Addressing Resilience in Project Development

U.S. Department of Transportation
Federal Highway Administration

Wildfire and Precipitation Impacts to a Culvert

This study focuses on the impacts of future changes in precipitation and wildfire risk on the design and performance of a culvert crossing.[1]

Site Context and Facility Overview

The culvert selected for study is located on US 34 northwest of Denver, Colorado between Loveland and Estes Park. US 34 runs along the Big Thompson River using the Big Thompson Canyon, and has a history of devastating floods. Severe flooding in July 1976 and September 2013 destroyed many sections of US 34 through the canyon. The 1976 flood greatly exceeded 100-year flood estimates, while the 2013 flood was roughly at 100-year flood levels.

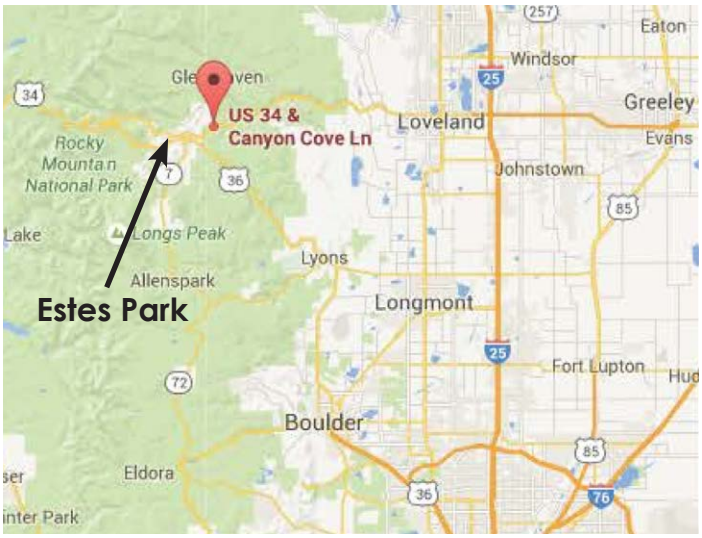

Figure 1: Map of study area.
Image Source: Google Maps

In addition to flooding concerns, the study site is in an area that is at-risk for wildfire occurrence. Wildfire burns are known to have significant impacts on post-fire flood events, as the fire-scarred land is more prone to increased flooding and debris flows. Thus, the combination of wildfire and extreme precipitation events can cause significantly more damage than either one alone.

Notably, the occurrence and impact of wildfire in Colorado has been increasing from less than 500 events per year with 100,000 acres per year burned in the 1960s to over 2,000 events per year with more than 1 million acres burned in the 2000s. While many factors may have contributed to this increasing trend, it is reasonable to expect that wildfire risk will increase if these factors persist and are magnified by changing future conditions.

The culvert, situated within the canyon, conveys a small unnamed stream under US 34 to its point of discharge into the Big Thompson River. The culvert was constructed during reconstruction work after the 1976 Big Thompson River flood. It has twin cells, each of which are eight-foot wide by five-foot high reinforced concrete boxes.

Environmental Stressors and Scenarios

The intensity of precipitation is expected to increase. Wildfire potential may increase in several ways. For example, the moisture state of potential fuel sources or daily weather conditions (e.g. hot and dry conditions) influence fire potential.

The research team investigated the following specific stressors:

- Chance in wildfire potential, which is a measure of the chance that a fire of a certain severity will occur. Specifically, the team considered changes in the Keetch-Byram Drought Index (KBDI), an indicator of conditions conducive to wildfires, which considers fuel and soil moisture levels and weather conditions.
- Changes in the magnitude of the 2-, 5-, 10-, 25-, 50-, 100-, and 500-year precipitation events.

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

The projections show general increases in the expected wildfire potential (based on KBDI scores) under each of the future conditions narratives. While the KBDI scores indicated an increasing trend, specific probabilities of fire occurrence could not be determined by this study. Precipitation projections from the analysis exhibited varied trends across the narratives, with increases, decreases, and minimal change resulting.

The results of the analysis were grouped into three simulations for further analysis in the engineering study (Simulations 1, 2, and 3). Simulations 1, 2, and 3 are representative of the 10th, 50th, and 90th percentile conditions for the 33 climate models, respectively. Samples of the future projections by simulation are shown in Table 1 and 2.

Year	KBDI (number of wildfire potential days)		
	Sim. 1	Sim. 2	Sim. 3
Baseline	163		
2045	217	185	188
2065	260	214	179
2085	256	217	187

Table 1: Projected change in wildfire potential expressed as a number of yearly days with increased risk KBDI values. Data is reported as the mid-point year of a 30-year ensemble.

Return Period	Obs. (NOAA)	2085		
		Sim. 1	Sim. 2	Sim. 3
10 Year	2.41	-4%	-2%	+24%
50 Year	3.75	-9%	-3%	+27%
100 Year	4.49	-11%	-4%	+27%

Table 2: Projected changes (in inches) of the daily 10-, 50-, and 100-year storm event precipitation for year 2085 (relative to the NOAA Atlas 14 Baseline).

A comparison of the simulations shows that future projections with decreases in extreme event precipitation (i.e. drier climates) result in significant increases in wildfire risk, while increases in extreme event precipitation are associated with more moderate shifts in wildfire risk.

Analytical Approach - Overview

The research team divided the analytic approach for this study into two primary groups: watershed hydrology and facility hydraulics. First, researchers performed the watershed hydrology analyses to determine the stream flow rates based upon watershed and precipitation characteristics. Then the team created variants of the watershed model by incorporating wildfire burn effects and projected future precipitation amounts.

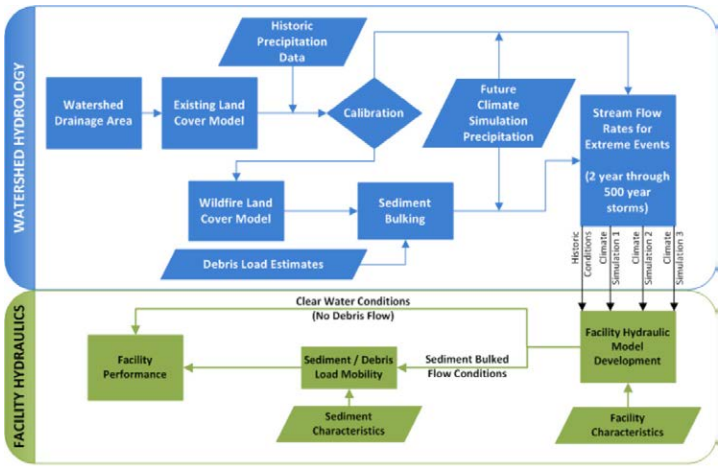

Figure 2. Analytic approach to the CO Wildfire Study.

The team utilized the stream flow rates from the watershed hydrology analyses 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 general process followed in the analytic approach is shown Figure 2.

Overcoming Challenges

The team encountered a significant hurdle in quantifying soil burn severity for the development of the wildfire burn watershed model. Soil burn severity is only mapped after a burn has occurred, but is a common metric used in wildfire burn models. Development of a predictive model for soil burn severity is a necessary step in the development of a proactive model that includes wildfire effects. For this case study, the research team performed a cross-correlation between soil burn severity and a predicted wildfire intensity[2] to bridge this gap.

Results

The design standard for the study culvert is to convey the 25-year storm, which is 838 cubic feet per second. Based on the hydraulic study, the existing culvert meets the design storm under current conditions. However, it would not meet design standards under possible future conditions such as Simulation 2, starting at mid-century. Furthermore, the existing structure would be substantially overtopped by flooding under all wildfire simulations. The analysis indicates that the impact of wildfires is dramatic, with flows increasing by up to 330 percent over non-fire conditions.

Furthermore, under post-wildfire conditions, significant debris flows are expected in the stream. Under debris flow conditions, 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 flows being more readily conveyed across the roadway surface, causing damage to the roadway and loss of service.

Adaptation Options

As shown in Table 3, the research team developed five possible adaptation options for the site to provide added resilience for the culvert. These options include three proactive adaptation options that would be constructed in the present day, and two reactive adaptations that would be pre-planned but built only after a wildfire event occurs.

Proactive Adaptation Options - Present Day Construction			
Adaptation	1	2	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
Design Target	50-year storm with wildfire, Simulation 3	25-year storm, Simulation 3	50-year storm with wildfire, Simulation 2
Pro	Conveys all storms	Lowest cost	Nexus of cost and performance
Con	Highest cost	Limited conveyance/ poor wildfire performance	Does not meet worst-case climate/wildfire condition
Present Day Capital Cost	$9.07M	$530,000	$753,600

Reactive Adaptation Options		
Adaptation	X	Y
Design	Post-fire culvert adaptation	Post-fire watershed treatment
Present Day Construction Features	Twin cell 8-foot by 8-foot box culvert with road-way upgrades	Maintenance up-keep of current culvert
Future Construction Features	Expansion of culvert with a third 8-foot by 8-foot culvert cell	Debris basin, silt fence, hydromulch, and erosion barriers/dams
Pro	Delays construction until necessary; minimizes current and future costs	Treats source of flows/ debris; protection of property/infrastructure outside of culvert
Con	Does not meet worst-case climate/ wildfire condition	Cost; right-of-way constraints
Present Day Capital Cost	$550,000	$0
Future Capital Cost *if* a Wildfire Occurs	$450,000	$3.26M

Table 3. Summary of adaptation options.

[2] Wildfire intensity for the state is mapped by the Colorado Wildfire Risk Assessment Program.

Economic Analysis

The economic analysis performed by the team consisted of evaluation of economic impacts due to loss of service on US 34, which were then utilized in a Monte Carlo analysis of benefit/cost performance of proactive Adaptations 1 through 3. The Monte Carlo analysis developed by the team included a scenario approach, which included different variations of wildfire occurrence/non-occurrence in the determination of adaptation performance/benefits. The team could not perform a Monte Carlo analysis on reactive Adaptation Options X and Y due to the lack of wildfire probability, which the researchers judged to be necessary for cross-evaluation between the reactive and proactive approaches.

Economic impacts considered in the analysis included loss of tourism revenue and increased travel times. The team determined benefits for each option as the limitation of economic impacts. Capital costs and maintenance costs were included on the cost side of the relationship.

The results of the economic analysis indicated that Adaption 3 provided the greatest benefit-cost relationship of the three proactive alternatives. However, implementation of Adaptation 3 would still require significant capital outlay, as it would need to be applied to multiple culverts in the area since it is unknown which culvert(s) would experience a wildfire event.

Recommended Course of Action

Due to the high cost of Adaptation 3, the research team recommended implementation of a reactive approach, which involves waiting until a wildfire event occurs before modifying the culvert. The study team made this recommendation because the probability of wildfire occurrence at a specific location is low, despite increasing trends as indicated by the KBDI evaluation.

Among the two reactive approaches, the research team recommends Adaptation X due to both initial capital costs and long-term maintenance costs of the two approaches.

Key Lessons Learned

- Research is needed on the impacts of future environmental conditions on wildfire probability. A better understanding of wildfire probability for a given area would add to the robustness of engineering studies and economic analyses.
- 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 scenario, masked much of the plausible future conditions and did not provide an adequate representation of the individual model storylines.
- The impact of wildfire burns on watershed hydrologic processes and stream runoff can be much more significant than the impact of potential changes in precipitation.

For More Information

Resources:

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

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

Contacts:

Robert Hyman
Sustainable Transportation & Resilience Team, FHWA
Robert.Hyman@dot.gov, 202-366-5843

Robert Kafalenos
Sustainable Transportation & Resilience Team, FHWA
Robert.Kafalenos@dot.gov, 202-366-2079

Brian Beucler
Hydraulics and Geotechnical Engineering Team, FHWA
Brian.Beucler@dot.gov, 202-366-4598

Khalid Mohamed
Hydraulics and Geotechnical Engineering Team, FHWA
Khalid.Mohamed@dot.gov, 202-366-0886