildfire occurrence. Under this recommendation, a facility management plan that monitors conditions and maintains sufficient maintenance staff operational capabilities is needed. In addition, the owner/agency is recommended to establish and maintain funding mechanisms that allow for quick mobilization of resources (staff/engineering consultants/contractors) to respond and implement adaptations to wildfire events.

In the event that a wildfire burnout of the watershed were to occur, more intensive maintenance operations are advisable, even if the recommended adaptation option is constructed. As noted by the research team in the analysis of the facility performance curves, low flows for each of the adaptation options have channel boundary shear stresses that are insufficient to mobilize debris flow sediments. While these low flows will not mobilize significant volumes of debris sediments, the researchers expect that smaller amounts of debris sediments will be. Incremental accumulation of these smaller volumes of sediment at the entrance to the culverts will impair the culverts hydraulic performance over a short period of time (on the order of months). Periodic maintenance clean-outs will be required to mitigate these sediment accumulations. If the existing facility remains, or if an adaptation option with a lower degree of sediment mobility is chosen, more frequent sediment clean-outs will be necessary, as higher flows will drop more significant volumes of sediment.

Also, in the event of a wildfire burn-out in the watershed, the impacts of large woody debris in the debris flows are a performance concern for the US 34 crossings. The research team did not include large woody debris in the sediment/debris flow analysis as means for estimating the concentration and characteristics of large woody debris were not found in the available literature. However, the potential for accumulation of large woody debris at the US 34 crossings must not be discounted by CDOT and should be monitored for build-up and immediately removed as a maintenance activity.

In the event of a wildfire burn of the watershed, it is highly recommended that the watershed best management practices as documented in the BAERCat publication be implemented as a mitigation measure. Even with the construction of a more resilient crossing at US 34, there will be performance risks due to incremental sediment accumulation and any large woody debris blockages. Additionally, the mobilization of watershed sediments will represent a health and water quality impact to the downstream natural fish waters.

At the study site, monitoring of both changing precipitation patterns and of regional wildfire occurrence are recommended. Trends in precipitation for the facility owner to track include: depth of precipitation during extreme precipitation events, peak intensity of extreme precipitation events, and frequency of extreme precipitation events. Changing trends in each of these precipitation characteristics may be indicative of shifts in the climate of the region. The research team also recommends that the facility owner track trends in regional wildfire occurrences, drought occurrences and longevity, and forest stand mortality for indications of changing wildfire risk at the project site.

Lessons Learned

The study on the US 34 culvert provides a framework for an engineering analysis method that could be followed by roadway designers to incorporate the hydrologic impacts of a future wildfire burn on the size of roadway crossings. However, several limitations that influence the robustness of the study should be addressed by future research, including:

- **Research is needed on the impacts of climate change on wildfire probability.** A better understanding of the future probability of wildfire occurrence for a given area would add to the robustness of engineering studies and economic analyses. While there are potential models[124] for prediction of wildfire occurrence, the available models found in literature have prohibitively complex model inputs. More research on this topic would help lower the barrier to conducting similar analyses in other locations.

- **Care is needed when processing and interpreting projection information, particularly when some models/scenarios project negative changes and others project positive changes.** The traditional approach for developing precipitation projections, which utilized ensemble statistics for each climate scenario, masked much of the plausible future conditions and did not provide an adequate representation of the individual model storylines. For example, some models projected significant increases in precipitation and others projected significant decreases; taking an average of the results could misleadingly indicate a change close to zero. To address this issue, the research team developed a binned approach to data processing that pulled out samples of future conditions to provide a better representation of the potential range of future conditions which ranged from wetter to drier conditions.
- **When considering more than one future climate variable (e.g. precipitation and wildfire risk), different climate/model scenarios can exhibit different outcomes for each climate variable under consideration. An example may be a scenario/model combination that shows the greatest decrease in precipitation may not be the one that shows the greatest increase in wildfire risk (and in fact, it might show a decrease in wildfire risk).** Therefore a study considering multiple climate variables will need to consider a range of scenario / model combinations to determine the best representation for all variables of interest. In this case study, wildfire occurrence is influenced by multiple factors besides just precipitation, although in general, the most extreme decreases in precipitation tended to be associated with decreases in wildfire risk. So, the research team developed 3 different simulations narratives that represented varied levels of future precipitation projections with corresponding changes in wildfire risk (KBDI).
- **The impact of wildfire burns on watershed hydrologic processes and stream runoff can be much more significant than the impact of climate change on precipitation.** Thus, it is important that more research is focused on understanding the impacts of climate change on wildfire. Focusing on precipitation-related aspects of climate change will not provide a full picture of potential impacts on watershed hydrologic processes and stream runoff.
- **An improved method for projecting post-fire burn severity is needed.** Wildfire burn watershed models are generally dependent on mapping of the watershed's soil burn severity after a wildfire occurs. Development of a predictive model for soil burn severity

[124] Preidler et al., 2004.

is a necessary step in the development of predictive design models that include wildfire burn. For this case study, the research team performed a cross-correlation between soil burn severity and wildfire intensity in an attempt to bridge this gap. However, the analysis was limited to a single data set (High Park Fire data set). So, although the analysis yielded a conversion relationship between the wild fire intensity rankings and soil burn severity, this relationship has only regional applicability. The research team was not able to include multi-variate data sets into the analysis, but felt that other factors such as soils types, initial soil moisture content, or groundwater level should influence the correlation between the fire intensity and soil burn severity rankings.

- **Additional research is needed into the rates of transport for debris flows with hyper-concentrated sediment loads to supplement the current study findings.** The research team chose the use of relative channel boundary stress versus critical shear stress to quantify the ability of stream system and US 34 crossing to convey sediment/debris flow. However, the research team recognizes that shear stress analysis only represents part of the sediment transport process. Transport rate relationships would supplement the shear stress based analysis by quantifying not only the ability of the channel to move a certain size sediment, but also by identifying the rate at which the sediment is conveyed by stream flows. Determination of sediment conveyance rates and comparative conveyance rates at the upstream and through hydraulic crossings (such as culverts or bridges) would allow for a more in-depth investigation into channel aggradation patterns under debris flow conditions.
- **Additional research into the large woody debris content and shape/size properties for post-wildfire debris flows would be required to supplement the current study findings.** The debris flow considerations included in this study focused on the sediment content of the debris flows. The research team recognizes that large woody debris is reasonably expected to be present in post-wildfire debris flows and would alter the dynamics of debris flows, particularly at the entrance to a culvert. Large woody debris in the post-wildfire debris flows would be expected to consist of the partially burnt remains of large tree limbs or trunks that have been felled and transported to the channel. The inclusion of large woody debris in the debris flows represents an increased risk of debris jamming at the entrance to a culvert and a substantial decrease in the sediment/debris transport efficiency of that structure.
- **More guidance and research is needed regarding the proper use of sub-24 hour precipitation projection information.** There are inherent uncertainties in the statistical frequency analysis of extreme precipitation events, and the use of projected climate data to inform these analyses to produce reliable and robust results is an area actively being researched. However, in the practice of hydrologic analysis, the use of sub-24 hour data is frequently necessary for proper calibration of peak stream flows from

watersheds. The need for sub-24 hour data increases with the analysis of smaller watersheds. As this is an area of active research, the climate modeling community may be moving towards providing such guidance and confidence in using sub 24-hour data in such frequency analysis. In addition, as more climate data become publically available, downscaled sub 24-hour data may become available in the future to inform such analysis.

- **HEC-RAS may not be the best resource for modeling riverine conditions when hyper-concentrated sediment flows are anticipated.** The use of HEC-RAS for modeling of riverine conditions is a standard practice for hydraulic engineers in the development of designs for highway bridge and culvert crossings. However, in the case of hyper-concentrated sediment flows, such as post-fire debris flows, the use of HEC-RAS needs to be carefully considered. The basic mechanics behind the computations in HEC-RAS assume that the flowing fluids are acting as Newtonian fluids. A debris flow may not necessarily act following the properties of a Newtonian fluid, depending on the level of sediment concentration. In practice, it is accepted that flows with bulking factors up to two can be modeled as Newtonian flows in HEC-RAS. Application of other models, such as FLO-2D, that have specific debris flow capabilities should be considered in other applications with hyper-concentrated debris flows that exceed a bulking factor of two.

Appendix 1: Damages

Table A-1 presents the estimated mean total storm damages for each alternative across the three time periods. Scenarios are limited to the narrowed set identified in the KBDI analysis (see Table 27 for more information).

Table A-1: Estimated Total Storm Damage.

Scenario[1]	Adaptation	Climate Simulation	Mean Damages (millions of dollars)		
			Undiscounted	3%	7%
Scenario 1 (F,F,F)	1	1	$1.19	$0.44	$0.20
	2	1	$49.00	$10.79	$2.60
	3	1	$0.67	$0.23	$0.10
Scenario 2 (F,F,N)	1	2	$0.79	$0.38	$0.20
	2	2	$46.11	$16.27	$5.19
	3	2	$0.80	$0.32	$0.14
Scenario 3 (F,N,F)	1	3	$0.79	$0.31	$0.18
	2	3	$42.20	$8.22	$2.17
	3	3	$0.50	$0.18	$0.10
	1	1	$0.80	$0.17	$0.03

Scenario 4 (N,F,F)	2	1	$44.31	$8.22	$1.34
	3	1	$0.47	$0.10	$0.02
Scenario 5 (N,N,F)	1	2	$0.40	$0.05	$0.00
	2	2	$36.20	$4.79	$0.39
	3	2	$0.28	$0.04	$0.00
Scenario 6 (N,F,N)	1	3	$0.41	$0.12	$0.03
	2	3	$37.06	$11.18	$2.60
	3	3	$0.54	$0.15	$0.03
Scenario 7 (F,N,N)	1	3	$0.39	$0.26	$0.17
	2	3	$9.40	$5.20	$2.64
	3	3	$0.26	$0.17	$0.11
Scenario 8 (N,N,N)	1	3	$0.00	$0.00	$0.00
	2	3	$0.35	$0.11	$0.05
	3	3	$0.00	$0.00	$0.00

[1]Each scenario is followed by 3 letters in parentheses separated by commas. Each letter represents the presence (F) or absence (N) of a fire in the given period. So (F, N, F) signifies that a fire occurred in the first and third time period, and no fire occurred in the second time period.

Appendix 2: Avoided Damages

Table A-2 presents the estimated mean total avoided storm damages for each alternative across the three time periods. These estimates represent the avoided damages that result from constructing one of the design alternatives compared to using the existing structure. Scenarios are limited to the narrowed set identified in the KBDI analysis (see Table 27 for more information).

Table A-2: Estimated Total Avoided Storm Damage.

Scenario[1]	Adaptation	Climate Simulation	Mean Avoided Damages (millions of dollars)		
			Undiscounted	3%	7%
Scenario 1 (F,F,F)	1	1	$97.89	$26.10	$7.56
	2	1	$16.10	$5.40	$2.18
	3	1	$97.56	$26.11	$7.61
Scenario 2 (F,F,N)	1	3	$55.64	$20.53	$7.11
	2	3	$10.32	$4.64	$2.12
	3	3	$55.63	$20.59	$7.17
Scenario 3 (F,N,F)	1	2	$48.05	$10.98	$3.58
	2	2	$6.63	$3.07	$1.58
	3	2	$48.33	$11.11	$3.66
Scenario 4 (N,F,F)	1	1	$67.07	$13.87	$2.45
	2	1	$23.56	$5.83	$1.14
	3	1	$67.40	$13.95	$2.46
Scenario 5 (N,N,F)	1	2	$37.78	$5.05	$0.43
	2	2	$1.99	$0.31	$0.04
	3	2	$37.91	$5.06	$0.43
Scenario 6 (N,F,N)	1	3	$41.59	$12.46	$2.89
	2	3	$4.94	$1.41	$0.31
	3	3	$41.45	$12.43	$2.88
Scenario 7 (F,N,N)	1	3	$14.58	$8.23	$4.30
	2	3	$5.57	$3.30	$1.84
	3	3	$14.71	$8.33	$4.37
Scenario 8 (N,N,N)	1	3	$0.53	$0.17	$0.07
	2	3	$0.19	$0.06	$0.03
	3	3	$0.53	$0.17	$0.07

[1]Each scenario is followed by 3 letters in parentheses separated by commas. Each letter represents the presence (F) or absence (N) of a fire in the given period. So (F, N, F) signifies that a fire occurred in the first and third time period, and no fire occurred in the second time period.

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