COLORADO
Department of Transportation

Colorado Department of Transportation

Risk and Resilience Analysis Procedure

A Manual for Calculating Risk to CDOT Assets from Flooding, Rockfall, and Fire Debris Flow

2020

aem

This procedure was developed, prepared, and reviewed between 2018-2020 by Applied Engineering Management Corporation (AEM) and a team of CDOT subject matter experts representing all CDOT regions and many disciplines. This procedure, parameters, variables and text have been developed explicitly for the Colorado Department of Transportation. The risk assessments examples listed in this procedure are examples taken from the I-70 Pilot Risk and Resilience Project completed in 2017 and the procedure has not been tested outside of the I-70 mainline facility. The procedures represent the best-known estimates of risk to specific highway assets from specific threats at this time. The state of the practice at this time is emerging and more research is needed to standardize methods across the highway industry.

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LIST OF EXHIBITS

GLOSSARY

Adaptation - Adjustment in natural or human systems in anticipation of or response to a changing environment that effectively uses beneficial opportunities or reduces negative effects.

Asset - An item, thing, or entity that is owned by and has potential or actual value to an organization.

Asset Management - The strategic and systematic practice of procuring, operating, inspecting, maintaining, rehabilitating, and replacing capital assets to manage their performance, risks, and costs over their life cycles, for the purpose of providing safe, cost-effective, and reliable transportation service.

Asset Replacement Cost – The anticipated cost to replace a damaged highway asset utilizing planning level estimates of unit costs.

Avulsion - The process in which a debris flow obstructs the main channel of movement and proceeds to spill over and outside the boundaries of the original hydraulic channel.

Climate Change - Refers to any significant change in the measures of climate lasting for an extended period. Climate change includes major variations in temperature, precipitation, or wind patterns, among other environmental conditions, that occur over several decades or longer. Changes in climate may manifest as a rise in sea level, as well as increase the frequency and magnitude of extreme weather events.

Consequence - The outcome of an event, including immediate, short and long-term, direct and indirect losses and effects.

Countermeasures - What is in place or could be put in place to reduce the vulnerability of an asset, and/or the probability that an attack will succeed in causing failure or significant damage.

Critical Assets - Assets, that if lost or damaged, would severely degrade or curtail an owner's ability to perform core functions or its mission.

Criticality – A measure of the importance of an asset to the resilience of an overall system.

Extreme Weather Events - Weather events that can include significant anomalies in temperature, precipitation and winds and can manifest as heavy precipitation and flooding, heatwaves, drought, wildfires and windstorms (including tornadoes and tropical storms). Consequences of extreme weather events can include safety concerns, damage, destruction, and/or economic loss. Climate change can also cause or influence extreme weather events.

Lane Mile - One continuous mile of highway that includes one single travel lane.

Mitigation - An action or investment to reduce or eliminate risk to people and property from potential hazards and their effects.

Performance Measure - A measurable result related to either quantitative or qualitative answers.

Preparedness - Actions taken to plan, organize, equip, train, and exercise to build, apply, and sustain the capabilities necessary to prevent, protect against, ameliorate the effects of, respond to, and recover from climate change related damages to life, health, property, livelihoods, ecosystems, and national security.

Redundancy - A measure of alternative routes available.

Resiliency - The ability of a system to rebound, positively adapt to, or thrive amidst changing conditions or challenges, including human-caused and natural disasters, and to maintain quality of life, healthy growth, durable systems, economic vitality, and conservation of resources for present and future generations.

Risk - An uncertainty that can have either positive or negative impacts.

Risk Management - Inclusive management strategies that address risks, including mitigation strategies and preparedness approaches for emergencies.

River Flood - Occurs when the river water levels rise and overflow their banks or the edges of their main channel and inundate areas that are normally dry and can be caused by heavy rainfall, dam failure, rapid snowmelt and ice jams.

Rockfall - A fragment of rock (a block) detached by sliding, toppling or falling, that falls along a vertical or sub-vertical cliff, proceeds down slope by bouncing and flying along ballistic trajectories or by rolling on talus or debris slopes.

Bridge Scour - The erosion caused by water to the soil surrounding a bridge foundation (piers and abutments).

Threat - Any indication, circumstance, or event with the potential to cause the loss of, or damage to, an asset, system or network.

Threat Characterization - Process to identify possible scenarios and describe in enough detail to estimate vulnerability and consequences.

Threat Likelihood - Probability that an event will occur.

Threat Assessment - A systematic process of estimating threat likelihood, determined based on historical frequencies or predictions from scientific tools and expert opinion.

Vulnerability - The probability of a successful event. The probability that the anticipated Worst Reasonable Consequence for a specific magnitude of an event occurs.

Vulnerability Assessment - A systematic process to estimate an asset or network vulnerability to a specific threat using scientific studies and/or expert opinion.

Work Zone – A restriction of roadway throughput resulting from full or partial lane closures.

Worst Reasonable Consequence -The largest anticipated magnitude of an event.

TERMS

C2....................vehicle running cost ($/vehicle-mile)
C3....................freight running cost ($/truck-mile)
C4....................average value of time ($/adult-hour)
C5....................average value of freight time ($/truck-hour)
C7....................difference in distance between detour and original route (mile)
C8....................vehicle running cost ($/vehicle-hour)
C9....................freight running cost ($/truck-hour)
D_{FC}..................number of full closure days (days)
D_{PC}..................number of days of partial closure (days)
Dt....................extra travel time on detour (minutes)
L......................length of roadway
LM..................lane miles
LW..................lost wages ($)
LW_{FC}................lost wages full closure ($)
LW_{PC}................lost wages partial closure ($)
O.....................average occupancy (adult/vehicle)
OC...................owner consequence *i*
OC_i..................owner consequence for a given event *i* ($)
OR...................owner risk ($)
OR_{Annual}...........total annual owner risk ($)
OR_T.................total owner risk ($)
R_{Annual}..............total annual risk ($)
T......................threat likelihood
TAR................total annual risk ($)
Ti.....................threat likelihood for a given event *i*
UC...................user consequences ($)
UC_{FC}................user consequences full closure ($)
UC_i..................user consequence for a given event *i* ($)
UC_{PC}................user consequence partial closure ($)
UR...................user risk ($)
UR_{Annual}...........total annual user risk ($)
UR_T.................total user risk ($)
V.....................vulnerability
Vi....................vulnerability for a given event *i*
VOC................vehicle operating costs ($)
VOC_{PC}.............vehicle operating costs delay ($)
VOC_{FC}.............vehicle operating costs full closure ($)
W.....................roadway width (feet)
WL..................work zone length (mile)
WZS................work zone speed limit (mph)
WZSR.............work zone speed reduction (mph)

ACRONYMS

AADT..............Annual Average Daily Traffic
AASHTO ....Association of American State Highway and Transportation Officials
AEM Corp ......Applied Engineering Management Corporation
ARC.................Asset Replacement Cost
BAER...............Burned Area Emergency Response
CBC ....Concrete Box Culvert
CDOT..............Colorado Department of Transportation
CGS ....Colorado Geological Survey
CWCB ....Colorado Water Conservation Board
DF ....Debris Flow
ER ....Emergency Relief
FEMA..............Federal Emergency Management Administration
FHWA.............Federal Highway Administration
FIRM ....Flood Insurance Rate Maps
GIS...................Geographic Information System
LOR ....Level of Resilience
MAP-21...........Moving Ahead for Progress in the 21st Century
NBI ....National Bridge Inventory
NOAA.............National Oceanic and Atmospheric Administration
PTCS................Post Tension Concrete Slab
RITA................Research and Innovative Technology Administration
RnR..................Risk and Resilience
SoVI®..............Social Vulnerability Index
USGS...............United States Geological Survey
WCR................Worst Reasonable Case

UNITS

in......................inches
lin ft.................linear feet
Q ....hydraulic discharge in cubic feet per second (cfs)
sf ....square feet
yr(s) ....year(s)
cu ft..................cubic feet
cu yds..............cubic yards
mph ....miles per hour

CHAPTER 1: INTRODUCTION

Transportation owners and operators are responsible for the delivery of a range of services and functions through the management of a multifaceted system of assets. These systems must be managed notwithstanding aging and deteriorating infrastructure and fiscally constrained resources. Many agencies are moving towards performance-based resource allocation while simultaneously recognizing risks that may undermine their strategic goals. As these risks impact every component of a highway system to a greater or lesser extent, accurately accounting for and addressing these risks within a highway agency enterprise-wide management program is a goal currently lacking robust analysis tools.

Risk for transportation highway assets can range from:

- Natural: Natural threats include hurricanes, flooding, rockfall, tornados, landslides, ice storms, earthquakes, and long-term changes in climate.
- Dependency: Threats between dependent entities such as electricity, communications, and water systems and the transportation system.
- Cyber: Threats that seek to disrupt or hold hostage day to day business of highway agencies including impeding traffic management systems, servers, and computer networks such as the ransomware malware attack Colorado Department of Transportation (DOT) suffered in March of 2018.
- Physical Malevolent: Directed threats that include theft, sabotage, explosive attacks, and active shooters.
- Individual Concerns: Unique threats to a highway system such as train derailments, high-vehicle bridge strikes, funding uncertainty, regulatory changes, and political threats.

Risk management requires the identification and assessment of threats, evaluation of potential mitigation actions to reduce the impact of those threats, and processes to prioritize mitigation plans that align with overall agency strategic performance goals. Integrating risk into asset and performance management requires standard processes, methods, and tools. The objective of this project is to create a process to support the Colorado Department of Transportation (CDOT) in implementing quantitative risk assessment techniques for incorporation into a risk-based asset management program.

Motivation for Risk and Resilience Analysis

CDOT adopted a quantitative risk assessment method to build back better after the devastating 2013 flood event that caused over $750 million in damage to highway systems and the loss of eight lives. At the time, Federal Highway Administration's (FHWA) Emergency Relief (ER) Program highlighted the desire for agencies to address system resilience and reduce requests of the ER Program from similar events anticipated to damage assets in the future. Working within the requirements of the ER Program, CDOT analyzed several damaged sites that staff anticipated could be at risk from future flood damage given previous historical performance. The process provided data-driven outcomes that supported the decision-making process for CDOT and FHWA investments in "betterments" and "replace to current standard" designs to reduce potential future losses from similar events.

Since the 2013 flood event, CDOT has experienced additional emergencies eligible for FHWA ER funds, including a dramatic rockfall event in 2016 that closed I-70 in the Glenwood Canyon area for a period of approximately two weeks. In addition to the damage that incurred when a vehicle sized boulder fell onto I-70, alternative routes also experienced damage due to increased traffic volumes and heavy vehicle traffic on roadways not designed to accommodate such demand.

Recognizing the need to better proactively address potential vulnerabilities in the CDOT system, in August 2016, CDOT initiated a Risk and Resilience Pilot of mainline I-70 from Kansas to Utah. The goal of the pilot was to determine if quantitative risk assessment information is useful to typical CDOT programs ranging from operations, planning, asset management, maintenance, and engineering design. In addition, the goal was determining how annual risk data generated could be incorporated into management programs to reduce system risk from physical threats and improve system resilience.

Legislation

Recent legislative requirements mandate transportation agencies perform risk assessments on bridges and pavements at a minimum in addition to developing mitigation plans for twice-damaged assets that have qualified for Federal Highway Administration (FHWA) Emergency Relief (ER) funds in the past twenty years. Moving Ahead for Progress in the 21st Century (MAP-21) (P.L. 112-114) legislation mandates transportation agencies develop and apply risk-based asset management processes to preserve or improve the performance of National Highway System bridges and pavement, at a minimum, and encourages assessment of additional asset classes. However, one of the challenges to incorporating risk and resilience assessment within asset management is the lack of a standard framework to identify and prioritize critical assets, and to quantify the potential impact of physical threats to highway assets.

Risk and Resilience Analysis Procedure Purpose and Scope

The purpose of this guidance is to establish an approach for prioritizing highway assets considering applicable risks and to determine potential financial impacts to highway asset owners and their users from these threats. The approach provides methods for assessing criticality of the study location to overall CDOT system resilience, cost estimating procedures for replacement of damaged assets from natural hazards, user impact procedures for estimating additional user travel time/distance due to natural hazards, vulnerability tables for a range of assets to a range of physical threats, and methods/sources to estimate threat probabilities of select natural hazards in Colorado.

The procedure is intended to support CDOT staff in their analysis of risk from physical threats to highway assets. Given the relatively new field of quantitative risk assessment to highway assets from physical threats, the procedure is focused on the following threat-asset pairs:

- Rockfall-Roadway Prism
- Rockfall-Bridge
- Rockfall-PTCS
- Flood-Roadway Prism
- Flood-Bridge
- Flood-Bridge Approach
- Flood-Minor Culvert
- Flood-Major Culvert
- Scour-Bridge
- Fire-Debris Flow-Culvert
- Fire-Debris Flow-Roadway Prism

For each threat-asset pair that was deemed reasonable to anticipate physical losses to CDOT assets or to impact travel, a methodology has been developed to allow the user to analyze the anticipated annual risk to a particular asset under analysis from that specific physical threat.

The threats included in this guidance were considered as the most prevalent to the CDOT highway system. In addition, two of the three assets included in this guidance both address the requirements of recent legislation as well as represent typical at-risk assets within the CDOT highway system.

Risk and Resilience Analysis Procedure – Development Process

Given the potential range of solutions to mitigate risk and to grow the knowledge and acceptance of risk and resilience assessment, several groups of CDOT staff were engaged in this effort. Oversight for the project was provided by the Executive Oversight Committee (EOC), in addition, a Working Group (WG) oversaw specific portions of the guidance related to global decisions that affected the entire document. Finally, a group of Subject Matter Experts (SMEs) convened over multiple days to establish specific default values for planning level analysis of risk assessment and information related to the anticipated performance of assets under various threats. Individuals engaged in these three groups are noted here and thanked for their time and knowledge that contributed to the overall development of this procedure.

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Randy Jensen - FWHA Program Delivery Team Leader (retired)
Josh Laipply - CDOT Chief Engineer (former)
Johnny Olson - Deputy Director (retired)
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Wes Templeton - Region 4 Maintenance
William Johnson – Asset Management

Document Organization

This document is organized into four primary chapters. In Chapter 2, the user is introduced to the concept of determining the criticality of each asset on the CDOT system to the system's overall operational performance. In Chapter 3, the user is introduced to a range of terms, equations, and methods to quantitatively assess annual risk to highway assets from physical threats. Chapter 3 serves as a repository for information needed to complete specific threat-asset analyses presented in the next chapter. In Chapter 4, specific information needed to complete a quantitative assessment of annual risk to a specific asset from a specific threat is provided, for example, the anticipated annual risk to a specific bridge from flood risk. Finally, in Chapter 5, an approach to estimate system resilience is provided using example data from the completed I-70 Risk and Resilience Pilot. In addition, the user is provided sample economic analyses of potential mitigation of at-risk assets from physical threats for areas analyzed in the I-70 Pilot.

Chapter 2: Criticality Assessment Process
Chapter 3: Risk Assessment Process
Chapter 4: Risk and Resilience Assessment Models
Chapter 5: Risk and Resilience Management

CHAPTER 2: CRITICALITY ASSESSMENT PROCESS

Introduction

Criticality is a measure of the importance of an asset to the overall highway system operations. Determining an asset's criticality level is used in conjunction with an asset's overall *annual risk* (Chapter 4) to determine its *Level of Resilience (LOR),* as explained in Chapter 5.

The criticality model and resulting map developed for the Risk and Resilience I-70 Pilot, includes National Highway System (NHS) and CDOT owned highways. The model incorporates six factors intended to capture the three pillars of resilience identified by the Colorado Resilience Plan: social, environmental, and economic considerations to improve resilience. The six factors include: *Average Annual Daily Traffic (AADT)*; the Association of American State Highway and Transportation Officials (AASHTO) *Roadway Classification; Freight Value* at the county level in millions of dollars per year; *Tourism Dollars* generated at the county level in millions of dollars per year (Colorado Tourism Office June 2016 Report); *Social Vulnerability Index (SoVI®)* at the county level (University of South Carolina Hazards and Vulnerability Research Institute 2010 – 2014); and S*ystem Redundancy,* calculated by CDOT GIS Staff. The factors used in the criticality model, data sources to gather such data, and the year the data sources used are shown in Exhibit 2.1.

EXHIBIT 2.1 CRITICALITY MODEL FACTORS

Factor	Data Source	Publications Year
AADT	OTIS Highways feature class	2015
Roadway Classification	OTIS Highways feature class	2015
Freight ($millions)	IHS Market's *Transearch*	2010
Tourism ($millions)	Colorado Tourism Office*	2016
SoVI®	University of South Carolina**	2014
System Redundancy	CDOT GIS Staff	2015

* Dean Runyan Associates, Colorado Travel Impacts: 1996-2015, prepared for the Colorado Tourism Office, June 2016

** Social Vulnerability Index 2010-2014. Retrieved from http://artsandsciences.sc.edu/geog/hvri/sovi%C2%AE-evolution

Data for the six factors is classified into five *quantiles* as shown in Exhibit 2.2. Each factor's quantiles are assigned an index value ranging from one (low criticality) to five (very high criticality). Note, the quantiles within Exhibit 2.2 are based on data sources accessed between 2015-2017 and should be updated as new data become available. To determine the *Criticality Score*, users enter specific data for the site being analyzed, determine the individual criteria score for each factor based on that data, and sum the individual scores to determine the overall Criticality Score.

EXHIBIT 2.2 CRITICALITY FACTOR QUANTILES

Criteria	1 Very Low	2 Low	3 Moderate	4 High	5 Very High
AADT	≤ 720	721 - 1,900	1,901 - 4,600	4,601 - 15,000	≥ 15,000
AASHTO Functional Class	Minor Collectors	Major Collectors	Minor Arterial	Principal Arterial	Interstate Freeway Expressway
Freight ($ Millions)	≤ 4,422	6,423 - 6,513	6,514 - 6,685	6,686, - 8,806	≥ 8,806
Tourism ($ Millions)	≤ 152	153 - 479	480 - 1,050	1,051 - 3,414	≥ 3,414
SoVI®	≤ (-2.93)	(-2.92) - (-1.24)	(-1.23) - 0.67	0.68 - 2.51	≥ 2.52
Redundancy	≥ 4.5	3.01 - 4.5	2.01 - 3	1.51 - 2.0	≤ 1.0

Criticality Level Assessment

The indices for the six criticality factors are summed to calculate an overall criticality level. Total scores fall into one of three categories as shown in Exhibit 2.3.

EXHIBIT 2.3 CRITICALITY LEVEL ASSESSMENT

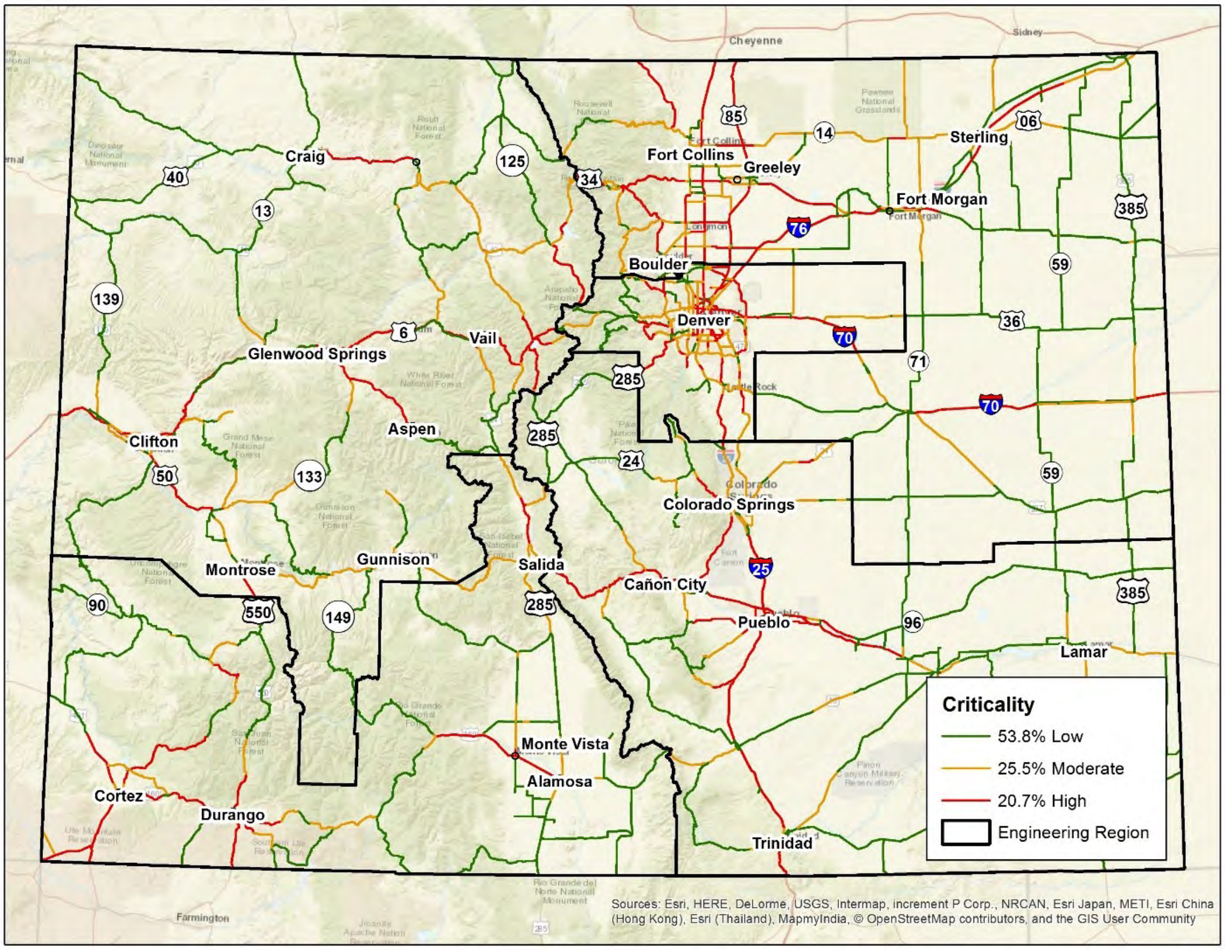
Criticality Level	Score Range
Low	6 to 20
Moderate	21 to 22
High	23 to 30

Exhibit 2.4 includes the resulting statewide Criticality Map for System Operations for the CDOT system based on the model included in Exhibit 2.2. As shown, approximately 20% of the centerline miles in the CDOT system are deemed highly critical and would be *one factor* when determining system resilience. As is discussed in Chapters 3 and 4, another factor to include is the *anticipated losses from physical threats* to the highway system such as flooding, rockfall, or debris flow post fire. In Chapter 5, an index for estimating *Level of Resilience* is discussed using example data from the I-70 Risk and Resilience Pilot that brings together both the measure of *criticality* as well as the anticipated *annual risk* from applicable threats to highway assets.

Level of Resilience can be used to better understand both how critical an asset is to overall system operations as well as whether or not it is anticipated to experience losses to CDOT, or users should an event occur. If an analyst only considers criticality or annual risk, it is possible that precious resources will be applied to areas that may not warrant such an investment when considering the system as a whole and in a manner that takes into account the probabilistic nature of threats.

EXHIBIT 2.4 CRITICALITY MAP FOR CDOT SYSTEM OPERATIONS

CDOT Highway Criticality Map



Sources: Spatial data for highways were downloaded for CDOT's Online Transportation Information System (OTIS).

Criticality Factors

1) AADT
2) AASHTO Functional Class
3) Freight Revenue
4) Tourist Revenue
5) SoVI Index
6) Redundancy

Criticality Level Example Problem

In this example, data has been collected for a fictional asset to demonstrate how to estimate an asset's Criticality. The example asset has the following characteristics:

- AADT – 2,050 vehicles per day
- AASHTO Functional Class – *Major Collector*
- Annual Freight Revenue Within County – $7,000,000
- Annual Tourism Dollars Generated Within County – $350,000,000
- SoVI® Score – 0.7
- Redundancy Score – 2.2

As shown in Exhibit 2.5, the overall criticality score for this fictional asset is 18. This score corresponds to a criticality level of "low" as shown in Exhibit 2.3. A Criticality Level of "low" can be interpreted to mean that the fictional asset is not considered highly critical to overall CDOT operations in that the asset carries low traffic volumes, has moderate redundancy (meaning alternative routes are available to move traffic around a closure), these factors along with the remaining factors imply this asset is not expected to result in a dramatic reduction of overall CDOT system operational performance should it be damaged or fail from applicable threats.

EXHIBIT 2.5 CRITICALITY EXAMPLE DATA

Criteria	Data	Index
AADT	2,050	3
AASHTO Functional Class	Major Collector	2
Freight ($ Millions)	7,000	4
Tourism ($ Millions)	350	2
SoVI®	0.7	4
Redundancy	2.2	3
	Total Score	**18**

CHAPTER 3: QUANTITATIVE RISK ASSESSMENT PROCESS

Introduction

Quantitative risk assessment methods estimate the potential loss of assets from physical threats and loss of service. The proposed approach in this procedure is probabilistically based, monetarily quantifiable, and a function of consequences, hazard frequency or likelihood, and the vulnerability of an asset to an identified threat or event. The steps for conducting risk analysis are illustrated in Exhibit 3.1.

EXHIBIT 3.1 RISK CALCULATION METHODOLOGY

Step 1: Threat Data Collection
Threat Data Source
Threat Likelihood

Step 2: Asset Data Collection
Asset Data Needs

Step 3: Owner Consequence Calculation
Owner Worst Reasonable Case (WRC) for Threat-Asset Pair
Asset Unit Cost Estimation

Step 4: User Consequence Calculation
User Worst Reasonable Case (WRC) for Threat-Asset Pair
Vehicle Operating Cost (VOC) and Lost of Wages (LW)
Detour Estimation (Extra Travel Length and Time)
Calculations
Total User Consequence

Step 5: Vulnerability Assessment
Threat-Asset Pair Vulnerability

Step 6: Risk Assessment
Annual Owner Risk Calculation
Annual User Risk Calculation
Total Annual Total Risk

Step 1: Threat Data Collection

For purposes of this procedure, *threat* is defined as any indication, circumstance, or event with the potential to cause the loss of, or damage to, an asset, system or network. *Threat likelihood* refers to the annual historical frequency of a potential hazard. Threat maps are used to identify the spatial extent of a hazard as well as to identify assets at risk. For example, bridges that fall within the limits of a floodplain on a Flood Insurance Rate Map (FIRM) are potentially at risk for flood damage. Examples of threat maps include Federal Emergency Management Administration (FEMA) FIRMs (Exhibit 3.3), landslide inventories, fire perimeters, debris flow runout zones (Exhibit 3.4), and rockfall runout zones (Exhibit 3.5). Data sources for the threats discussed in this procedure are shown in Exhibit 3.2.

EXHIBIT 3.2 THREAT DATA SOURCES

Threat	Layer	Source
Flood/Scour	Floodplain	FEMA
Rockfall	Runout Zone	Software***
Post-fire Debris Flow*	Runout Zone	CGS, CWCB, Software***
Post-fire Debris Flow**	Volume/Volume Probability	USGS (BAER)
Post-fire Debris Flow**	Burn Scar	USGS (BAER)

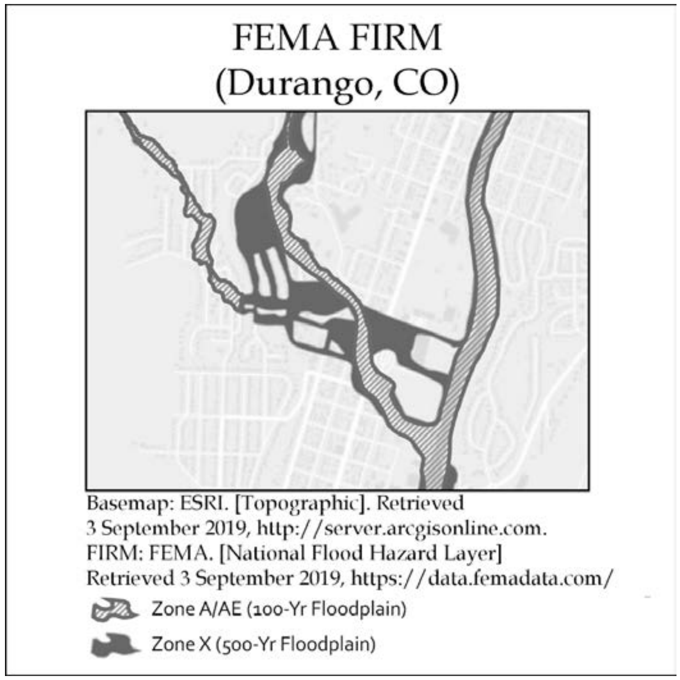
*Colorado Water Conservation Board (CWCB) data only available for Boulder County as of June 2019. The Colorado Geological Survey (CGS) provides debris flow maps for El Paso, Jefferson and Larimer Counties. Flow-R or other software can be used to generate debris flow runout zones for other areas.

**USGS Burned Area Emergency Response (BAER) data is spatial data that includes projections of estimated debris flow likelihoods and debris flow volumes for a watershed that has recently burned.

***Examples of software modeling tools include Flow-R (https://www.flow-r.org/) and Rocky3D (http://www.ecorisq.org/images/ecorisq/services/Window_Rockyfor3D.jpg).

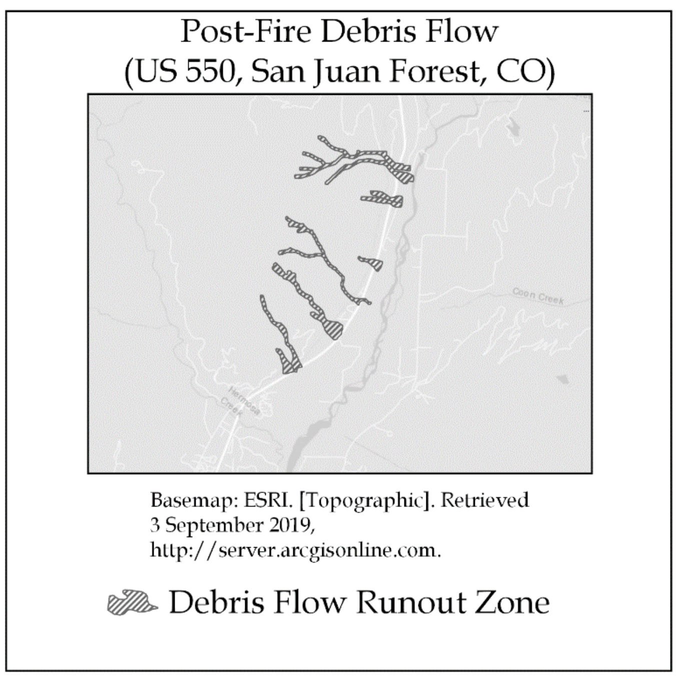
As shown in Exhibit 3.3, FEMA may provide information on applicable 100-yr and 500-yr floodplains where such studies have been conducted. In Exhibit 3.3, *Zone AE* indicates the 100-yr floodplain while *Zone X* indicates 500-yr floodplain.

EXHIBIT 3.3 FEMA FIRM PANEL



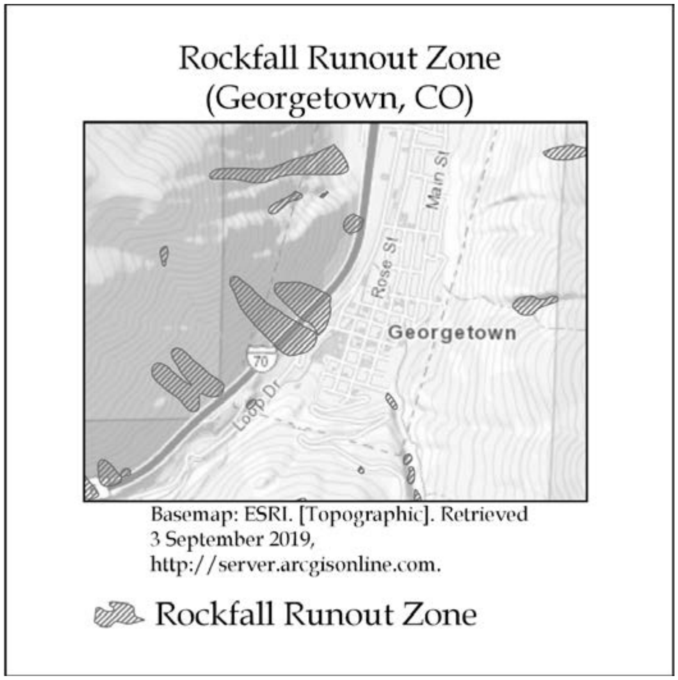
As shown in Exhibit 3.4, post-fire debris flow runout zones can be generated by software or developed by the Colorado Geological Survey (CGS), for certain fires when deemed necessary by CGS. In this exhibit, debris flow runout zones were modeled with Flow-R, a software flow path assessment tool of gravitational hazards at a regional scale.

EXHIBIT 3.4 POST FIRE DEBRIS-FLOW RUNOUT ZONES



An example rockfall runout zone is shown in Exhibit 3.5, in this case Flow-R software was used to model the anticipated rockfall run-out for the Georgetown area in Colorado.

EXHIBIT 3.5 ROCKFALL RUNOUT ZONES, MODELED WITH FLOW-R SOFTWARE



Threat Likelihood and Magnitude

Threat likelihood is derived from historical records, such as government records, agency maintenance records, news articles, etc. Commonly, a threat likelihood is described with a return period, such as a 100-yr flood. In this case it is assumed that, on average, a 100-yr flood occurs once every 100 years or an annual probability of one percent. Magnitude refers to the severity of the event. In general, longer return period events are more severe than shorter return period events, meaning a 500-yr flood is expected to be more severe than a 100-yr flood. Note this approach does not take into account the affects of climate change or changes in patterns of extreme weather and is considered a conservative approach to threat likelihood assessment.

This document contains information on flood analysis for two return periods, 100-yr and 500-yr for flood events and the following assets: roadway, bridge, bridge approach and major culverts. Minor culverts are evaluated for a range of flows as described and post-fire debris flow is evaluated for a range of rainfall events in Chapter 4. See Exhibit 3.6 for a summary of flood/rain event recurrence intervals.

EXHIBIT 3.6 FLOOD/RAINFALL ANNUAL THREAT LIKELIHOOD

Recurrence Interval* (Year)	Annual Threat Likelihood
1	1/1
2	1/2
5	1/5
10	1/10
25	1/25
50	1/50
100	1/100
500	1/500

*Flood/Rain recurrence intervals do not necessarily constitute the same flow rate.

In addition, to calculate total probability for post-fire debris flow, the post-fire debris storm event likelihood is multiplied by a conditional probability (probability of debris flow occurring) as shown in Equation 3.1.

EQUATION 3.1

$$Debris\ Flow\ Probablity = Probability\ DF^{*}\ \ x\ \ Probability\ Rainfall\ Event$$

*from USGS

Annual rockfall probability has been established by the CDOT Geohazard Program for specific magnitudes of rockfall for the I-70 corridor within Glenwood Canyon as shown in Exhibit 3.7. Note that this information is specific to I-70 and the user is encouraged to engage with the CDOT Geohazard Program Staff to determine the annual threat likelihood and relevant magnitudes for corridors other than I-70 in Glenwood Canyon.

EXHIBIT 3.7 ROCKFALL EVENT THREAT LIKELIHOOD

Rockfall Event Magnitude	Volume (cu yds)	Annual Threat Likelihood
Small	≤ 100	1
Medium	100 – 499	1/6
Large	≥ 500	1/20

Step 2: Asset Data Collection

Asset replacement cost is needed to complete annual owner risk calculations. Data needed to complete each of the threat-asset pair risk assessments are provided in each of the example threat-asset pair risk assessments examples in Chapter 4.

Step 3: Owner Consequences Calculation

Owner Consequences are the direct consequences inflicted upon an asset due to a realized threat. The owner consequences are focused on asset repairs and replacement, as well as cleanup costs when applicable. To normalize the anticipated losses to CDOT from relevant threats, the cost of replacement including construction costs need to be established. Information gathered from CDOT staff through a series of workshops in 2019 was used to establish planning level estimates of the cost of replacement of damaged assets from realized threats. The following sections include information for the unit cost associated with the range of assets included in this document. These values have been developed specifically for this application and should be used in risk assessment until no longer considered reasonable.

Asset Unit Costs for All Assets Other Than Minor Culverts

Exhibit 3.8 includes unit costs for bridge approaches, bridges, culvert (concrete box culvert), PTCS, and roadway prism.

EXHIBIT 3.8 UNIT COSTS

Asset	Units	Unit Cost
Bridge Approach**	sq ft	$350
Bridge*	sq ft	$600
Culvert***	cu ft	$55
PTCS**	sq ft	$550
Roadway Prism (Asphalt)**	sq yds	$150
Roadway Prism (Concrete)**	sq yds	$350

* Bridge area is defined as deck length multiplied by deck width, derived from NBI Items 49 and 52, respectively.

**Bridge approach, roadway, and PTCS width are derived from CDOT OTIS Highways feature class using fields for lane width, lane count, and shoulder width.

***For culverts (CBC), the volume, in cubic feet, is calculated by multiplying the box height by the box width by the length. These values are derived from the culverts feature class maintained by C-PLAN, CDOT's interactive online mapping platform.

Unit Costs for Minor Culverts

Feedback from CDOT staff was used to estimate culvert replacement costs. Pipe diameter can be used to determine planning level estimates of replacement costs regardless of material type. Exhibit 3.9 includes unit costs for culverts other than CBCs.

EXHIBIT 3.9
UNIT COSTS FOR MINOR CULVERTS

Pipe Diameter (in)	Unit Cost ($/lin ft)
<48	2,205
48	2,225
54	2,660
60	3,135
66	3,660
72	4,235
78	4,865
84	5,550
90	10,325
96	11,690
102	13,160
108	14,770
120	18,325
138	24,695

Worst Reasonable Case (WRC) for Owner Consequence

To support the quantitative risk assessment, an understanding of the anticipated response of an asset to an applicable threat is required. For purposes of this procedure, a term is established known as "Worst Reasonable Case" (WRC) where WRC represents the maximum realistic losses to an asset from an applicable threat. The WRC for all threat-asset pairs included in this document are summarized in Exhibit 3.10.

EXHIBIT 3.10
SUMMARY OF WRC FOR OWNER CONSEQUENCE

		Threat			
		Debris Flow	**Flood**	**Scour**	**Rockfall**
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

**ARC = Asset Replacement Cost*

Step 4: User Consequence Calculation

Introduction

User Consequence refers to the indirect costs imposed upon the public due to interruptions of the transportation network. For the purposes of this procedure, User Consequence is limited to the additional cost of operating vehicles and value of time lost to the additional travel time and/or distance necessitated by detours and delays.

The following section describes data requirements and equations used to estimate user costs for full and partial closures as well as costs incurred by commercial drivers and everyday travelers.

Exhibit 3.11 provides default values for a range of factors associated with the cost associated with operating vehicles, value of time, and occupancy that are updated annually by the various federal government agencies. Note the values included in Exhibit 3.11 were gathered in June of 2019 and will vary in future years.

EXHIBIT 3.11 CONSTANTS USED IN USER CONSEQUENCE CALCULATIONS

User Cost Terms	Variable	Value	Year Published
Average Vehicle Occupancy	*O*	1.77	2019
Car Running Cost per Mile	*C2*	$0.59	2019
Truck Running Cost per Mile	*C3*	$0.96	2015
Average Value of Time per Adult per Hour	*C4*	$10.62	2015
Average Value of Freight Driver Cost per Hour	*C5*	$25.31	2015
Car Running Cost per Hour	*C8*	$26.52	2015
Truck Running Cost per Hour	*C9*	$44.24	2015

Worst Reasonable Consequences – User Consequences

For User Consequences, the WRC is the maximum number of *full* or *partial closure days* associated with a given event. WRC depends upon the type of asset and natural hazard being analyzed. The suggested number of full and partial closure days is provided in Exhibit 3.12.

EXHIBIT 3.12
I-70 Risk and Resilience Pilot
NUMBER OF FULL CLOSURE AND PARTIAL CLOSURE DAYS FOR WRC

Asset	Threat	Full Closure Days (d_{FC})	Partial Closure Days (d_{PC})
Bridge Approach	All	2	0
Bridge	Flood	180	0
Bridge	Debris Flow	2	0
Bridge	Rockfall	4	14
Culvert	Debris Flow	1	0
Culvert	Flood	3	0
PTCS	Rockfall	4	14
Roadway (<=% Width)	Flood	1	0
Roadway (> 50% Width)	Flood	3	0
Roadway (2 Directions)	Flood	3	0
Roadway	Rockfall	4	14

Detour Selection Criteria

To estimate the user consequence, the anticipated detour around a potential highway closure needs to be established. Example detours used for the I-70 Risk and Resilience Pilot and the worked examples in this document are listed in Exhibit 3.13. Note that *Additional Travel Distance* refers to the additional miles a traveler must travel on detour in comparison to the original route, and *Additional Travel Time* is the additional time a traveler must travel on detour in comparison to the original route. CDOT Operations can provide further guidance on estimating detours from closures for highways other than I-70.

EXHIBIT 3.13
I-70 RISK AND RESILIENCE PILOT DETOUR TABLE

Starting Milepost	Ending Milepost	Additional Travel Distance (miles) (*C7*)	Additional Travel Time (minutes) (*Dt*)
1	14	146	189
14	90	90	112
90	155	140	167
155	205	98	126
205	231	83	109
231	245	49	77
245	288	3	7
288	353	15	24
353	360	71	96
360	404	76	73
404	438	69	70
438	450	63	77

User Consequence

Damage to the roadway may result in full or partial closures to through traffic and necessitate the use of a temporary work zone for construction and cleanup. Total User Consequences is the sum of user consequence due to full and partial closures as shown in Equation 3.2.

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

Where:

$User\ Consequence_{FC}$ = User consequences due to full closure
$User\ Consequence_{PC}$ = User consequences due to partial closure

User consequences for full closure are the sum of vehicle operating costs incurred due to travel on detour, lost wages, and truck revenue due to travel on detour as shown in Equation 3.3.

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

Where:

VOC_{FC} = Vehicle operating costs incurred due to full closure
LW_{FC} = Lost wages/truck revenue incurred due to full closure

User consequences for partial closures are the sum of vehicle operating costs incurred due to traffic delays, lost wages, and truck revenue due to delays incurred while driving through a partial closure as shown in Equation 3.4.

EQUATION 3.4

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

Where:

VOC_{PC} = Vehicle operating costs incurred due to partial closure
LW_{PC} = Lost wages/truck revenue incurred due to partial closure

Equation 3.5 is the equation for calculating vehicle operating costs for full closures.

EQUATION 3.5

$$VOC_{FC} = \left(\left(C2\ x\ AADT_{Vehicle}\right) + \left(C3\ x\ AADT_{Truck}\right)\right)\ x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C2$	=	Vehicle running cost ($/vehicle-mile)
$C3$	=	Freight running cost ($/truck-mile)
d_{FC}	=	Number of full closure days (days)
$C7$	=	Difference in distance between detour and original route (mile)

Equation 3.6 is used for calculating lost wages and truck revenue for full closures.

EQUATION 3.6

$$LW_{FC} = \left(\left(C4\ x\ O\ x\ AADT_{Vehicle}\right) + \left(C5\ x\ AADT_{Truck}\right)\right)\ x\ d_{FC}\ x\ \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C4$	=	Average value of time ($/adult-hour)
O	=	Average occupancy (adult/vehicle)
$C5$	=	Average value of freight time($/truck-hour)
d_{FC}	=	Number of full closure days (days)
Dt	=	Extra travel time on detour (minutes)

Equation 3.7 is used for calculating vehicle operating costs due to partial closures.

EQUATION 3.7

$$VOC_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right)\ x\ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x\ WZS}\right)\ x\ \left(\left(C8\ x\ AADT_{Vehicle}\right) + \left(C9\ x\ AADT_{Truck}\right)\right)\ x\ d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)

$AADT_{Truck}$	=	Average annual daily truck traffic
$C8$	=	Vehicle running cost ($/vehicle-hour)
$C9$	=	Freight running cost ($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Equation 3.8 is used for calculating lost wages and truck revenue due to partial closures.

EQUATION 3.8

$$LW_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x\ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x\ WZS} \right) x\ ((C4\ x\ AADT_{Vehicle}\ x\ O) + (C5\ x\ AADT_{Truck}))\ x\ d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C4$	=	Average value of time ($/adult-hour)
O	=	Average occupancy (adult/vehicle)
$C5$	=	Average value of freight time($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Step 5: Vulnerability Assessment

Vulnerability is the measure of an asset's susceptiblity to damage from a natural hazard. It is quantified as the probability of the Worst Reasonable Case occuring if an event is realized. Vulnerability is the expected probability of loss within a range between nearly zero and nearly one. Vulnerability represents a number of factors that literature and emperical data imply may influence an asset's susceptability to incur damage from threats included in this procedure. While there may be other factors that influence vulnerability, the factors included in this procedure are available to CDOT staff in a range of databases and field observations and have been vetted by Subject Matter Experts who participated in this study.

Step 6: Risk Assessment

Annual Owner Risk Calculation

Calculate total annual owner risk by multiplying the owner consequences by the vulnerability for each event by the threat likelihood then summing the annual owner risk for all events utilizing to Equation 3.9. In the case of scour-bridge analysis, the probability of failure (PF) is a combined threat and vulnerability probability utilizing Equation 3.10.

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ Risk_i = Owner\ Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n = number of events

EQUATION 3.10 (Scour-Bridge)

$$Annual\ Owner\ Risk = Owner\ Consequence\ x\ PF\ x\ K$$

Where $K = K_1 * K_2$
K_1 is a bridge type factor based on NBI data, and K_2 is a foundation type factor based on information.

Annual User Risk Calculation

Calculate total annual user risk by multiplying the owner consequences by the vulnerability for each magnitude of event the threat likelihood then summing the annual user risk for all events, utilizing Equation 3.11. Again, in the case of scour-bridge analysis, the probability of failure (PF) is a combined threat and vulnerability probability utilizing Equation 3.12.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ Risk_i = Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n = number of events

EQUATION 3.12 (Scour-Bridge)

$$Annual\ User\ Risk = Owner\ Consequence\ x\ PF$$

Total Annual Risk Calculation

EQUATION 3.13

$$Total\ Annual\ Risk\ = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

Where n= number of events

Calculate total annual risk by adding total annual owner risk to total annual user risk utilizing Equation 3.13.

Chapter 4 contains specific threat-asset pair procedures and example problems for the following threat-asset pairs:

- Rockfall-Roadway Prism
- Rockfall-Bridge
- Rockfall-PTCS
- Flood-Roadway Prism
- Flood-Bridge
- Flood-Bridge Approach
- Flood-Minor Culvert
- Flood-Major Culvert
- Scour-Bridge
- Post Fire-Debris Flow-Culvert*
- Post Fire-Debris Flow-Roadway Prism*

* Note: given the post-fire analysis required by the United States Geological Survey (USGS) and the use of GIS to analyze post-fire debris flow, results are provided for five areas in the state that were deemed susceptible to debris flow by USGS in reports generated prior to 2019. At the time of this publication, it is possible that these areas have recovered from their fire events and users should engage local experts to determine if any such recovery has occurred.

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CHAPTER 4: RISK AND RESILIENCE ASSESSMENT MODELS

4.1 - Rockfall Assessment

Rockfall is defined as "a fragment of rock (a block) detached by sliding, toppling, or falling, that falls along a vertical or sub-vertical cliff, proceeds down slope by bouncing and flying along ballistic trajectories or by rolling on talus or debris slopes" (Varnes, 1987). Rockfall is most common in areas of steep slope and significant elevation change, such as the Front Range, central mountains and western portions of Colorado. Colorado DOT currently monitors 750 rockfall sites across the state to proactively mitigate damage from potential rockfall events. In 2005, the Colorado Geological Survey categorized the areas listed here as "Tier One" meaning, "serious cases needing immediate or ongoing action or attention because of the severity of potential impacts" (Rogers, 2005).

- Clear Creek Forks Junction Rockslide, Clear Creek County
- Georgetown Incline Rockfall Area, I-70, Clear Creek County
- Booth Creek Rockfall Hazard Area, Vail, Eagle County
- Manitou Springs Town Site, El Paso County
- Black Mesa Rockfall Corridor, CO 92, Gunnison and Montrose Counties
- Clear Creek Canyon/US 6 Rockfall Areas, Jefferson and Clear Creek Counties

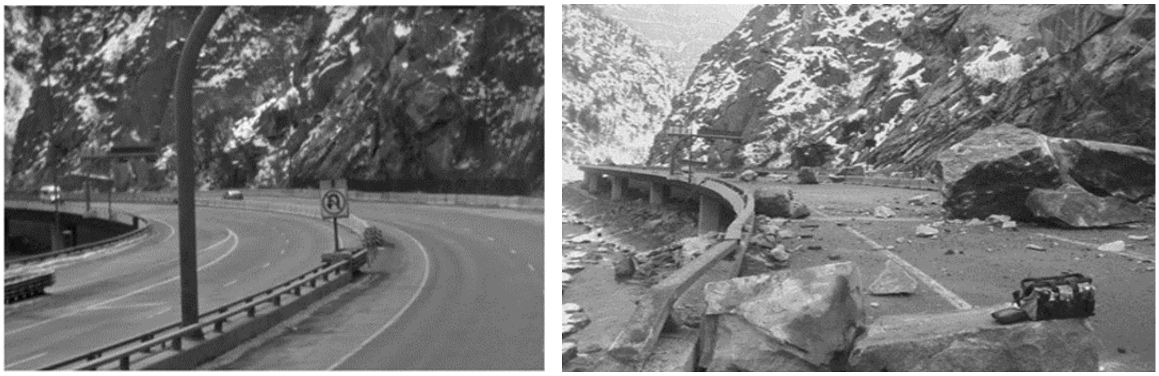
CDOT's 2019 annual rockfall management budget is approximately $10 million, however, a single event can match or exceed this sum. For example, the estimated total repair cost for the February 15, 2016 rockfall event in Glenwood Canyon that damaged I-70 and alternative routes used to detour traffic from I-70 approached $10 million. To assist in identifying high risk highway facilities, a quantitative risk assessment method has been developed in conjunction with the CDOT Geohazards Program Staff. In the following sections, an approach that can be used to assess risk to Post-Tension Concrete Slabs (PTCS), bridges, and roadway prisms is provided.

Note: specific rockfall return rates or frequencies were utilized for the I-70 Glenwood Canyon area in this procedure. It is recommended that the user contact the CDOT Geohazards Program Staff to develop annual return rates for other areas of the state. This data is not readily available without such consultation.

4.1.1 Rockfall-PTCS Risk Assessment

Post-Tension Concrete Slabs (PTCS) in Glenwood Canyon are present between milepost 119 and milepost 129. The PTCS sections abut the steep slopes of Glenwood Canyon on the westbound side and are particularly vulnerable to impacts from large boulders. Exhibit 4.1.1.1 includes an example of damage from rockfall at milepost 125 on I-70.

EXHIBIT 4.1.1.1 BEFORE AND AFTER ROCKFALL, FEBRUARY 2016, I-70, MP 125



Rockfall-PTCS Risk Assessment Methodology

Exhibit 4.1.1.2 illustrates the basic methodology and steps used in risk analysis of rockfall to PTCS.

EXHIBIT 4.1.1.2 ROCKFALL-PTCS RISK ASSESSMENT METHODOLOGY

Step 1: Threat Data Collection
Rockfall Annual Likelihood (Exhibit 4.1.1.3)

↓

Step 2: Asset Data Collection
Asset (PTCS) Data Needs (Exhibit 4.1.1.4)

↓

Step 3: Owner Consequence Calculation
Owner Worst Reasonable Case (WRC) for Rockfall-PTCS (Exhibit 4.1.1.5)
PTCS Unit Cost Estimation (Exhibit 4.1.1.6)

↓

Step 4: User Consequence Calculation
User Worst Reasonable Case (WRC) for Rockfall-PTCS (Exhibit 4.1.1.5)
Vehicle Operating Cost (VOC) and Lost of Wages (LW) (Exhibit 4.1.1.7)
Detour Estimation (Extra Travel Length and Time) (Exhibits 4.1.1.8 and 4.1.1.9)
Calculations (Equations 3.5 through 3.8)
Total User Consequence (Equation 3.2)

↓

Step 5: Vulnerability Assessment
Rockfall Vulnerability (Exhibit 4.1.1.10)

↓

Step 6: Risk Assessment
Annual Owner Risk Calculation (Equation 3.9)
Annual User Risk Calculation (Equations 3.2 through 3.8 and 3.11)
Annual Total Risk (Equation 3.13)

Computational Steps

Step 1: Threat Data Collection

The traditional method for conducting magnitude-threat likelihood analysis is to conduct rockfall inventories following rockfall events, counting the number or rocks per size (diameter) in the vicinity of the most recent event. Likelihoods for small, medium, and large events vary from corridor to corridor and historical data can support the development of threat probabilities. Discussions with the CDOT Geohazard Program Team cautioned the standardization of threat likelihood of rockfall events across the CDOT system given the variation in geographic features from the Plains in the east to the Rocky Mountains and the Western Slope. However, recent risk assessment work for the I-70 Glenwood Canyon Corridor provides some insight as to the return intervals expected in this stretch of highway. Exhibit 4.1.1.3 lists estimates of rockfall frequency and magnitude for I-70 in Glenwood Canyon based on past events. Users of this document are encouraged to seek additional input on threat likelihood of rockfall events along other highways on the CDOT system from CDOT Geohazard Program Staff.

EXHIBIT 4.1.1.3 ROCKFALL EVENT THREAT LIKELIHOOD FOR I-70 IN GLENWOOD CANYON

Rockfall Event Magnitude	Volume (cu yds)	Annual Threat Likelihood
Small	< 100	1
Medium	100 – 499	1/6
Large	≥ 500	1/20

Step 2: Asset Data Collection

Data needed to assess the annual risk from rockfall events includes Asset Replacement Cost (ARC), user costs, and vulnerability. The OTIS Highways feature class supplies the dimensions for roadway features necessary to calculate ARC, as well as traffic volumes for calculating user consequences. In addition, rockfall mitigation data, as well as the *Rockfall Hazard Rating System (RHRS)*, is used for the vulnerability estimation. Exhibit 4.1.1.4 provides a summary of the data needed to complete the analysis for the annual risk of rockfall to PTCS.

EXHIBIT 4.1.1.4 DATA NEEDS FOR ROCKFALL-PTCS RISK ANALYSIS

	Data Needs	Data Source
Asset Replacement Cost	**Milepost (beginning and end)**	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Site Length	500 ft (recommended length)
	Roadway Geometry	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
Vulnerability	**Rockfall Mitigation**	CDOT Geotechnical
	Slope Type and Lithology	CDOT Geotechnical
	Roadway (rockfall) Ditch	CDOT Geotechnical
User Consequences	**AADT Vehicles**	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	AADT Trucks	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Roadway Damaged	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Detour	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Detour Distance	CDOT Operations
	Detour Time	CDOT Operations
	Number of Closure Days	See Exhibit 4.1.1.9
	Number of Partial Closure Days	See Exhibit 4.1.1.9
	Average Vehicle Occupancy	FHWA https://www.fhwa.dot.gov/tpm/guidance/avo_factors.pdf
	Car Running Costs	(RITA)/Texas A&M Transportation Institute
	Truck Running Costs	American Transportation Research Institute
	Average Value of Time	(RITA)/Texas A&M Transportation Institute

Step 3: Owner Consequence Assessment

Owner consequences represent the anticipated impact to the owner (CDOT) in terms of cost of repairs, cleanup, maintenance and related agency operational cost. WRC for rockfall on PTCS sections is used for all owner risk calculations, regardless of magnitude, as defined in Exhibit 4.1.1.5. The owner consequence for a rockfall event on PTCS sections, PTCS unit cost in Exhibit 4.1.1.6, is estimated to be approximately $2,800,000 based on repairs for 25% of the replacement value of a 500 ft PTCS section and in cleanup costs for 2,000 cu yds of rockfall debris.

EXHIBIT 4.1.1.5 SUMMARY OF WRC FOR OWNER CONSEQUENCE

		Threat			
		Debris Flow	**Flood**	**Scour**	**Rockfall**
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

EXHIBIT 4.1.1.6 UNIT COSTS

Asset	Units	Unit Cost
Bridge Approach**	sq ft	$350
Bridge*	sq ft	$600
Culvert***	cu ft	$55
PTCS**	sq ft	$550
Road Prism (Asphalt)**	sq yds	$150
Road Prism (Concrete)**	sq yds	$350

* Bridge area is defined as deck length multiplied by deck width, derived from NBI Items 49 and 52, respectively.

**Bridge approach, roadway and PTCS width are derived from CDOT OTIS Highways feature class using fields for lane width, lane count, and shoulder width.

***For culvert (CBC), the volume, in cubic feet, is calculated by multiplying the box height by the box width by the length. These values are derived from the culverts feature class maintained by C-PLAN, CDOT's interactive online mapping platform.

$$Owner\ Consequence = 25\%\ x\ ARC + \$200{,}000$$

$$\boldsymbol{Owner\ Consequence} \approx \ \$\mathbf{2,800,000}^{*}$$

Default value that can be used when site specific data is not available

Step 4: User Consequence Assessment

User consequences measure the impact to the public in terms of lost wages and increased vehicle operating costs due to delays and longer drive distances and times. Required inputs include AADT, percent truck traffic, average vehicle occupancy, average hourly wage, detour length, work zone length, speed on detour, number of days of closure, and number of days of partial closure, Exhibits 4.1.1.7 through 4.1.1.9. For user consequences, the estimated WRC of rockfall events, on the I-70 corridor for PTCS sections is the result of a "large" rockfall events and are expected to result in four days of full closure plus 14 days of partial closure, see Exhibit 4.1.1.8. For further explanation on how to calculate user consequences see Equations 3.2 through 3.8 and 3.11.

Exhibit 4.1.1.7 provides default values for a range of factors associated with the cost associated with operating vehicles, value of time, and occupancy that are updated annually by the various federal government agencies. Note the values included in Exhibit 4.1.1.7 were gathered in June of 2019 and will vary in future years.

EXHIBIT 4.1.1.7 CONSTANTS USED IN USER CONSEQUENCE CALCULATIONS

User Cost Terms	Variable	Value	Year Published
Average Vehicle Occupancy	*O*	1.77	2019
Car Running Cost per Mile	*C2*	$0.59	2019
Truck Running Cost per Mile	*C3*	$0.96	2015
Average Value of Time per Adult per Hour	*C4*	$10.62	2015
Average Value of Freight Driver Cost per Hour	*C5*	$25.31	2015
Car Running Cost per Hour	*C8*	$26.52	2015
Truck Running Cost per Hour	*C9*	$44.24	2015

The suggested number of full and partial closure days, derived from the I-70 Pilot, are provided in Exhibit 4.1.1.8. It is suggested that this table be used as guidance for all other corridor's for estimating closures days, both full and partial.

EXHIBIT 4.1.1.8 I-70 RISK AND RESILIENCE PILOT NUMBER OF FULL CLOSURE AND PARTIAL CLOSURE DAYS FOR WRC

Asset	Threat	Full Closure Days (d_{FC})	Partial Closure Days (d_{PC})
Bridge Approach	All	2	0
Bridge	Flood	180	0
Bridge	Debris Flow	2	0
Bridge	Rockfall	4	14
Culvert	Debris Flow	1	0
Culvert	Flood	3	0
PTCS	Rockfall	4	14
Roadway (<=% Width)	Flood	1	0
Roadway (> 50% Width)	Flood	3	0
Roadway (2 Directions)	Flood	3	0
Roadway	Rockfall	4	14

Example detours used for the I-70 Risk and Resilience Pilot and the worked examples in this document are listed in Exhibit 4.1.1.9. Note that *Additional Travel Distance* refers to the additional miles a traveler must travel on detour in comparison to the original route, and *Additional Travel Time* is the additional time a traveler must travel on detour in comparison to the original route. CDOT Operations can provide further guidance on estimating detours from closures for highways other than I-70.

EXHIBIT 4.1.1.9 I-70 RISK AND RESILIENCE PILOT DETOUR TABLE

Starting Milepost	Ending Milepost	Additional Travel Distance (miles) (*C7*)	Additional Travel Time (minutes) (*Dt*)
1	14	146	189
14	90	90	112
90	155	140	167
155	205	98	126
205	231	83	109
231	245	49	77
245	288	3	7
288	353	15	24
353	360	71	96
360	404	76	73
404	438	69	70
438	450	63	77

Total User Consequences is the sum of user consequence due to full and partial closures as shown in Equation 3.2.

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

Where:

$User\ Consequence_{FC}$ = User consequences due to full closure
$User\ Consequence_{PC}$ = User consequences due to partial closure

User consequences for full closure are the sum of vehicle operating costs incurred due to travel on detour, lost wages, and truck revenue due to travel on detour as shown in Equation 3.3.

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

Where:

VOC_{FC} = Vehicle operating costs incurred due to full closure
LW_{FC} = Lost wages/truck revenue incurred due to full closure

User consequences for partial closures are the sum of vehicle operating costs incurred due to traffic delays, lost wages, and truck revenue due to delays incurred while driving through a partial closure as shown in Equation 3.4.

EQUATION 3.4

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

Where:

VOC_{PC} = Vehicle operating costs incurred due to partial closure
LW_{PC} = Lost wages/truck revenue incurred due to partial closure

Equation 3.5 is the equation for calculating vehicle operating costs for full closures.

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$ = Average annual daily traffic (non-truck)
$AADT_{Truck}$ = Average annual daily truck traffic
$C2$ = Vehicle running cost ($/vehicle-mile)
$C3$ = Freight running cost ($/truck-mile)
d_{FC} = Number of full closure days (days)
$C7$ = Difference in distance between detour and original route (mile)

Equation 3.6 is used for calculating lost wages and truck revenue for full closures.

EQUATION 3.6

$$LW_{FC} = \left((C4 \; x \; O \; x \; AADT_{Vehicle}) + (C5 \; x \; AADT_{Truck})\right) x \; d_{FC} \; x \; \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$ = Average annual daily traffic (non-truck)
$AADT_{Truck}$ = Average annual daily truck traffic
$C4$ = Average value of time ($/adult-hour)
O = Average occupancy (adult/vehicle)
$C5$ = Average value of freight time($/truck-hour)
d_{FC} = Number of full closure days (days)
Dt = Extra travel time on detour (minutes)

Equation 3.7 is used for calculating vehicle operating costs due to partial closures.

EQUATION 3.7

$$VOC_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x \; (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x \; WZS}\right) x \left((C8 \; x \; AADT_{Vehicle}) + (C9 \; x \; AADT_{Truck})\right) x \; d_{PC}$$

Where:

WL = Work zone length (miles)
WZS = Work zone speed limit (mph)
$WZSR$ = Work zone speed limit reduction (mph)
$AADT_{Vehicle}$ = Average annual daily traffic (non-truck)
$AADT_{Truck}$ = Average annual daily truck traffic
$C8$ = Vehicle running cost ($/vehicle-hour)
$C9$ = Freight running cost ($/truck-hour)
d_{PC} = Number of days of partial closure (days)

Equation 3.8 is used for calculating lost wages and truck revenue due to partial closures.

EQUATION 3.8

$$LW_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x\ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x\ WZS}\right) x\ ((C4\ x\ AADT_{Vehicle}\ x\ O) + (C5\ x\ AADT_{Truck}))\ x\ d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C4$	=	Average value of time ($/adult-hour)
O	=	Average occupancy (adult/vehicle)
$C5$	=	Average value of freight time($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Calculate total annual user risk by multiplying the owner consequences by the vulnerability for each magnitude of event the threat likelihood then summing the annual user risk for all events, utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ \boldsymbol{R}isk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n = number of events

Step 5: Vulnerability Assessment

Vulnerability of PTCS from rockfall is dependent on multiple factors. For this procedure, a vulnerability table was developed for rockfall risk based on literature, expert opinion, and empirical data. For rockfall, the Working Group decided that one vulnerability table could be used to assess annual risk for PTCS, bridges, and roadway prisms. However, risk calculations will differ depending on the asset type given WRC variability. See Exhibit 4.1.1.10 for complete rockfall vulnerability estimates previously provided in Chapter 3. In addition, the following assumptions are made: 1) Large events cannot be effectively mitigated; 2) Assets that are proximate to natural slopes are more vulnerable than assets proximate to *cut-slopes* (engineered); 3) *Rock slopes* (slopes with exposed bedrock) are more hazardous than slopes where the predominate surficial geology is loose, unconsolidated sediments 4) Ditches are effective in mitigating small events.

EXHIBIT 4.1.1.10 ROCKFALL VULNERABILITY TABLE

Magnitude	Factors				Vulnerability		
Return Period (years)	Natural or Cut Slope	Lithology	Ditch	Monitored	No Mitigation	Slope Maintained	Installed Mitigation
1-year (≤ 100 cu yds)	Cut Slope	Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
		Non-Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.00	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.00	0.00
	Natural	Rock Slope	Absent	Yes	0.01	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
		Non-Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
6-year (101 - 499 cu yds)	Cut Slope	Rock Slope	Absent or Width ≤ 10 ft	Yes	0.35	0.30	0.15
				No	0.65	0.50	0.25
			Width > 10 ft	Yes	0.30	0.25	0.15
				No	0.60	0.45	0.25
		Non-Rock Slope	Absent or Width ≤ 10 ft	Yes	0.30	0.25	0.15
				No	0.55	0.45	0.25
			Width > 10 ft	Yes	0.25	0.20	0.10
				No	0.50	0.40	0.20
	Natural	Rock Slope		Yes	0.40	0.30	0.15
				No	0.80	0.50	0.25
		Non-Rock Slope		Yes	0.35	0.30	0.15
				No	0.30	0.25	0.15
20-year (≥ 500 cu yds)	NA			0.99			

Step 6: Risk Calculation (Owner & User)

Annual Owner Risk

Annual owner risk is calculated for each event magnitude (small, medium, and large) using the owner consequence (Step 3), vulnerability (Step 5), and threat likelihood (Step 1) then the owner risk for all events is summed to calculate total annual risk utilizing Equation 3.9.

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ Risk_i = Owner\ Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

Annual User Risk

Annual user risk is calculated for each event magnitude (small, medium, and large) using the user consequence (Step 4), vulnerability (Step 5), and threat likelihood (Step 1) then the user risk for all events is summed to calculate total annual risk utilizing Equation 3.11. The user consequence for rockfall on PTCS sections is based on the estimated WRC of four days of full closure plus 14 days of partial closure, Exhibit 4.1.1.8.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ Risk_i = \ Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

Total Annual Risk

The total annual risk for rockfall on PTCS sections accounts for the annual owner risk as well as the annual user risk from all rockfall events magnitudes. Use Equation 3.13 to calculate total annual risk to both CDOT and the traveling public from rockfall.

EQUATION 3.13

$$Total\ Annual\ Risk = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

Where n= number of events

An example problem demonstrating the use of this approach is provided next.

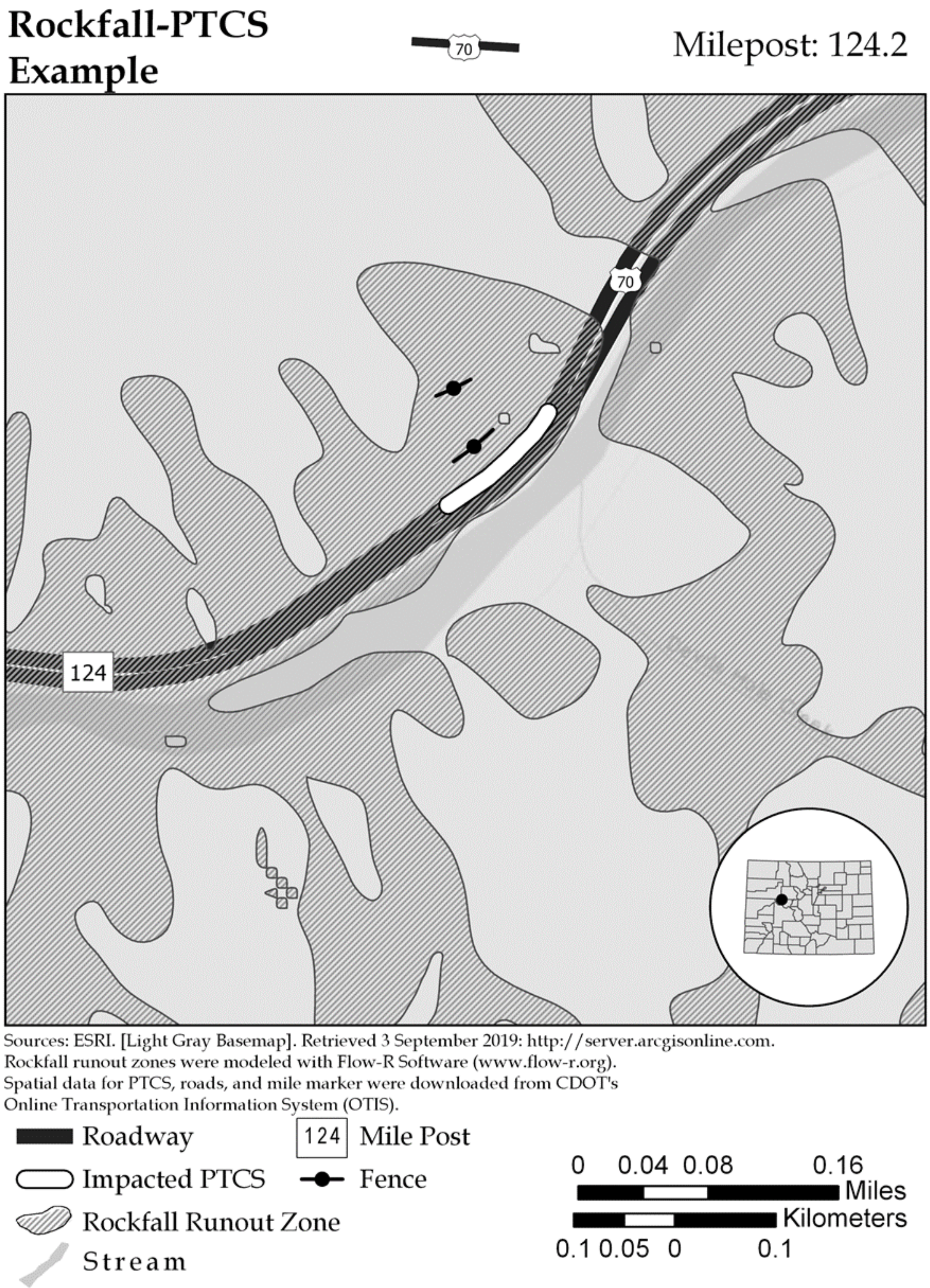
Example Problem – Rockfall-PTCS Risk Assessment

This example demonstrates the risk assessment methodology developed for rockfall-PTCS presented in Exhibit 4.1.1.2. The task is to calculate the annual owner risk, user risk, and total risk from rockfall on a PTCS section in Glenwood Canyon. Exhibit 4.1.1.11 includes a graphic of the example site on I-70 in the vicinity of MP 124. Several severe rockfall events have occurred in this area within the last 15 years, costing millions of dollars in direct and indirect losses. Information for the site is provided here:

Site Overview

- Location: I-70, MP 124.23 – MP 124.34, Glenwood Canyon
- Four-lane freeway (two-lanes in each direction)
- Full roadway width, each direction = 38 ft
- Unit cost for PTCS = $550/sq ft
- $AADT_{Vehicle}$ = 11,375 vehicles
- $AADT_{Truck}$ = 1,625 trucks
- Detour length = 140 miles
- Detour time = 167 minutes
- Work zone length = 9 miles
- Normal speed limit = 55 mph
- Work zone speed reduction = 15 mph
- Number of days of full closure = 4 days
- Number of days of partial closure = 14 days
- Slope-type = natural
- *Lithology* = rock slope
- Slope does not have a ditch.
- Slope is not *actively monitored*.
- Rockfall mitigation = four 2-kj fences

EXHIBIT 4.1.1.11 EXAMPLE ROCKFALL SITE, I-70, MP 124.2



Sources: ESRI. [Light Gray Basemap]. Retrieved 3 September 2019: http://server.arcgisonline.com.
Rockfall runout zones were modeled with Flow-R Software (www.flow-r.org).
Spatial data for PTCS, roads, and mile marker were downloaded from CDOT's Online Transportation Information System (OTIS).

Following the rockfall-PTCS methodology presented in Exhibit 4.1.1.2:

Step 1: Threat Data Collection

Use the estimated annual threat likelihoods included in Exhibit 4.1.1.12 to calculate annual risk for small, medium, and large rockfall events.

EXHIBIT 4.1.1.12 ROCKFALL EVENT THREAT LIKELIHOOD FOR I-70 IN GLENWOOD CANYON

Rockfall Event Magnitude	Volume (cu yds)	Annual Threat Likelihood
Small	< 100	1
Medium	100 – 499	1/6
Large	≥ 500	1/20

Step 2: Asset Data Collection

Exhibit 4.1.1.4 describes the data needs and sources to perform the risk assessment. Actual values are listed under "Site Overview" previously provided.

Step 3: Owner Consequence

The WRC for a rockfall-PTCS event, Exhibit 4.1.1.13, is calculated as 25% of ARC, rounded up to the nearest $50, for a 500 ft section plus $200,000 for debris removal. The unit cost for PTCS, Exhibit 4.1.1.14, is $550/sq ft. To calculate area, multiply the full width (38 ft) by the length of the study section (500 ft). The complete calculation is shown here:

EXHIBIT 4.1.1.13 SUMMARY OF WRC FOR OWNER CONSEQUENCE

		Threat			
		Debris Flow	**Flood**	**Scour**	**Rockfall**
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

EXHIBIT 4.1.1.14
UNIT COSTS

Asset	Units	Unit Cost
Bridge Approach**	sq ft	$350
Bridge*	sq ft	$600
Culvert***	cu ft	$55
PTCS**	sq ft	$550
Road Prism (Asphalt)**	sq yds	$150
Road Prism (Concrete)**	sq yds	$350

* Bridge area is defined as deck length multiplied by deck width, derived from NBI Items 49 and 52, respectively.
**Bridge approach, roadway and PTCS width are derived from CDOT OTIS Highways feature class using fields for lane width, lane count, and shoulder width.
***For culvert (CBC), the volume, in cubic feet, is calculated by multiplying the box height by the box width by the length. These values are derived from the culverts feature class maintained by C-PLAN, CDOT's interactive online mapping platform.

$$Owner\ Consequence = \left(25\%\ x\ \left((38\ ft\ x\ 500\ ft)\ x\ \frac{\$550}{sq\ ft}\right)\right) + \$200{,}000$$

$$Owner\ Consequence = \$2{,}612{,}500 + \$200{,}000$$

$$\boldsymbol{Owner\ Consequence} = \$\mathbf{2{,}812{,}500}*$$

The default value of $2,800,000 was not used in this case as site specific data was available.

Step 4: User Consequence

The estimated WRC from rockfall on a PTCS section is a large event and it is based on the cost to the user due to four days of full closure plus 14 days of partial closure, Exhibit 4.1.1.8. User consequences for full closure factor in the additional costs incurred while driving on the provided detour, Exhibit 4.1.1.9. Calculating user consequences for PTCS-Rockfall requires calculating vehicle and truck operating costs (VOC), as well as the value of lost wages and freight revenue (LW), for both full and partial closure, Exhibit 4.1.1.7, as described here.

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

User Consequence for Full Closure (FC):

Use Equation 3.5 to calculate vehicle operating costs for the full closure:

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$ = 11,375 average annual daily traffic (non-truck)
$AADT_{Truck}$ = 1,625 average annual daily truck traffic
$C2$ = \$0.59 vehicle running cost (\$/vehicle-mile)
$C3$ = \$0.96 freight running cost (\$/truck-mile)
d_{FC} = 4 days of full closure
$C7$ = 140 miles difference in distance between detour and original route

$$VOC_{FC} = \left(\left(\frac{\$0.59}{mile}\ x\ 11{,}375\frac{vehicle}{day}\right) + \left(\frac{\$0.96}{mile}\ x\ 1{,}625\frac{truck}{day}\right)\right)\ x\ 4\ days\ x\ 140\ miles$$

$$\boldsymbol{VOC_{FC} = \$4,631,900}$$

Use Equation 3.6 to calculate lost wages and truck revenue for the full closure:

EQUATION 3.6

$$LW_{FC} = \left((C4\ x\ O\ x\ AADT_{Vehicle}) + (C5\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$ = 11,375 average annual daily traffic (non-truck)
$AADT_{Truck}$ = 1,625 average annual daily truck traffic
$C4$ = \$10.62 average value of time (\$/hour-adult)
O = 1.77 average occupancy (adult/vehicle)
$C5$ = \$25.31 average value of freight time(\$/hour-truck)
d_{FC} = 4 days of full closure
Dt = 167 minutes of extra travel time on detour

$$LW_{FC} = \left(\left(\frac{\$10.62}{hour - adult}\ x\ 1.77\frac{adult}{vehicle}\ x\ 11{,}375\frac{vehicle}{day}\right) + \left(\frac{\$25.31}{hour - truck}\ x\ 1{,}625\frac{truck}{day}\right)\right)\ x\ 4\ days\ x\frac{167\ min}{60\ \frac{min}{hour}}$$

$$\boldsymbol{LW_{FC} = \$2,838,434}$$

User consequences for full closure are the sum of vehicle operating costs incurred due to travel on detour and the lost wages and truck revenue due to travel on detour utilizing Equation 3.3.

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

$$User\ Consequence_{FC} = \$4{,}631{,}900 + \$2{,}838{,}434$$

$$\boldsymbol{User\ Consequence_{FC} = \$7,470,334}$$

User Consequence for Partial Closure (PC):

Calculating user consequence for partial closure varies from the calculations for full closures and includes the additional travel time incurred during work zone operations instead of the additional travel time and distance incurred on the detour.

Use Equation 3.7 to calculate vehicle operating costs due to partial closures:

EQUATION 3.7

$$VOC_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right)\ x\ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x\ WZS}\right)\ x\ \left((C8\ x\ AADT_{Vehicle}) + (C9\ x\ AADT_{Truck})\right)\ x\ d_{PC}$$

Where:

WL	=	Work zone length, 9 miles
WZS	=	Work zone speed limit, 55 mph
$WZSR$	=	Work zone speed limit reduction, 15 mph
$AADT_{Vehicle}$	=	11,375 average annual daily traffic (non-truck)
$AADT_{Truck}$	=	1,625 average annual daily truck traffic
$C8$	=	\$26.52 vehicle running cost (\$/hour)
$C9$	=	\$44.24 freight running cost (\$/hour)
d_{PC}	=	14 days of partial closure

$$VOC_{PC} = \left(\left(\frac{1}{\left(\frac{1}{9\ miles}\right) x\ (55\ mph - 15\ mph)}\right) - \left(\frac{1}{\left(\frac{1}{9\ miles}\right) x\ 55\ mph}\right)\right)\ x\ \left(\left(\frac{\$26.52}{vehicle - hour} x\ 11{,}375 \frac{vehicle}{day}\right) + \left(\frac{\$44.24}{truck - hour}\ x\ 1{,}625 \frac{truck}{day}\right)\right)\ x\ 14\ days$$

$$\boldsymbol{VOC_{PC} = \$320,918}$$

Use Equation 3.8 to calculate vehicle operating costs due to partial closures.

EQUATION 3.8

$$LW_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x\ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x\ WZS}\right) x\ ((C4\ x\ AADT_{Vehicle}\ x\ O) + (C5\ x\ AADT_{Truck}))\ x\ d_{PC}$$

Where:

WL	=	Work zone length, 9 miles
WZS	=	Work zone speed limit, 55 mph
$WZSR$	=	Work zone speed limit reduction, 15 mph
$AADT_{Vehicle}$	=	11,375 average annual daily traffic (non-truck)
$AADT_{Truck}$	=	1,625 average annual daily truck traffic
$C4$	=	$10.62 average value of time ($/hour-vehicle)
O	=	1.77 average occupancy (adult/vehicle)
$C5$	=	$25.31 average value of freight time($/hour-truck)
d_{PC}	=	14 days of partial closure

$$LW_{PC} = \left(\left(\frac{1}{\left(\frac{1}{9\ miles}\right) x\ (55\ mph - 15\ mph)}\right) - \left(\frac{1}{\left(\frac{1}{9\ miles}\right) x\ 55\ mph}\right)\right) x\ \left(\left(\frac{\$10.62}{vehicle - hour} x\ 1.77\ \frac{adult}{vehicle}\ x\ 11{,}375\frac{vehicle}{day}\right) + \left(\frac{\$25.31}{truck - hour}\ x\ 1{,}625\frac{truck}{day}\right)\right) x\ 14\ days$$

$$\boldsymbol{LW_{PC} = \$219,025}$$

Use Equation 3.4 to sum VOC_{PC} and LW_{PC} to calculate total consequences for partial closures.

EQUATION 3.4

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

$$User\ Consequence_{PC} = \$320{,}918 + \$219{,}025$$

$$\boldsymbol{User\ Consequence_{PC} = \$539,943}$$

Total User Consequence:

Finally, sum together user consequences from full and partial closures as shown in Equation 3.2:

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

$$Total\ User\ Consequence = \$7{,}470{,}334 + \$539{,}943$$

$$\boldsymbol{Total\ User\ Consequence} = \$\mathbf{8,010,277}$$

Step 5: Vulnerability Assessment

The following information is needed to estimate the vulnerability of PTCS sections for rockfall events: 1) presence of mitigation; 2) presence of catchment ditch; 3) slope monitoring activity; 4) type of (cut slope or natural slope); 5) type of surficial geology (loose, unconsolidated sediments); and 6) highway type (divided or not).

The characteristics of the example site location are provided here and shown in Exhibit 4.1.1.15 to determine vulnerability values:

- Slope is a natural slope
- Lithology is rock slope
- Slope does not have a ditch.
- Slope is not *actively monitored*.
- Slope has mitigation installed (rockfall fences).
- Roadway segment is on a divided highway and adjacent to the hazardous slope.

EXHIBIT 4.1.1.15 ROCKFALL VULNERABILITY TABLE

Magnitude	Factors				Vulnerability		
Return Period (years)	Natural or Cut Slope	Lithology	Ditch	Monitored	No Mitigation	Slope Maintained	Installed Mitigation
1-year (≤ 100 cu yds)	Cut Slope	Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
		Non-Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.00	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.00	0.00
	Natural	Rock Slope	Absent	Yes	0.01	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
		Non-Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
6-year (101 - 499 cu yds)	Cut Slope	Rock Slope	Absent or Width ≤ 10 ft	Yes	0.35	0.30	0.15
				No	0.65	0.50	0.25
			Width > 10 ft	Yes	0.30	0.25	0.15
				No	0.60	0.45	0.25
		Non-Rock Slope	Absent or Width ≤ 10 ft	Yes	0.30	0.25	0.15
				No	0.55	0.45	0.25
			Width > 10 ft	Yes	0.25	0.20	0.10
				No	0.50	0.40	0.20
	Natural	Rock Slope		Yes	0.40	0.30	0.15
				No	0.80	0.50	0.25
		Non-Rock Slope		Yes	0.35	0.30	0.15
				No	0.30	0.25	0.15
20-year (≥ 500 cu yds)	NA				0.99		

For a natural, lithology is a rock slope, no active monitoring, and no ditch, with mitigation installed the vulnerability for a small event is 0.00 and for a medium event, 0.25. The vulnerability for large rockfall events is always the default value of 0.99.

Step 6: Risk Assessment

Annual Owner Risk

Annual owner risk, user risk and total risk are calculated in Step 6. Calculating annual owner risk, requires the threat likelihood (Step 1), owner consequences (Step 3), and vulnerability probabilities (Step 5). The resulting values have been included in Exhibit 4.1.1.16. Total annual owner risk is calculated by multiplying the threat likelihood by owner consequences by the vulnerability for each event, then summing the annual owner risk for all events utilizing Equation 3.9.

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ Risk_i = Owner\ Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

EXHIBIT 4.1.1.16 SUMMARY OF ANNUAL OWNER RISK CALCULATION

Rockfall Event Magnitude	Owner Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual Owner Risk ($)
Small	$2,812,500	0.00	1	$0
Medium	$2,812,500	0.25	1/6	$117,188
Large	$2,812,500	0.99	1/20	$139,219
			TOTAL	$256,407

Annual User Risk

To calculate annual user risk, use the threat likelihood (Step 1), user consequences (Step 4), and vulnerability probabilities (Step 5). The resulting values have been included in Exhibit 4.1.1.17. Total Annual User Risk is calculated by multiplying the threat likelihood by the owner consequences by the vulnerability for each event, then summing the annual user risk for all events utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ Risk_i = Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

EXHIBIT 4.1.1.17 SUMMARY OF ANNUAL USER RISK CALCULATIONS

Rockfall Event Magnitude	User Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual Owner Risk ($)
Small	$8,010,277	0.00	1	$0
Medium	$8,010,277	0.25	1/6	$333,762
Large	$8,010,277	0.99	1/20	$396,509
			TOTAL	$730,271

Total Annual Risk

The total annual risk, owner risk plus user risk is calculated utilizing Equation 3.13. The resulting values have been included in Exhibit 4.1.1.18.

EQUATION 3.13

$$Total\ Annual\ Risk = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

Where n= number of events

EXHIBIT 4.1.1.18 SUMMARY OF TOTAL ANNUAL RISK CALCULATION

Annual Owner Risk ($)	Annual User Risk ($)	Total Annual Risk ($)
$256,407	$730,271	$986,678

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4.1.2 Rockfall-Bridge Risk Assessment

It is estimated that over 900 CDOT-owned bridges lie within rockfall hazard zones. Similar to PTCS, bridges have an elevated deck that is vulnerable to puncture from large rocks. Exhibit 4.1.2.1 outlines the methodology for estimating the annual risk to bridges from rockfall.

EXHIBIT 4.1.2.1 ROCKFALL-BRIDGE RISK ASSESSMENT METHODOLOGY

Step 1: Threat Data Collection
Rockfall Annual Likelihood (Exhibit 4.1.2.2)

↓

Step 2: Asset Data Collection
Asset (Bridge) Data Needs (Exhibit 4.1.2.3)

↓

Step 3: Owner Consequence Calculation
Owner Worst Reasonable Case (WRC) for Rockfall-Bridge (Exhibit 4.1.2.4)
Bridge Unit Cost Estimation (Exhibit 4.1.2.5)

↓

Step 4: User Consequence Calculation
User Worst Reasonable Case (WRC) for Rockfall-Bridge (Exhibit 4.1.2.4)
Vehicle Operating Cost (VOC) and Lost of Wages (LW) (Exhibit 4.1.2.6)
Detour Estimation (Extra Travel Length and Time) (Exhibits 4.1.2.7 and 4.1.2.8)
Calculations (Equations 3.5 through 3.8)
Total User Consequence (Equation 3.2)

↓

Step 5: Vulnerability Assessment
Rockfall Vulnerability (Exhibit 4.1.2.9)

↓

Step 6: Risk Assessment
Annual Owner Risk Calculation (Equation 3.9)
Annual User Risk Calculation (Equations 3.2 through 3.8 and 3.11)
Annual Total Risk (Equation 3.13)

Computational Steps

Step 1: Threat Data Collection

In this step, the annual threat likelihood for rockfall is determined. As discussed in section 4.1.1, threat likelihood is traditionally based on empirical, historical data gathered over an extended period of time. The values utilized in this document are specific to the Glenwood Canyon area on I-70. Users of this document are encouraged to seek additional input on threat likelihood of rockfall events along other highways on the CDOT system from the CDOT Geohazard Program Staff. Exhibit 4.1.2.2 lists estimates of rockfall frequency and magnitude for I-70 in Glenwood Canyon, based on past events.

EXHIBIT 4.1.2.2 ROCKFALL EVENT THREAT LIKELIHOOD FOR I-70 IN GLENWOOD CANYON

Rockfall Event Magnitude	Volume (cu yds)	Annual Threat Likelihood
Small	< 100	1
Medium	100 – 499	1/6
Large	≥ 500	1/20

Step 2: Asset Data Collection

Data needed to assess the annual risk from rockfall events includes asset replacement cost, user costs, and vulnerability. The *FHWA's National Bridge Inventory* provides dimensions necessary for calculating asset replacement cost and Owner Consequences. The OTIS Highways feature class provides dimensions for roadway features required to calculate asset replacement cost, as well as traffic volumes for calculating user consequences. In addition, rockfall mitigation data, as well as the RHRS, is used for the vulnerability estimation. Exhibit 4.1.2.3 provides a summary of the data needed to complete the analysis for the annual risk of rockfall to bridges.

EXHIBIT 4.1.2.3 DATA NEEDS FOR ROCKFALL-BRIDGE RISK ANALYSIS

	Data Needs	Data Source
Asset Replacement Cost	**Milepost (beginning and end)**	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Bridge Length (NBI 49)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm
	Bridge Width (NBI 52)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm
Vulnerability	**Structure ID (NBI 8)**	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm
	Rockfall Mitigation	CDOT Geotechnical
	Slope Type and Lithology	CDOT Geotechnical
	Roadway (rockfall) Ditch	CDOT Geotechnical
User Consequences	**AADT Vehicles**	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	AADT Trucks	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Roadway Damaged	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Detour	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Detour Distance	CDOT Operations
	Detour Time	CDOT Operations
	Number of Closure Days	See Exhibit 4.1.2.7
	Number of Partial Closure Days	See Exhibit 4.1.2.7
	Average Vehicle Occupancy	FHWA https://www.fhwa.dot.gov/tpm/guidance/avo_factors.pdf
	Car Running Costs	(RITA)/Texas A&M Transportation Institute
	Truck Running Costs	American Transportation Research Institute
	Average Value of Time	(RITA)/Texas A&M Transportation Institute

Step 3: Owner Consequence Assessment

The WRC for rockfall-bridge is used for all owner risk calculations, regardless of magnitude, as defined in Exhibit 4.1.2.4. The WRC is capped at $2,500,000 for bridges with a deck length of 100 ft or greater based on input from CDOT Geohazard Program and Staff Bridge. This value is derived from 100% asset replacement cost for a bridge 100 ft or longer in length plus $200,000 in cleanup costs, rounded to the nearest $100,000 as shown here.

EXHIBIT 4.1.2.4 SUMMARY OF WRC FOR OWNER CONSEQUENCE

Asset		Threat: Debris Flow	Threat: Flood	Threat: Scour	Threat: Rockfall
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

EXHIBIT 4.1.2.5 UNIT COSTS

Asset	Units	Unit Cost
Bridge Approach**	sq ft	$350
Bridge*	sq ft	$600
Culvert***	cu ft	$55
PTCS**	sq ft	$550
Road Prism (Asphalt)**	sq yds	$150
Road Prism (Concrete)**	sq yds	$350

* Bridge area is defined as deck length multiplied by deck width, derived from NBI Items 49 and 52, respectively.

**Bridge approach, roadway and PTCS width are derived from CDOT OTIS Highways feature class using fields for lane width, lane count, and shoulder width.

***For culvert (CBC), the volume, in cubic feet, is calculated by multiplying the box height by the box width by the length. These values are derived from the culverts feature class maintained by C-PLAN, CDOT's interactive online mapping platform.

$$ARC_{Bridge\ 100\ ft\ long} = \left((100\ ft\ x\ 38\ ft)\ x\ \frac{\$600}{sq\ ft} \right) + \$200{,}00$$

$$ARC_{Bridge\ 100\ ft\ long} = \$2{,}480{,}000$$

$$WRC = \$2{,}480{,}000 \approx \$\mathbf{2,500,000}^*$$

Default value can be used when site specific data is not available.
For bridges less than 100 ft in length, the WRC is 100% ARC + $200,000.

Step 4: User Consequence Assessment

User consequences measure the impact to the public in terms of lost wages and increased vehicle operating costs due to delays and longer drive distances and times. Required inputs include AADT, percent truck traffic, average vehicle occupancy, and WRC from rockfall on a bridge. For further explanation on how to calculate user consequences, see Equations 3.2 through 3.8 and 3.11.

Exhibit 4.1.2.6 provides default values for a range of factors associated with the cost associated with operating vehicles, value of time, and occupancy that are updated annually by the various federal government agencies. Note the values included in Exhibit 4.1.2.6 were gathered in June of 2019 and will vary in future years.

EXHIBIT 4.1.2.6 CONSTANTS USED IN USER CONSEQUENCE CALCULATIONS

User Cost Terms	Variable	Value	Year Published
Average Vehicle Occupancy	*O*	1.77	2019
Car Running Cost per Mile	*C2*	$0.59	2019
Truck Running Cost per Mile	*C3*	$0.96	2015
Average Value of Time per Adult per Hour	*C4*	$10.62	2015
Average Value of Freight Driver Cost per Hour	*C5*	$25.31	2015
Car Running Cost per Hour	*C8*	$26.52	2015
Truck Running Cost per Hour	*C9*	$44.24	2015

The suggested number of full and partial closure days, derived from the I-70 Pilot, are provided in Exhibit 4.1.2.7. It is suggested that this table be used as guidance for all other corridor's for estimating closures days, both full and partial.

EXHIBIT 4.1.2.7 I-70 RISK AND RESILIENCE PILOT NUMBER OF FULL CLOSURE AND PARTIAL CLOSURE DAYS FOR WRC

Asset	Threat	Full Closure Days (d_{FC})	Partial Closure Days (d_{PC})
Bridge Approach	All	2	0
Bridge	Flood	180	0
Bridge	Debris Flow	2	0
Bridge	Rockfall	4	14
Culvert	Debris Flow	1	0
Culvert	Flood	3	0
PTCS	Rockfall	4	14
Roadway (<=% Width)	Flood	1	0
Roadway (> 50% Width)	Flood	3	0
Roadway (2 Directions)	Flood	3	0
Roadway	Rockfall	4	14

Example detours used for the I-70 Risk and Resilience Pilot and the worked examples in this document are listed in Exhibit 4.1.2.8. Note that *Additional Travel Distance* refers to the additional miles a traveler must travel on detour in comparison to the original route, and *Additional Travel Time* is the additional time a traveler must travel on detour in comparison to the original route. CDOT Operations can provide further guidance on estimating detours from closures for highways other than I-70.

EXHIBIT 4.1.2.8 I-70 RISK AND RESILIENCE PILOT DETOUR TABLE

Starting Milepost	Ending Milepost	Additional Travel Distance (miles) (*C7*)	Additional Travel Time (minutes) (*Dt*)
1	14	146	189
14	90	90	112
90	155	140	167
155	205	98	126
205	231	83	109
231	245	49	77
245	288	3	7
288	353	15	24
353	360	71	96
360	404	76	73
404	438	69	70
438	450	63	77

Total User Consequences is the sum of user consequence due to full and partial closures as shown in Equation 3.2.

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

Where:

$User\ Consequence_{FC}$ = User consequences due to full closure
$User\ Consequence_{PC}$ = User consequences due to partial closure

User consequences for full closure are the sum of vehicle operating costs incurred due to travel on detour, lost wages, and truck revenue due to travel on detour as shown in Equation 3.3.

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

Where:

VOC_{FC} = Vehicle operating costs incurred due to full closure
LW_{FC} = Lost wages/truck revenue incurred due to full closure

User consequences for partial closures are the sum of vehicle operating costs incurred due to traffic delays, lost wages, and truck revenue due to delays incurred while driving through a partial closure as shown in Equation 3.4.

EQUATION 3.4

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

Where:

VOC_{PC} = Vehicle operating costs incurred due to partial closure
LW_{PC} = Lost wages/truck revenue incurred due to partial closure

Equation 3.5 is the equation for calculating vehicle operating costs for full closures.

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$ = Average annual daily traffic (non-truck)
$AADT_{Truck}$ = Average annual daily truck traffic
$C2$ = Vehicle running cost ($/vehicle-mile)
$C3$ = Freight running cost ($/truck-mile)
d_{FC} = Number of full closure days (days)
$C7$ = Difference in distance between detour and original route (mile)

Equation 3.6 is used for calculating lost wages and truck revenue for full closures.

EQUATION 3.6

$$LW_{FC} = \left(\left(C4 \ x \ O \ x \ AADT_{Vehicle}\right) + \left(C5 \ x \ AADT_{Truck}\right)\right) x \ d_{FC} \ x \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$ = Average annual daily traffic (non-truck)
$AADT_{Truck}$ = Average annual daily truck traffic
$C4$ = Average value of time ($/adult-hour)
O = Average occupancy (adult/vehicle)
$C5$ = Average value of freight time($/truck-hour)
d_{FC} = Number of full closure days (days)
Dt = Extra travel time on detour (minutes)

Equation 3.7 is used for calculating vehicle operating costs due to partial closures.

EQUATION 3.7

$$VOC_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x \ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x \ WZS}\right) x \left(\left(C8 \ x \ AADT_{Vehicle}\right) + \left(C9 \ x \ AADT_{Truck}\right)\right) x \ d_{PC}$$

Where:

WL = Work zone length (miles)
WZS = Work zone speed limit (mph)
$WZSR$ = Work zone speed limit reduction (mph)
$AADT_{Vehicle}$ = Average annual daily traffic (non-truck)
$AADT_{Truck}$ = Average annual daily truck traffic
$C8$ = Vehicle running cost ($/vehicle-hour)
$C9$ = Freight running cost ($/truck-hour)
d_{PC} = Number of days of partial closure (days)

Equation 3.8 is used for calculating lost wages and truck revenue due to partial closures.

EQUATION 3.8

$$LW_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x\ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x\ WZS}\right) x\ ((C4\ x\ AADT_{Vehicle}\ x\ O) + (C5\ x\ AADT_{Truck}))\ x\ d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C4$	=	Average value of time ($/adult-hour)
O	=	Average occupancy (adult/vehicle)
$C5$	=	Average value of freight time($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Calculate total annual user risk by multiplying the owner consequences by the vulnerability for each magnitude of event the threat likelihood then summing the annual user risk for all events, utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ \boldsymbol{R}isk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n = number of events

Step 5: Vulnerability Assessment

See Exhibit 4.1.2.9 for the vulnerability probabilities for rockfall-bridge analysis. As discussed in Section 4.1.1, several factors influence asset vulnerability from rockfall, and these factors are consistent between PTCS and bridges.

EXHIBIT 4.1.2.9 ROCKFALL VULNERABILITY TABLE

Magnitude	Factors				Vulnerability		
Return Period (years)	Natural or Cut Slope	Lithology	Ditch	Monitored	No Mitigation	Slope Maintained	Installed Mitigation
1-year (≤ 100 cu yds)	Cut Slope	Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
		Non-Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.00	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.00	0.00
	Natural	Rock Slope	Absent	Yes	0.01	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
		Non-Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
6-year (101 - 499 cu yds)	Cut Slope	Rock Slope	Absent or Width ≤ 10 ft	Yes	0.35	0.30	0.15
				No	0.65	0.50	0.25
			Width > 10 ft	Yes	0.30	0.25	0.15
				No	0.60	0.45	0.25
		Non-Rock Slope	Absent or Width ≤ 10 ft	Yes	0.30	0.25	0.15
				No	0.55	0.45	0.25
			Width > 10 ft	Yes	0.25	0.20	0.10
				No	0.50	0.40	0.20
	Natural	Rock Slope		Yes	0.40	0.30	0.15
				No	0.80	0.50	0.25
		Non-Rock Slope		Yes	0.35	0.30	0.15
				No	0.30	0.25	0.15
20-year (≥ 500 cu yds)	NA			0.99			

Step 6: Risk Calculation

Annual Owner Risk

Annual owner risk is calculated for each event magnitude (small, medium, and large) using the owner consequence (Step 3), vulnerability (Step 5), and threat likelihood (Step 1) then the owner risk for all events is summed to calculate total annual risk utilizing Equation 3.9.

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ Risk_i = Owner\ Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

Annual User Risk

The user consequence for a rockfall impacting a bridge is based on the defined WRC and it is estimated to be four days of full closure plus 14 days of partial closure. Total annual user risk is calculated by multiplying the threat likelihood by the owner consequences by the vulnerability for each event, then summing the annual user risk for all events utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ Risk_i = Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

Total Annual Risk

The total annual risk for rockfall on bridges accounts for the annual owner risk as well as the annual user risk from all rockfall events magnitudes. Utilize Equation 3.13 to calculate total annual risk.

EQUATION 3.13

$$Total\ Annual\ Risk\ = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

Where n= number of events

An example problem demonstrating the use of this approach is provided next.

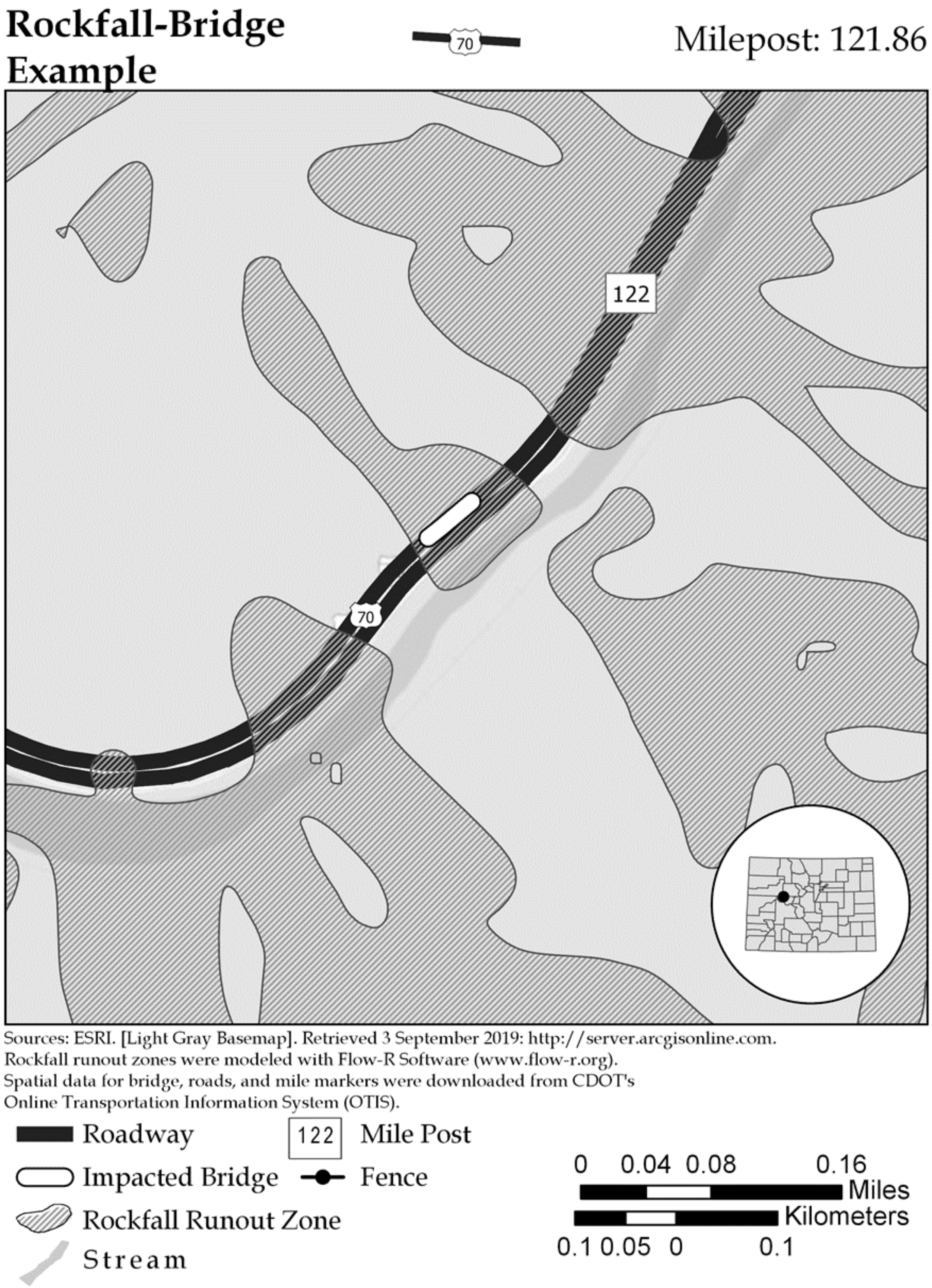
Example Problem - Rockfall-Bridge Risk Assessment

This example demonstrates the risk assessment methodology developed for rockfall-bridge as presented in Exhibit 4.1.2.1. The task is to calculate the annual owner risk, user risk, and total risk from rockfall for a bridge in Glenwood Canyon. Exhibit 4.1.2.10 includes the example site on I-70 in the vicinity of MP 121.86. Additional site information is provided here:

Site Overview

- Location: I-70, MP 121.86, Glenwood Canyon
- Four-lane freeway (two-lanes in each direction)
- Deck length = 187 ft
- Deck width = 38 ft
- Unit cost for bridge = $600/sq ft
- $AADT_{Vehicle}$ = 11,950 vehicles
- $AADT_{Truck}$ = 2,050 trucks
- Detour length = 140 miles
- Detour time = 167 minutes
- Work zone length = 1 mile
- Normal speed limit = 55 mph
- Work zone speed reduction = 15 mph
- Number of days of full closure = 4 days
- Number of days of partial closure = 14 days
- Slope is a natural slope.
- Lithology = rock slope
- Slope does not have a ditch.
- Slope is not actively monitored.
- Slope does not have mitigation installed.

EXHIBIT 4.1.2.10 EXAMPLE ROCKFALL SITE, I-70, MP 121.86



Sources: ESRI. [Light Gray Basemap]. Retrieved 3 September 2019: http://server.arcgisonline.com.
Rockfall runout zones were modeled with Flow-R Software (www.flow-r.org).
Spatial data for bridge, roads, and mile markers were downloaded from CDOT's Online Transportation Information System (OTIS).

Following the rockfall-bridge methodology presented in Exhibit 4.1.2.1:

Step 1: Threat Data Collection

Use the estimated annual threat likelihoods included in Exhibit 4.1.2.8.

EXHIBIT 4.1.2.11 ROCKFALL EVENT THREAT LIKELIHOOD FOR I-70 IN GLENWOOD CANYON

Rockfall Event Magnitude	Volume (cu yds)	Annual Threat Likelihood
Small	< 100	1
Medium	100 – 499	1/6
Large	≥ 500	1/20

Step 2: Asset Data Collection

Exhibit 4.1.2.3 describes the data needs and sources to perform the risk assessment. Actual values are listed under "Site Overview".

Step 3: Owner Consequences

From the NBI dataset, the deck length is 187 ft from Item 49 of the database. According to Exhibit 4.1.2.12, if the deck length is over 100 ft, then the anticipated owner consequences for rockfall-bridge is the default value of $2.5 million.

EXHIBIT 4.1.2.12 SUMMARY OF WRC FOR OWNER CONSEQUENCE

		Threat			
		Debris Flow	Flood	Scour	Rockfall
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
Asset	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
Asset	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
Asset	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
Asset	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

$$WRC \approx \$2,500,000^{*}$$

Default value is to be used as bridge length is over 100ft.

Step 4: User Consequences

As with rockfall-PTCS, the WRC for User Consequences and rockfall-bridge is four days of closure and 14 days of partial closure, Exhibit 4.1.2.7. Calculating User Consequences for rockfall-bridge requires calculating vehicle and truck operating costs (VOC), Exhibit 4.1.2.6, as well as the value of lost wages and freight revenue (LW), for both full and partial closure, Exhibit 4.1.2.8, using Equations 3.2 to 3.8 and 3.11.

$$Total\ User\ Consequence = User\ Consequence_{FC} + \ User\ Consequence_{PC}$$

$$User\ Consequence_{FC} = VOC_{FC} + \ LW_{FC}$$

$$User\ Consequence_{PC} = VOC_{PC} + \ LW_{PC}$$

User Consequence for Full Closure (FC):

Use Equation 3.5 to calculate vehicle operating costs for full closures:

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$	=	11,950 average annual daily traffic (non-truck)
$AADT_{Truck}$	=	2,050 average annual daily truck traffic
$C2$	=	\$0.59 vehicle running cost (\$/vehicle-mile)
$C3$	=	\$0.96 freight running cost (\$/truck-mile)
d_{FC}	=	4 days of full closure
$C7$	=	140 miles difference in distance between detour and original route

$$VOC_{FC} = \left(\left(\frac{\$0.59}{vehicle - mile} x\ 11{,}950 \frac{vehicle}{day}\right) + \left(\frac{\$0.96}{truck - mile}\ x\ 2{,}050 \frac{truck}{day}\right)\right)\ x\ 4\ days\ x\ 140\ miles$$

$$\boldsymbol{VOC_{FC} = \$5{,}050{,}360}$$

Use Equation 3.6 to calculate lost wages and truck revenue for full closures:

EQUATION 3.6

$$LW_{FC} = \left((C4\ x\ O\ x\ AADT_{Vehicle}) + (C5\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$	=	11,950 average annual daily traffic (non-truck)
$AADT_{Truck}$	=	2,050 average annual daily truck traffic
$C4$	=	\$10.62 average value of time (\$/hour-adult)
O	=	1.77 average occupancy (adult/vehicle)
$C5$	=	\$25.31 average value of freight time(\$/hour-truck)
d_{FC}	=	4 days of full closure
Dt	=	167 minutes of extra travel time on detour

$$LW_{FC} = \left(\left(\frac{\$10.62}{hour - adult}\ x\ \frac{1.77\ adults}{vehicle}\ x\ 11{,}950\frac{vehicle}{day}\right) + \left(\frac{\$25.31}{hour - adult}\ x\ 2{,}050\frac{truck}{day}\right)\right) x\ 4\ days\ x\ \frac{167\ min}{60\ \frac{min}{hour}}$$

$$\boldsymbol{LW_{FC} = \$3,078,527}$$

User consequences for full closure are the sum of vehicle operating costs incurred due to vehicle travel on detour and the lost wages and truck revenue due to travel on detour as shown in Equation 3.3.

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

$$User\ Consequence_{FC} = \$5{,}050{,}360 + \$3{,}078{,}527$$

$$\boldsymbol{User\ Consequence_{FC} = \$8,128,887}$$

User Consequence for Partial Closure (PC):

Calculating user consequence for partial closure varies from the calculations for full closures and includes the additional travel time incurred during work zone operations instead of the additional travel time and distance incurred on the detour.

Use Equation 3.7 to calculate vehicle operating costs due to partial closures:

EQUATION 3.7

$$VOC_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right)\ x\ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x\ WZS}\right) x\ \left((C8\ x\ AADT_{vehicle}) + (C9\ x\ AADT_{truck})\right) x\ d_{PC}$$

Where:

WL = Work zone length, 1 mile

WZS	=	Work zone speed limit, 55 mph
$WZSR$	=	Work zone speed limit reduction, 15 mph
$AADT_{Vehicle}$	=	11,950 average annual daily traffic (non-truck)
$AADT_{Truck}$	=	2,050 average annual daily truck traffic
$C8$	=	\$26.52 vehicle running cost (\$/hour)
$C9$	=	\$44.24 freight running cost (\$/hour)
d_{PC}	=	14 days of partial closure

$$VOC_{PC} = \left(\left(\left(\frac{1}{\left(\frac{1}{1\ mile}\right) x\ (55\ mph - 15\ mph)}\right) - \left(\frac{1}{\left(\frac{1}{1\ mile}\right) x\ 55\ mph}\right)\right) x \left(\left(\frac{\$26.52}{vehicle - hour}\ x\ 11{,}950 \frac{vehicle}{day}\right) + \left(\frac{\$44.24}{truck - hour}\ x\ 2{,}050 \frac{truck}{day}\right)\right) x\ 14\ days\right.$$

$$\boldsymbol{VOC_{PC} = \$38,908}$$

Use Equation 3.8 to calculate lost wages and truck revenue due to partial closures:

EQUATION 3.8

$$LW_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right)\ x\ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right)\ x\ WZS}\right) x\ ((C4\ x\ AADT_{Vehicle}\ x\ O) + (C5\ x\ AADT_{Truck}))\ x\ \ d_{PC}$$

Where:

WL	=	Work zone length 1 mile
WZS	=	Work zone speed limit 55 mph
$WZSR$	=	Work zone speed limit reduction 15 mph
$AADT_{Vehicle}$	=	11,950 average annual daily traffic (non-truck)
$AADT_{Truck}$	=	2,050 average annual daily truck traffic
$C4$	=	\$10.62 average value of time (\$/hour-vehicle)
O	=	1.77 average occupancy (adult/vehicle)
$C5$	=	\$25.31 average value of freight time(\$/hour-truck)
d_{PC}	=	14 days of partial closure

$$LW_{PC} = \left(\left(\left(\frac{1}{\left(\frac{1}{1\ mile}\right) x\ (55\ mph - 15\ mph)}\right) - \left(\frac{1}{\left(\frac{1}{1\ mile}\right) x\ 55\ mph}\right)\right) x \left(\left(\frac{\$10.62}{adult - hour}\ x\ 1.77 \frac{adult}{vehicle}\ x\ 11{,}950 \frac{vehicle}{day}\right) + \left(\frac{\$25.31}{truck - hour}\ x\ 2{,}050 \frac{truck}{day}\right)\right)\ x\ 14\ days\right.$$

$$\boldsymbol{LW_{PC} = \$26,395}$$

Next, use Equation 3.4 to sum VOC_{PC} and LW_{PC} to calculate total user consequences for partial closures.

EQUATION 3.4

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

$$User\ Consequence_{PC} = \$38{,}908 + \$26{,}395$$

$$\boldsymbol{User\ Consequence_{PC} = \$65{,}303}$$

Total User Consequence:

Total user consequences include the sum of user consequence due to full and partial closures as shown in Equation 3.2.

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

$$Total\ User\ Consequence = \$8{,}128{,}887 + \$65{,}303$$

$$\boldsymbol{Total\ User\ Consequence = \$8{,}194{,}190}$$

Step 5: Vulnerability Assessment

As discussed in Section 4.1.1, several factors influence the vulnerability of highway assets to rockfall events. These factors are consistent for PTCS and bridges.

The characteristics of the example site location are provided here and shown in Exhibit 4.1.2.10 to determine vulnerability values for each magnitude of event analyzed:

- Slope is a natural slope.
- Lithology is rock slope.
- Slope does not have a ditch.
- Slope is not actively monitored.
- Slope does not have mitigation installed.
- Slope is on a divided highway and the direction of travel is adjacent to the hazardous slope.

EXHIBIT 4.1.2.13 ROCKFALL VULNERABILITY TABLE

Magnitude	Factors				Vulnerability		
Return Period (years)	Natural or Cut Slope	Lithology	Ditch	Monitored	No Mitigation	Slope Maintained	Installed Mitigation
1-year (≤ 100 cu yds)	Cut Slope	Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
		Non-Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.00	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.00	0.00
	Natural	Rock Slope	Absent	Yes	0.01	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
		Non-Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
6-year (101 - 499 cu yds)	Cut Slope	Rock Slope	Absent or Width ≤ 10 ft	Yes	0.35	0.30	0.15
				No	0.65	0.50	0.25
			Width > 10 ft	Yes	0.30	0.25	0.15
				No	0.60	0.45	0.25
		Non-Rock Slope	Absent or Width ≤ 10 ft	Yes	0.30	0.25	0.15
				No	0.55	0.45	0.25
			Width > 10 ft	Yes	0.25	0.20	0.10
				No	0.50	0.40	0.20
	Natural	Rock Slope		Yes	0.40	0.30	0.15
				No	0.80	0.50	0.25
		Non-Rock Slope		Yes	0.35	0.30	0.15
				No	0.30	0.25	0.15
20-year (≥ 500 cu yds)	NA				0.99		

For a natural, rock slope with no mitigation installed, no monitoring, and no ditch, the vulnerability for a small event is 0.01 and for a medium event 0.80. The vulnerability for large rockfall events is always the default value of 0.99.

Step 6. Risk Assessment

Annual Owner Risk:

Annual owner risk, user risk, and total risk are calculated in Step 6. Calculating annual owner risk, requires threat likelihood (Step 1), owner consequences (Step 3), and vulnerability probability (Step 5). The resulting values have been included in Exhibit 4.1.2.14. Total annual owner risk is calculated by multiplying the threat likelihood by the owner consequences by the vulnerability for each event, then summing the annual owner risk for all events utilizing Equation 3.9.

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ Risk_i = Owner\ Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

EXHIBIT 4.1.2.14 SUMMARY OF ANNUAL OWNER RISK CALCULATIONS

Rockfall Event Magnitude	Owner Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual Owner Risk ($)
Small	$2,500,000	0.01	1	$25,000
Medium	$2,500,000	0.80	1/6	$333,333
Large	$2,500,000	0.99	1/20	$123,750
			TOTAL	$482,083

Annual User Risk:

To calculate annual user risk, use the threat likelihood (Step 1), the user consequences (Step 4), and the vulnerability probability (Step 5). The resulting values have been included in Exhibit 4.1.2.15. Total Annual User Risk is calculated by multiplying the threat likelihood by the owner consequences by the vulnerability for each event, then summing the annual user risk for all events utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ Risk_i = Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

EXHIBIT 4.1.2.15 SUMMARY OF ANNUAL USER RISK CALCULATIONS

Rockfall Event Magnitude	User Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual Owner Risk ($)
Small	$8,194,190	0.01	1	$81,942
Medium	$8,194,190	0.80	1/6	$1,092,559
Large	$8,194,190	0.990	1/20	$405,612
			TOTAL	$1,580,113

Total Annual Risk:

The total annual risk, owner risk plus user risk, is calculated utilizing Equation 3.13. The resulting values have been included in Exhibit 4.1.2.16.

EQUATION 3.13

$$Total\ Annual\ Risk\ = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

Where n= number of events

EXHIBIT 4.1.2.16 SUMMARY OF TOTAL ANNUAL RISK CALCULATION

Annual Owner Risk ($)	Annual User Risk ($)	Total Annual Risk ($)
$482,083	$1,580,113	$2,062,196

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4.1.3 Rockfall-Roadway Prism Risk Assessment

Over 2,000 centerline miles of CDOT-managed roads fall within identified rockfall corridors. Frequent, small events require periodic maintenance to keep roads clear of debris while large events can result in cratering of the roadway surface and road closures.

Exhibit 4.1.3.1 illustrates the basic methodology and steps used in estimate the annual risk of roadway prisms to rockfall in Colorado.

EXHIBIT 4.1.3.1 ROCKFALL-ROADWAY PRISM RISK ASSESSMENT METHODOLOGY

Step 1: Threat Data Collection
Rockfall Annual Likelihood (Exhibit 4.1.3.2)

↓

Step 2: Asset Data Collection
Asset (Roadway Prism) Data Needs (Exhibit 4.1.3.3)

↓

Step 3: Owner Consequence Calculation
Owner Worst Reasonable Case (WRC) for Rockfall-Roadway Prism (Exhibit 4.1.3.4)
Roadway Prism Unit Cost Estimation (Exhibit 4.1.3.5)

↓

Step 4: User Consequence Calculation
User Worst Reasonable Case (WRC) or Rockfall-Roadway Prism (Exhibit 4.1.3.4)
Vehicle Operating Cost (VOC) and Lost of Wages (LW) (Exhibit 4.1.3.6)
Detour Estimation (Extra Travel Length and Time) (Exhibits 4.1.3.7 and 4.1.3.8)
Calculations (Equations 3.5 through 3.8)
Total User Consequence (Equation 3.2)

↓

Step 5: Vulnerability Assessment
Rockfall Vulnerability (Exhibit 4.1.3.9)

↓

Step 6: Risk Assessment
Annual Owner Risk Calculation (Equation 3.9)
Annual User Risk Calculation
(Equations 3.2 through 3.8 and 3.11)
Annual Total Risk (Equation 3.13)

Computational Steps

Step 1: Threat Data Collection

In this step, the annual threat likelihood for rockfall is determined. As discussed in section 4.1.1, threat likelihood is traditionally based on empirical, historical data over an extended period of time. The values utilized in this document are specific to the Glenwood Canyon area on I-70. Users of this document are encouraged to seek additional input on threat likelihood of rockfall events along other highways on the CDOT system from the CDOT Geohazard Program Staff. Exhibit 4.1.3.2 lists estimates of rockfall frequency and magnitude for I-70 in Glenwood Canyon based on past events.

EXHIBIT 4.1.3.2 ROCKFALL EVENT THREAT LIKELIHOOD ON I-70 IN GLENWOOD CANYON

Rockfall Event Magnitude	Volume (cu yds)	Annual Threat Likelihood
Small	< 100	1
Medium	100 – 499	1/6
Large	≥ 500	1/20

Step 2: Asset Data Collection

Data needed to assess the annual risk from rockfall events includes asset replacement costs, user costs, and vulnerability. The OTIS Highways feature class supplies the dimensions for roadway features necessary to calculate asset replacement cost, as well as traffic volumes for calculating user consequences. In addition, rockfall mitigation data, as well as the RHRS, is used for the vulnerability estimation. Exhibit 4.1.3.3 provides a summary of the data needed to complete the analysis for the annual risk of rockfall to roadway prism.

EXHIBIT 4.1.3.3 DATA NEEDS FOR ROCKFALL-ROADWAY PRISM RISK ANALYSIS

	Data Needs	Data Source
Asset Replacement Cost	**Milepost (beginning and end)**	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Area of Roadway Overtopped	GIS Layer Roadway-FIRM overlay
	Roadway Geometry	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
Vulnerability	**Terrain**	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Annual Number of Freezing-Thaw Days	SSURGO Soil Survey https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm
	AASHTO Soil Classification	USDA NRCS Soil Web Viewer https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/home/?cid=nrcs142p2_053620
User Consequences	**AADT Vehicles**	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	AADT Trucks	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Roadway Damaged	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Detour	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Detour Distance	CDOT Operations
	Detour Time	CDOT Operations
	Number of Closure Days	See Exhibit 4.1.3.7
	Number of Partial Closure Days	See Exhibit 4.1.3.7
	Average Vehicle Occupancy	FHWA https://www.fhwa.dot.gov/tpm/guidance/avo_factors.pdf
	Car Running Costs	(RITA)/Texas A&M Transportation Institute
	Truck Running Costs	American Transportation Research Institute
	Average Value of Time	(RITA)/Texas A&M Transportation Institute

Step 3: Owner Consequence Assessment

Owner consequences represent the anticipated impact to the owner (CDOT) in terms of cost of repairs, cleanup, maintenance, and related agency operational cost. The most severe but credible consequence (WRC) for rockfall-roadway is used for all owner risk calculations, regardless of magnitude, as defined in Exhibit 4.1.3.4. The most severe but credible consequence (WRC) for rockfall-roadway, based on past emergency repair projects, is estimated as 100% of the asset replacement cost of a 100 ft section plus $200,000 in cleanup costs to remove debris. Roadway Prism unit costs for either asphalt or concrete are defined in Exhibit 4.1.3.5.

EXHIBIT 4.1.3.4 SUMMARY OF WRC FOR OWNER CONSEQUENCE

		Threat			
		Debris Flow	Flood	Scour	Rockfall
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
Asset	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
Asset	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
Asset	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
Asset	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

EXHIBIT 4.1.3.5 UNIT COSTS

Asset	Units	Unit Cost
Bridge Approach**	sq ft	$350
Bridge*	sq ft	$600
Culvert***	cu ft	$55
PTCS**	sq ft	$550
Road Prism (Asphalt)**	sq yds	$150
Road Prism (Concrete)**	sq yds	$350

* Bridge area is defined as deck length multiplied by deck width, derived from NBI Items 49 and 52, respectively.

**Bridge approach, roadway and PTCS width are derived from CDOT OTIS Highways feature class using fields for lane width, lane count, and shoulder width.

***For culvert (CBC), the volume, in cubic feet, is calculated by multiplying the box height by the box width by the length. These values are derived from the culverts feature class maintained by C-PLAN, CDOT's interactive online mapping platform.

Step 4: User Consequence Assessment

User consequences measure the impact to the public in terms of lost wages and increased vehicle operating costs due to delays and longer travel distance and time. Required inputs include AADT, percent truck traffic, average vehicle occupancy, average hourly wage, detour length, work zone length, speed on detour, number of days of closure, and number of days of partial closure. For user consequences, the estimated WRC from rockfall on a roadway section is a large event and it is based on the cost of the user due to four days of full closure plus 14 days of partial closure. For further explanation on how to calculate user consequences, see Equations 3.2 through 3.8 and 3.11.

Exhibit 4.1.3.6 provides default values for a range of factors associated with the cost associated with operating vehicles, value of time, and occupancy that are updated annually by the various federal government agencies. Note the values included in Exhibit 4.1.3.6 were gathered in June of 2019 and will vary in future years.

EXHIBIT 4.1.3.6 CONSTANTS USED IN USER CONSEQUENCE CALCULATIONS

User Cost Terms	Variable	Value	Year Published
Average Vehicle Occupancy	*O*	1.77	2019
Car Running Cost per Mile	*C2*	$0.59	2019
Truck Running Cost per Mile	*C3*	$0.96	2015
Average Value of Time per Adult per Hour	*C4*	$10.62	2015
Average Value of Freight Driver Cost per Hour	*C5*	$25.31	2015
Car Running Cost per Hour	*C8*	$26.52	2015
Truck Running Cost per Hour	*C9*	$44.24	2015

The suggested number of full and partial closure days, derived from the I-70 Pilot, are provided in Exhibit 4.1.3.7. It is suggested that this table be used as guidance for all other corridor's for estimating closures days, both full and partial.

EXHIBIT 4.1.3.7 I-70 RISK AND RESILIENCE PILOT NUMBER OF FULL CLOSURE AND PARTIAL CLOSURE DAYS FOR WRC

Asset	Threat	Full Closure Days (d_{FC})	Partial Closure Days (d_{PC})
Bridge Approach	All	2	0
Bridge	Flood	180	0
Bridge	Debris Flow	2	0
Bridge	Rockfall	4	14
Culvert	Debris Flow	1	0
Culvert	Flood	3	0
PTCS	Rockfall	4	14
Roadway (<=% Width)	Flood	1	0
Roadway (> 50% Width)	Flood	3	0
Roadway (2 Directions)	Flood	3	0
Roadway	Rockfall	4	14

Example detours used for the I-70 Risk and Resilience Pilot and the worked examples in this document are listed in Exhibit 4.1.3.8. Note that *Additional Travel Distance* refers to the additional miles a traveler must travel on detour in comparison to the original route, and *Additional Travel Time* is the additional time a traveler must travel on detour in comparison to the original route. CDOT Operations can provide further guidance on estimating detours from closures for highways other than I-70.

EXHIBIT 4.1.3.8 I-70 RISK AND RESILIENCE PILOT DETOUR TABLE

Starting Milepost	Ending Milepost	Additional Travel Distance (miles) (*C7*)	Additional Travel Time (minutes) (*Dt*)
1	14	146	189
14	90	90	112
90	155	140	167
155	205	98	126
205	231	83	109
231	245	49	77
245	288	3	7
288	353	15	24
353	360	71	96
360	404	76	73
404	438	69	70
438	450	63	77

Total User Consequences is the sum of user consequence due to full and partial closures as shown in Equation 3.2.

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

Where:

$User\ Consequence_{FC}$ = User consequences due to full closure
$User\ Consequence_{PC}$ = User consequences due to partial closure

User consequences for full closure are the sum of vehicle operating costs incurred due to travel on detour, lost wages, and truck revenue due to travel on detour as shown in Equation 3.3.

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

Where:

VOC_{FC} = Vehicle operating costs incurred due to full closure
LW_{FC} = Lost wages/truck revenue incurred due to full closure

User consequences for partial closures are the sum of vehicle operating costs incurred due to traffic delays, lost wages, and truck revenue due to delays incurred while driving through a partial closure as shown in Equation 3.4.

EQUATION 3.4

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

Where:

VOC_{PC} = Vehicle operating costs incurred due to partial closure
LW_{PC} = Lost wages/truck revenue incurred due to partial closure

Equation 3.5 is the equation for calculating vehicle operating costs for full closures.

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right) x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C2$	=	Vehicle running cost ($/vehicle-mile)
$C3$	=	Freight running cost ($/truck-mile)
d_{FC}	=	Number of full closure days (days)
$C7$	=	Difference in distance between detour and original route (mile)

Equation 3.6 is used for calculating lost wages and truck revenue for full closures.

EQUATION 3.6

$$LW_{FC} = \left(\left(C4\ x\ O\ x\ AADT_{Vehicle}\right) + \left(C5\ x\ AADT_{Truck}\right)\right)\ x\ d_{FC}\ x\ \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C4$	=	Average value of time ($/adult-hour)
O	=	Average occupancy (adult/vehicle)
$C5$	=	Average value of freight time($/truck-hour)
d_{FC}	=	Number of full closure days (days)
Dt	=	Extra travel time on detour (minutes)

Equation 3.7 is used for calculating vehicle operating costs due to partial closures.

EQUATION 3.7

$$VOC_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right)\ x\ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right)\ x\ WZS}\right)\ x\ \left(\left(C8\ x\ AADT_{Vehicle}\right) + \left(C9\ x\ AADT_{Truck}\right)\right)\ x\ d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C8$	=	Vehicle running cost ($/vehicle-hour)
$C9$	=	Freight running cost ($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Equation 3.8 is used for calculating lost wages and truck revenue due to partial closures.

EQUATION 3.8

$$LW_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x \, (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x \, WZS} \right) x \, ((C4 \, x \, AADT_{Vehicle} \, x \, O) + (C5 \, x \, AADT_{Truck})) \, x \, d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C4$	=	Average value of time ($/adult-hour)
O	=	Average occupancy (adult/vehicle)
$C5$	=	Average value of freight time($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Calculate total annual user risk by multiplying the owner consequences by the vulnerability for each magnitude of event the threat likelihood then summing the annual user risk for all events, utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ \boldsymbol{R}isk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n = number of events

Step 5: Vulnerability Assessment

As discussed in Section 4.1.1, several factors influence asset vulnerability from rockfall. These factors are consistent between PTCS and roadway prisms. See Exhibit 4.1.3.9 for the vulnerability probabilities for rockfall-roadway prism analysis.

EXHIBIT 4.1.3.9 ROCKFALL VULNERABILITY TABLE

Magnitude	Factors				Vulnerability		
Return Period (years)	Natural or Cut Slope	Lithology	Ditch	Monitored	No Mitigation	Slope Maintained	Installed Mitigation
1-year (≤ 100 cu yds)	Cut Slope	Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
		Non-Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.00	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.00	0.00
	Natural	Rock Slope	Absent	Yes	0.01	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
		Non-Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
6-year (101 - 499 cu yds)	Cut Slope	Rock Slope	Absent or Width ≤ 10 ft	Yes	0.35	0.30	0.15
				No	0.65	0.50	0.25
			Width > 10 ft	Yes	0.30	0.25	0.15
				No	0.60	0.45	0.25
		Non-Rock Slope	Absent or Width ≤ 10 ft	Yes	0.30	0.25	0.15
				No	0.55	0.45	0.25
			Width > 10 ft	Yes	0.25	0.20	0.10
				No	0.50	0.40	0.20
	Natural	Rock Slope		Yes	0.40	0.30	0.15
				No	0.80	0.50	0.25
		Non-Rock Slope		Yes	0.35	0.30	0.15
				No	0.30	0.25	0.15
20-year (≥ 500 cu yds)	NA			0.99			

Step 6. Risk Calculation

Annual Owner Risk

The WRC for roadway-rockfall is limited to 100% ARC for a 100 ft section plus $200,000 for debris cleanup, rounded to the nearest $50. Annual owner risk is calculated for each event magnitude (small, medium, and large) using the owner consequence (Step 3), vulnerability (Step 5), and threat likelihood Step 1) then the owner risk for all events is summed to calculate total annual risk utilizing Equation 3.9.

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ Risk_i = Owner\ Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

Annual User Risk

The user consequence for a rockfall impacting a roadway section is based on the defined WRC and it is estimated to be four days of full closure plus 14 days of partial closure. Annual user risk is calculated for each event magnitude (small, medium, and large) using the user consequence (Step 4), vulnerability (Step 5), and threat likelihood (Step 1) then the user risk for all events is summed to calculate total annual risk utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ Risk_i = \ Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

Total Annual Risk

The total annual risk for rockfall for roadway accounts for the annual owner and user risk from all rockfall event magnitudes. Use Equation 3.13 to calculate total annual risk.

EQUATION 3.13

$$Total\ Annual\ Risk\ = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

Where n= number of events

An example problem demonstrating the use of this approach is provided next.

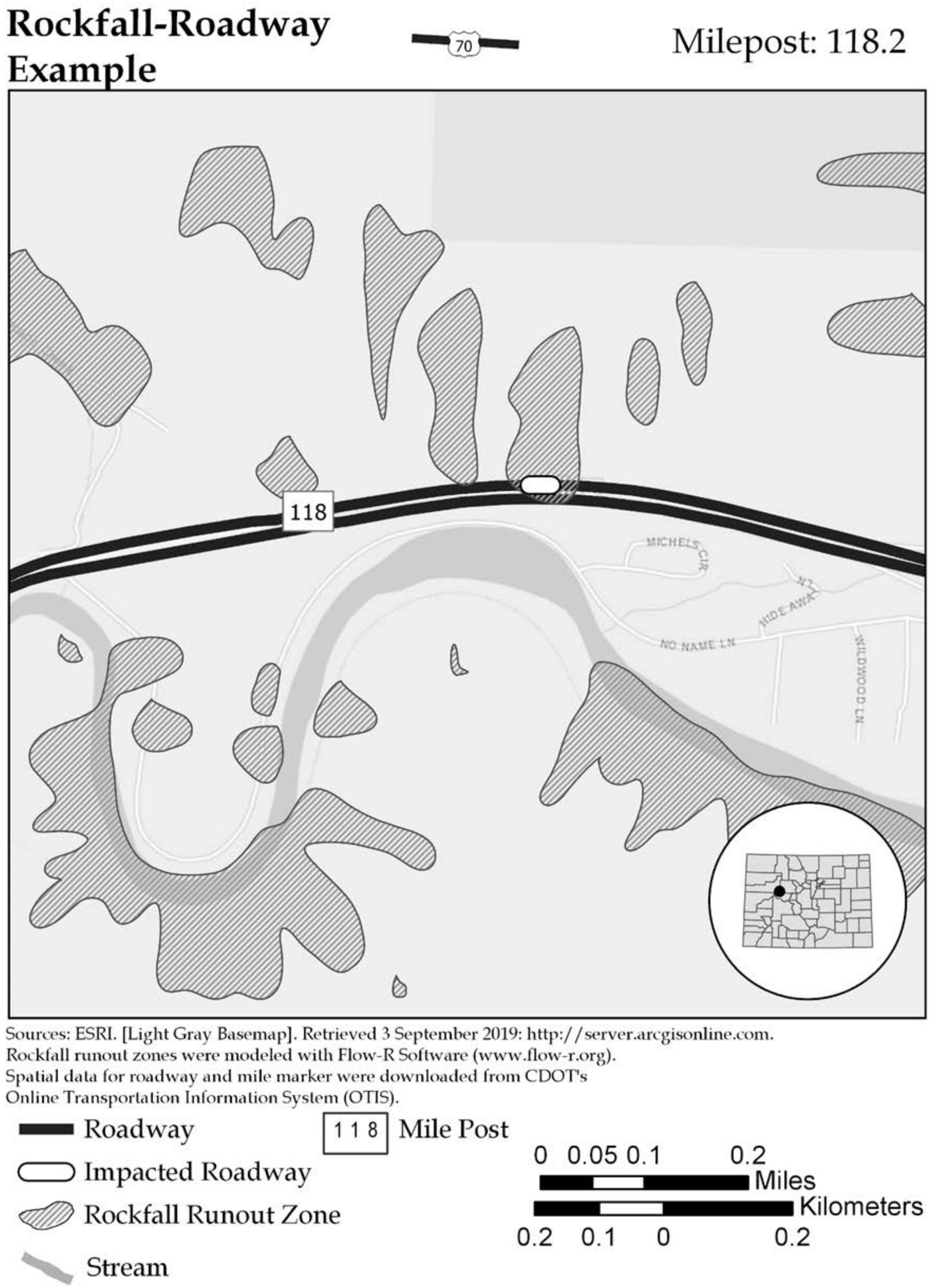
Example Problem - Rockfall-Roadway Prism Risk Assessment

This example demonstrates the risk assessment methodology developed for rockfall-roadway prism as included in Exhibit 4.1.3.1. The task is to calculate the annual owner risk, user risk, and total risk to rockfall for a section of roadway on I-70 at milepost 118.2. Exhibit 4.1.3.10 includes the example site on I-70 in the vicinity of MP 118. Additional site information is provided here:

Site Overview

- Location: I-70, MP 118.2, Glenwood Canyon
- Four-lane freeway (two-lanes in each direction)
- Roadway segment length = 100 ft
- Roadway width = 38 ft
- Unit cost for roadway/asphalt = $150/sq yd
- $AADT_{Vehicle}$ = 13,780 vehicles
- $AADT_{Truck}$ = 2,220 trucks
- Detour length = 140 miles
- Detour time = 167 minutes
- Work zone length = 1 mile
- Normal speed limit = 55 mph
- Work zone speed reduction = 15 mph
- Number of days of full closure = 4 days
- Number of days of partial closure = 14 days
- Slope type = natural
- Lithology = rock slope
- Slope does not have a ditch.
- Slope is not actively monitored.
- Rockfall mitigation = None

EXHIBIT 4.1.3.10 EXAMPLE ROCKFALL SITE, I-70, MP 118.2



Following the rockfall-roadway prism methodology presented in Exhibit 4.1.3.1

Step 1: Threat Data Collection

Use the estimated annual threat likelihoods tabulated in Exhibit 4.1.3.11 to calculate annual risk for small, medium, and large rockfall events.

EXHIBIT 4.1.3.11 ROCKFALL EVENT THREAT LIKELIHOOD FOR I-70 IN GLENWOOD CANYON

Rockfall Event Magnitude	Volume (cu yds)	Annual Threat Likelihood
Small	< 100	1
Medium	100 – 499	1/6
Large	≥ 500	1/20

Step 2: Asset Data Collection

Exhibit 4.1.3.3 describes the data needs and sources to perform the risk assessment for rockfall to roadway prism. Actual values are listed under "Site Overview" earlier in this chapter.

Step 3: Owner Consequence

The WRC for rockfall-roadway prism is 100% ARC of a 100-ft section of roadway plus $200,000 for debris cleanup, Exhibit 4.1.3.12. For the example problem, the width of the impacted 100 ft length of roadway is 38 ft. Thus, the impacted area is 422 sq yds and the unit cost for asphalt is $150 per sq yd, unit cost is defined in Exhibit 4.1.3.13. The full calculation for owner consequences follows.

EXHIBIT 4.1.3.12 SUMMARY OF WRC FOR OWNER CONSEQUENCE

		Threat			
		Debris Flow	**Flood**	**Scour**	**Rockfall**
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

EXHIBIT 4.1.3.13
UNIT COSTS

Asset	Units	Unit Cost
Bridge Approach**	sq ft	$350
Bridge*	sq ft	$600
Culvert***	cu ft	$55
PTCS**	sq ft	$550
Road Prism (Asphalt)**	sq yds	$150
Road Prism (Concrete)**	sq yds	$350

* Bridge area is defined as deck length multiplied by deck width, derived from NBI Items 49 and 52, respectively.
**Bridge approach, roadway and PTCS width are derived from CDOT OTIS Highways feature class using fields for lane width, lane count, and shoulder width.
***For culvert (CBC), the volume, in cubic feet, is calculated by multiplying the box height by the box width by the length. These values are derived from the culverts feature class maintained by C-PLAN, CDOT's interactive online mapping platform.

$$Owner\ Consequence = \left(100\%\ x\left(\left(\frac{(38\ ft\ x\ 100\ ft)}{9\ \frac{sq\ ft}{sq\ yd}}\right)x\ \frac{\$150}{sq\ yds}\right)\right) + \$200{,}000$$

$$Owner\ Consequence = \$63{,}333 + \$200{,}000$$

$$Owner\ Consequence = \$263{,}333$$

$$\boldsymbol{Owner\ Consequence \approx \$263{,}350^*}$$

Final value for owner consequences is rounded to the nearest $50.

Step 4: User Consequence

As with rockfall-PTCS, the WRC for user consequences for rockfall-roadway prism section is a large event that is expected to result in four days of full closure plus 14 days of partial closure, Exhibit 4.1.3.7. Calculating user consequences for rockfall-roadway prism requires calculating vehicle and truck operating costs (VOC) as well as the value of lost wages and freight revenue (LW), Exhibit 4.1.3.6, for both full and partial, Exhibit 4.1.3.8, using Equations 3.2 to 3.8 and 3.11.

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

User Consequence for Full Closure (FC):

Use Equation 3.5 to calculate vehicle operating costs for full closures:

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$ = 13,780 average annual daily traffic (non-truck)
$AADT_{Truck}$ = 2,220 average annual daily truck traffic
$C2$ = \$0.59 vehicle running cost (\$/vehicle-mile)
$C3$ = \$0.96 freight running cost (\$/truck-mile)
d_{FC} = 4 days of full closure
$C7$ = 140 difference in distance between detour and original route

$$VOC_{FC} = \left(\left(\frac{\$0.59}{vehicle - mile}\ x\ 13{,}780\frac{vehicle}{day}\right) + \left(\frac{\$0.96}{truck - mile}\ x\ 2{,}220\frac{truck}{day}\right)\right)\ x\ 4\ days\ x\ 140\ miles$$

$$\boldsymbol{VOC_{FC} = \$5,746,384}$$

Use Equation 3.6 to calculate lost wages and truck revenue for full closures:

EQUATION 3.6

$$LW_{FC} = \left((C4\ x\ O\ x\ AADT_{Vehicle}) + (C5\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$ = 13,780 average annual daily traffic (non-truck)
$AADT_{Truck}$ = 2,220 average annual daily truck traffic
$C4$ = \$10.62 average value of time (\$/hour-adult)
O = 1.77 average occupancy (adult/vehicle)
$C5$ = \$25.31 average value of freight time(\$/hour-truck)
d_{FC} = 4 days of full closure
Dt = 167 minutes of extra travel time on detour

$$LW_{FC} = \left(\left(\frac{\$10.62}{adult - hour}\ x\ 1.77\frac{adult}{vehicle}\ x\ 13{,}780\frac{vehicle}{day}\right) + \left(\frac{\$25.31}{truck - hour}\ x\ 2{,}220\frac{truck}{day}\right)\right)\ x\ 4\ days\ x\ \frac{167\ min}{60\ \frac{min}{hour}}$$

$$\boldsymbol{LW_{FC} = \$3,509,409}$$

User consequences for full closure are the sum of vehicle operating costs incurred due to travel on detour and the lost wages and truck revenue due to travel on detour as shown in Equation 3.3.

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

$$User\ Consequence_{FC} = \$5{,}746{,}384 + \$3{,}509{,}409$$

$$\boldsymbol{User\ Consequence_{FC} = \$9{,}255{,}793}$$

User Consequence for Partial Closure (PC):

Calculating user consequence for partial closures varies from full closure given the need to calculate the additional travel time incurred during work zone operations instead of calculating the additional travel time and distance incurred on a detour.

Use Equation 3.7 to calculate vehicle operating costs due to partial closures:

EQUATION 3.7

$$VOC_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x\ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x\ WZS} \right) x\ \left((C8\ x\ AADT_{Vehicle}) + (C9\ x\ AADT_{Truck}) \right) x\ d_{PC}$$

Where:

WL	=	Work zone length, 1 mile
WZS	=	Work zone speed limit, 55 mph
$WZSR$	=	Work zone speed limit reduction, 15 mph
$AADT_{Vehicle}$	=	13,780 average annual daily traffic (non-truck)
$AADT_{Truck}$	=	2,220 average annual daily truck traffic
$C8$	=	\$26.52 vehicle running cost (\$/hour)
$C9$	=	\$44.24 freight running cost (\$/hour)
d_{PC}	=	14 days of partial closure

$$VOC_{PC} = \left(\left(\frac{1}{\left(\frac{1}{1\ mile}\right) x\ (55\ mph - 15\ mph)} \right) - \left(\frac{1}{\left(\frac{1}{1\ mile}\right) x\ 55\ mph} \right) \right) x\ \left(\left(\frac{\$26.52}{vehicle - hour}\ x\ 13{,}780 \frac{vehicle}{day} \right) + \left(\frac{\$44.24}{truck - hour}\ x\ 2{,}220 \frac{truck}{day} \right) \right) x\ 14\ days$$

$$\boldsymbol{VOC_{PC} = \$44,258}$$

Next use Equation 3.8 to calculate lost wages and truck revenue due to partial closures:

EQUATION 3.8

$$LW_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) \; x \; (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) \; x \; WZS} \right) x \; ((C4 \; x \; AADT_{Vehicle} \; x \; O) + (C5 \; x \; AADT_{Truck})) \; x \; d_{PC}$$

Where:

WL	=	Work zone length, 1 mile
WZS	=	Work zone speed limit, 55 mph
WZSR	=	Work zone speed limit reduction, 15 mph
$AADT_{Vehicle}$	=	13,780 average annual daily traffic (non-truck)
$AADT_{Truck}$	=	2,220 average annual daily truck traffic
C4	=	$10.62 average value of time ($/hour-vehicle)
O	=	1.77 average occupancy (adult/vehicle)
C5	=	$25.31 average value of freight time($/hour-truck)
d_{PC}	=	14 days of partial closure

$$LW_{PC} = \left(\left(\frac{1}{\left(\frac{1}{1 \; mile}\right) x \; (50 \; mph - 15 \; mph)} \right) - \left(\frac{1}{\left(\frac{1}{1 \; mile}\right) x \; 55 \; mph} \right) \right) x \left(\left(\frac{\$10.62}{adult - hour} x \; 1.77 \frac{adult}{vehicle} \; x \; 13{,}780 \frac{vehicle}{day} \right) + \left(\frac{\$25.31}{truck - hour} \; x \; 2{,}220 \frac{truck}{day} \right) \right) x \; 14 \; days$$

$$\boldsymbol{LW_{PC} = \$30,089}$$

Finally, using Equation 3.4 sum VOC_{PC} and LW_{PC} to calculate total consequences for partial closures.

EQUATION 3.4

$$User \; Consequence_{PC} = VOC_{PC} + \; LW_{PC}$$

$$User \; Consequence_{PC} = \; \$44{,}258 + \$30{,}089$$

$$\boldsymbol{User \; Consequence_{PC} = \; \$74,347}$$

Total User Consequence:

Total user consequences include the sum of user consequences due to full and partial closures as shown in Equation 3.2.

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + \ User\ Consequence_{PC}$$

$$Total\ User\ Consequence = \$9{,}255{,}793 + \$74{,}347$$

$$\boldsymbol{Total\ User\ Consequence} = \$\mathbf{9,330,140}$$

Step 5: Vulnerability Assessment

As discussed in Section 4.1.1, several factors influence the vulnerability of highway assets to rockfall events. These factors are consistent for PTCS and roadway prism. The characteristics of the example site location are provided here and shown in Exhibit 4.1.3.14:

- Slope is a natural slope.
- Lithology is rock slope
- Slope does not have a ditch.
- Slope is not actively monitored.
- Slope does not have mitigation installed.
- Slope is a divided highway and the direction of travel is adjacent to the hazardous slope.

EXHIBIT 4.1.3.14 ROCKFALL VULNERABILITY TABLE

Magnitude	Factors				Vulnerability		
Return Period (years)	Natural or Cut Slope	Lithology	Ditch	Monitored	No Mitigation	Slope Maintained	Installed Mitigation
1-year (≤ 100 cu yds)	Cut Slope	Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
		Non-Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.00	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.00	0.00
	Natural	Rock Slope	Absent	Yes	0.01	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
		Non-Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
6-year (101 - 499 cu yds)	Cut Slope	Rock Slope	Absent or Width ≤ 10 ft	Yes	0.35	0.30	0.15
				No	0.65	0.50	0.25
			Width > 10 ft	Yes	0.30	0.25	0.15
				No	0.60	0.45	0.25
		Non-Rock Slope	Absent or Width ≤ 10 ft	Yes	0.30	0.25	0.15
				No	0.55	0.45	0.25
			Width > 10 ft	Yes	0.25	0.20	0.10
				No	0.50	0.40	0.20
	Natural	Rock Slope		Yes	0.40	0.30	0.15
				No	0.80	0.50	0.25
		Non-Rock Slope		Yes	0.35	0.30	0.15
				No	0.30	0.25	0.15
20-year (≥ 500 cu yds)	NA				0.99		

For a natural, rock slope with no mitigation installed, no monitoring, and no ditch, the vulnerability for a small event is 0.01 and for a medium event 0.80. The vulnerability for large rockfall events is always the default value of 0.99.

Step 6: Risk Assessment

Annual Owner Risk:

Annual owner risk, user risk, and total risk is calculated in Step 6. To calculate annual owner risk, use threat likelihood (Step 1), owner consequences (Step 3), and vulnerability scores (Step 5). The resulting values have been included in Exhibit 4.1.3.15. Total annual owner risk is calculated by multiplying the threat likelihood by the owner consequences by the vulnerability for each event then summing the annual owner risk for all events utilizing Equation 3.9.

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ Risk_i = Owner\ Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

EXHIBIT 4.1.3.15 SUMMARY OF ANNUAL OWNER RISK CALCULATIONS

Rockfall Event Magnitude	Owner Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual Owner Risk ($)
Small	$263,350	0.01	1	$2,634
Medium	$263,350	0.80	1/6	$35,113
Large	$263,350	0.99	1/20	$13,036
			TOTAL	$50,783

Annual User Risk:

To calculate annual user risk, use the threat likelihood (Step 1), the user consequences (Step 4), and the vulnerability probability (Step 5). The resulting values have been included in Exhibit 4.1.3.16. Total Annual User Risk is calculated by multiplying the threat likelihood by the owner consequences by the vulnerability for each event, then summing the annual user risk for all events utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ Risk_i = \ Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

EXHIBIT 4.1.3.16 SUMMARY OF ANNUAL USER RISK CALCULATIONS

Rockfall Event Magnitude	User Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual Owner Risk ($)
Small	$9,330,140	0.01	1	$93,301
Medium	$9,330,140	0.80	1/6	$1,244,019
Large	$9,330,140	0.99	1/20	$461,842
			TOTAL	$1,799,162

Total Annual Risk:

The total annual risk, owner risk plus user risk, is calculated utilizing Equation 3.13. The necessary values have been filled in Exhibit 4.1.3.17.

EQUATION 3.13

$$Total\ Annual\ Risk = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

Where n= number of events

EXHIBIT 4.1.3.17 SUMMARY OF TOTAL ANNUAL RISK CALCULATION

Annual Owner Risk ($)	Annual User Risk ($)	Total Annual Risk ($)
$50,783	$1,799,162	$1,849,945

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4.2 Flood Assessment

Approximately seventy-five percent of all nationwide Presidential Disaster Declarations are associated with flooding. Colorado has experience 14 major disaster declarations related to flood since 1955 with the most significant flood events including the September 2013 Front Range event; July 1997 Fort Collins event; July 1976 Big Thompson Canyon event; Denver/South Platte event in June 1965 and the June 1921 Arkansas River flood in Pueblo. (Federal Emergency Management Agency (FEMA), 2019). (National Oceanic and Atmospheric Administration (NOAA), 2019)

The September 2013 flood event in northern Colorado was considered one of the most extreme rainfall and flood events in recorded history of Colorado (Colorado Climate Center, 2019). This event included multiple flash floods and river floods. Historic rains and flooding affected six major river/tributaries, 14 counties, and over a dozen cities/towns in Colorado.

4.2.1 Flood-Roadway Prism Risk Assessment

CDOT maintains and repairs over 23,000 total lane miles of highway. Some of these roadways may be vulnerable to flooding. Exhibit 4.2.1.1 includes examples of the recent damaged incurred to the roadway prism from flooding in 2013.

EXHIBIT 4.2.1.1 DAMAGE TO ROADWAY PRISM ON US-34 EAST OF GREELEY (LEFT IMAGE) AND US-34 CANYON DURING 2013 FLOOD EVENT (RIGHT IMAGE)

Exhibit 4.2.1.2 illustrates the basic methodology and steps used in risk analysis of flood to roadway prism.

EXHIBIT 4.2.1.2 FLOOD - ROADWAY PRISM RISK ASSESSMENT METHODOLOGY

Step 1: Threat Data Collection
Flood Annual Likelihood (Exhibit 4.1.2.2)

↓

Step 2: Asset Data Collection
Asset (Roadway Prism) Data Needs (Exhibit 4.1.2.3)

↓

Step 3: Owner Consequence Calculation
Owner Worst Reasonable Case (WRC) for Flood-Roadway Prism (Exhibit 4.1.2.6)
Roadway Prism Unit Cost Estimation (Exhibit 4.1.2.7)

↓

Step 4: User Consequence Calculation
User Worst Reasonable Case (WRC) for Flood-Roadway Prism (Exhibit 4.1.2.6)
Vehicle Operating Cost (VOC) and Lost of Wages (LW) (Exhibit 4.2.1.9)
Detour Estimation (Extra Travel Length and Time) (Exhibits 4.2.1.10 and 4.2.1.11)
Calculations (Equations 3.5 through 3.8)
Total User Consequence (Equation 3.2)

↓

Step 5: Vulnerability Assessment
Flood-Roadway Prism Vulnerability (Exhibits 4.2.1.12 and 4.2.1.13)

↓

Step 6: Risk Assessment
Annual Owner Risk Calculation (Equation 3.9)
Annual User Risk Calculation (Equations 3.2 through 3.8 and 3.11)
Annual Total Risk (Equation 3.13)

Computational Steps

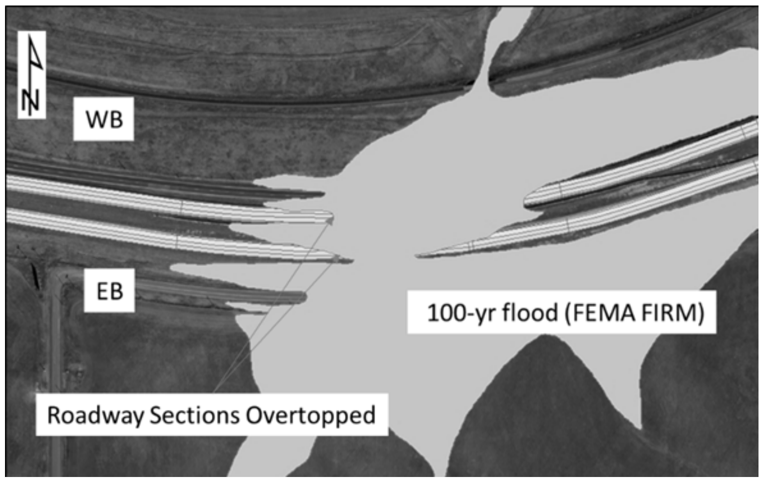
Step 1: Threat Data Collection

The traditional method for conducting flood frequency (threat likelihood) analysis is to use historical records of peak flows to estimate the expected behavior of future flooding. This information is used to estimate the frequency of occurrence of various magnitude

floods at specific locations (e.g. 100-yr flood events). FEMA Flood Insurance Rate Maps may also be utilized when available to generate information for 100-yr and 500-yr events.

For this procedure, visual inspection of FEMA FIRMs is suggested as a means of estimating the threat from flooding to the roadway prism. Exhibit 4.2.3 includes an example of a roadway prism under threat of flooding based on overtopping by the 100-yr and 500-yr FIRMs. While visual inspection is utilized for a planning level analysis of risk, a more detailed hydraulic analysis is typically utilized when determining potential mitigation to reduce flood risk.

EXHIBIT 4.2.1.3 ROADWAY PRISM OVERTOPPED BY POTENTIAL 100-YR FLOOD EVENT (100-YR FEMA FIRM)



The corresponding annual threat likelihoods for 100-yr and 500-yr flood events are presented in Exhibit 4.2.1.4. Note, this approach does not consider potential increases in threat likelihood due to climate change or the increase of extreme weather events. The use of static annual threat likelihoods is considered conservative and the user should consider empirical data if available in the analysis.

EXHIBIT 4.1.2.4 FLOOD/RAINFALL ANNUAL THREAT LIKELIHOOD

Recurrence Interval* (Year)	Annual Threat Likelihood
1	1/1
2	1/2
5	1/5
10	1/10
25	1/25
50	1/50
100	1/100
500	1/500

*Flood/Rain recurrence intervals do not necessarily constitute the same flow rate.

Step 2: Asset Data Collection

Data needed to assess the annual risk from flood events includes asset replacement costs, user costs, and vulnerability. The OTIS Highways feature class supplies the dimensions for roadway features necessary to calculate asset replacement cost, as well as traffic volumes for calculating user consequences. Exhibit 4.2.1.5 provides a summary of the data needs and sources to assess risk for flood-roadway prism.

EXHIBIT 4.2.1.5 DATA NEEDS FOR FLOOD-ROADWAY PRISM RISK ANALYSIS

	Data Needs	Data Source
Asset Replacement Cost	Milepost (beginning and end)	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Area of Roadway Overtopped	GIS Layer Roadway-FIRM overlay
	Roadway Geometry	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
Vulnerability	Terrain	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Annual Number of Freezing-Thaw Days	SSURGO Soil Survey https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm
	AASHTO Soil Classification	USDA NRCS Soil Web Viewer https://www.nrcs.usda.gov/wps/portal/nrcs /detailfull/soils/home/?cid=nrcs142p2_053620
User Consequences	AADT Vehicles	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	AADT Trucks	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Roadway Damaged	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Detour	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Detour Distance	CDOT Operations
	Detour Time	CDOT Operations
	Number of Closure Days	See Exhibit 4.2.1.10
	Number of Partial Closure Days	See Exhibit 4.2.1.10
	Average Vehicle Occupancy	FHWA https://www.fhwa.dot.gov/tpm/guidance/avo_factors.pdf
	Car Running Costs	(RITA)/Texas A&M Transportation Institute
	Truck Running Costs	American Transportation Research Institute
	Average Value of Time	(RITA)/Texas A&M Transportation Institute

Step 3: Owner Consequence Assessment

Owner consequence measures the impact to the owner (CDOT) in terms of cost of repairs, cleanup, maintenance, and related agency operational costs. The most severe but credible consequence Worst Reasonable Consequence (WRC) for flood-bridge, based on past emergency repair projects, is estimated as 100% the replacement cost of the area of the roadway prism section overtopped by either a 100-yr or 500-yr FEMA FIRM plus

$5,000 in cleanup costs to remove debris as shown in Exhibit 4.2.1.6. The asset replacement unit cost for can be found in Exhibit 4.2.1.7.

EXHIBIT 4.2.1.6 SUMMARY OF WRC FOR OWNER CONSEQUENCE

		Threat			
		Debris Flow	Flood	Scour	Rockfall
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

EXHIBIT 4.2.1.7 UNIT COSTS

Asset	Units	Unit Cost
Bridge Approach**	sq ft	$350
Bridge*	sq ft	$600
Culvert***	cu ft	$55
PTCS**	sq ft	$550
Road Prism (Asphalt)**	sq yds	$150
Road Prism (Concrete)**	sq yds	$350

* Bridge area is defined as deck length multiplied by deck width, derived from NBI Items 49 and 52, respectively.

**Bridge approach, roadway and PTCS width are derived from CDOT OTIS Highways feature class using fields for lane width, lane count, and shoulder width.

***For culvert (CBC), the volume, in cubic feet, is calculated by multiplying the box height by the box width by the length. These values are derived from the culverts feature class maintained by C-PLAN, CDOT's interactive online mapping platform.

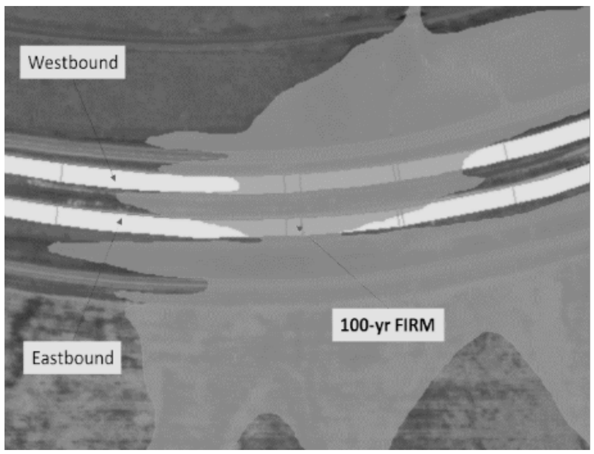
Step 4: User Consequence Assessment

User consequences estimate the impact to the public in terms of lost wages and increased vehicle operating costs due to delays, longer travel distances, and drive times.

Required input includes AADT, percent truck traffic, average vehicle occupancy, average hourly wage, detour length, work zone length, speed on detour, number of days of closure, and number of days of partial closure. For user consequences, the estimated WRC from flood on a roadway section is considered failure if the roadway section is overtopped by a FIRM and it is based on the cost to the user due to full or partial closure depending on the width of roadway overtopped.

Exhibit 4.2.1.8 includes examples of full and partial overtopping that may cause full or partial roadway closures. For further explanation on how to calculate user consequences, see Exhibits 4.2.1.9 through 4.2.1.11 and Equations 3.2 through 3.8 and 3.11.

EXHIBIT 4.2.1.8 EXAMPLE OF FULL AND PARTIAL OVERTOPPING BY A 100-YR FIRM



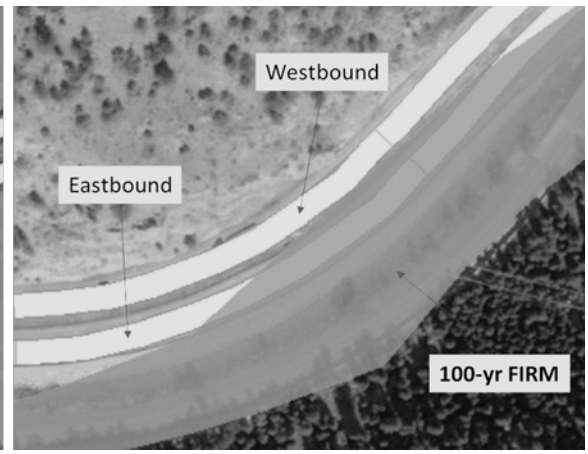


Exhibit 4.2.1.9 provides default values for a range of factors associated with the cost associated with operating vehicles, value of time, and occupancy that are updated annually by the various federal government agencies. Note the values included in Exhibit 4.2.1.9 were gathered in June of 2019 and will vary in future years.

EXHIBIT 4.2.1.9 CONSTANTS USED IN USER CONSEQUENCE CALCULATIONS

User Cost Terms	Variable	Value	Year Published
Average Vehicle Occupancy	*O*	1.77	2019
Car Running Cost per Mile	*C2*	$0.59	2019
Truck Running Cost per Mile	*C3*	$0.96	2015
Average Value of Time per Adult per Hour	*C4*	$10.62	2015
Average Value of Freight Driver Cost per Hour	*C5*	$25.31	2015
Car Running Cost per Hour	*C8*	$26.52	2015
Truck Running Cost per Hour	*C9*	$44.24	2015

The suggested number of full and partial closure days, derived from the I-70 Pilot, are provided in Exhibit 4.2.1.10. It is suggested that this table be used as guidance for all other corridor's for estimating closures days, both full and partial.

EXHIBIT 4.2.1.10 I-70 RISK AND RESILIENCE PILOT NUMBER OF FULL CLOSURE AND PARTIAL CLOSURE DAYS FOR WRC

Asset	Threat	Full Closure Days (d_{FC})	Partial Closure Days (d_{PC})
Bridge Approach	All	2	0
Bridge	Flood	180	0
Bridge	Debris Flow	2	0
Bridge	Rockfall	4	14
Culvert	Debris Flow	1	0
Culvert	Flood	3	0
PTCS	Rockfall	4	14
Roadway (<=% Width)	Flood	1	0
Roadway (> 50% Width)	Flood	3	0
Roadway (2 Directions)	Flood	3	0
Roadway	Rockfall	4	14

Example detours used for the I-70 Risk and Resilience Pilot and the worked examples in this document are listed in Exhibit 4.2.1.11. Note that *Additional Travel Distance* refers to the additional miles a traveler must travel on detour in comparison to the original route, and *Additional Travel Time* is the additional time a traveler must travel on detour in comparison to the original route. CDOT Operations can provide further guidance on estimating detours from closures for highways other than I-70.

EXHIBIT 4.2.1.11 I-70 RISK AND RESILIENCE PILOT DETOUR TABLE

Starting Milepost	Ending Milepost	Additional Travel Distance (miles) (*C7*)	Additional Travel Time (minutes) (*Dt*)
1	14	146	189
14	90	90	112
90	155	140	167
155	205	98	126
205	231	83	109
231	245	49	77
245	288	3	7
288	353	15	24
353	360	71	96
360	404	76	73
404	438	69	70
438	450	63	77

Total User Consequences is the sum of user consequence due to full and partial closures as shown in Equation 3.2.

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

Where:

$User\ Consequence_{FC}$ = User consequences due to full closure
$User\ Consequence_{PC}$ = User consequences due to partial closure

User consequences for full closure are the sum of vehicle operating costs incurred due to travel on detour, lost wages, and truck revenue due to travel on detour as shown in Equation 3.3.

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

Where:

VOC_{FC} = Vehicle operating costs incurred due to full closure
LW_{FC} = Lost wages/truck revenue incurred due to full closure

User consequences for partial closures are the sum of vehicle operating costs incurred due to traffic delays, lost wages, and truck revenue due to delays incurred while driving through a partial closure as shown in Equation 3.4.

EQUATION 3.4

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

Where:

VOC_{PC} = Vehicle operating costs incurred due to partial closure
LW_{PC} = Lost wages/truck revenue incurred due to partial closure

Equation 3.5 is the equation for calculating vehicle operating costs for full closures.

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right) x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C2$	=	Vehicle running cost ($/vehicle-mile)
$C3$	=	Freight running cost ($/truck-mile)
d_{FC}	=	Number of full closure days (days)
$C7$	=	Difference in distance between detour and original route (mile)

Equation 3.6 is used for calculating lost wages and truck revenue for full closures.

EQUATION 3.6

$$LW_{FC} = \left((C4 \; x \; O \; x \; AADT_{Vehicle}) + (C5 \; x \; AADT_{Truck}) \right) x \; d_{FC} \; x \left(\frac{Dt}{60} \right)$$

Where:

$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C4$	=	Average value of time ($/adult-hour)
O	=	Average occupancy (adult/vehicle)
$C5$	=	Average value of freight time($/truck-hour)
d_{FC}	=	Number of full closure days (days)
Dt	=	Extra travel time on detour (minutes)

Equation 3.7 is used for calculating vehicle operating costs due to partial closures.

EQUATION 3.7

$$VOC_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x \; (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x \; WZS} \right) x \left((C8 \; x \; AADT_{Vehicle}) + (C9 \; x \; AADT_{Truck}) \right) x \; d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C8$	=	Vehicle running cost ($/vehicle-hour)
$C9$	=	Freight running cost ($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Equation 3.8 is used for calculating lost wages and truck revenue due to partial closures.

EQUATION 3.8

$$LW_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x\ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x\ WZS} \right) x\ ((C4\ x\ AADT_{Vehicle}\ x\ O) + (C5\ x\ AADT_{Truck}))\ x\ d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C4$	=	Average value of time ($/adult-hour)
O	=	Average occupancy (adult/vehicle)
$C5$	=	Average value of freight time($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Calculate total annual user risk by multiplying the owner consequences by the vulnerability for each magnitude of event the threat likelihood then summing the annual user risk for all events, utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ \boldsymbol{R}isk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n = number of events

Step 5. Vulnerability Assessment

Vulnerability of the roadway prism from flood events is dependent on multiple factors as documented in published literature. For this procedure, a vulnerability table was developed for roadway prism from flood risk based on CDOT staff expert opinion and empirical data gathered from recent flood events. The main factors identified for the vulnerability assessment include: 1) terrain and 2) embankment erodibility. The embankment erodibility is determined based on the annual number of freezing-thawing days and the AASHTO soil classification of the area. Utilizing the embankment erodibility factor obtained with Exhibit 4.2.1.12 along with the terrain of the site, the vulnerability of roadway prism can be obtained for either 100-yr and 500-yr flood events using Exhibit 4.2.1.13.

EXHIBIT 4.2.1.12 EMBANKMENT ERODIBILITY TABLE

AASHTO Soil Classification	Frost Action			
	None	Low	Moderate	High
A1 - A3	Very Low	Low	Moderate	High
A4 - A8	Moderate	High	Very High	Very High

EXHIBIT 4.2.1.13 FLOOD-ROADWAY PRISM VULNERABILITY FOR 100-YR AND 500-YR FLOOD EVENT MAGNITUDES

Flood Event Magnitude	Terrain	Embankment Erodibility Potential				
		Very Low	Low	Moderate	High	Very High
100-yr	Level	0.22	0.23	0.25	0.31	0.33
	Rolling	0.26	0.28	0.30	0.36	0.39
	Mountainous	0.35	0.37	0.40	0.48	0.52
500-yr	Level	0.55	0.59	0.63	0.77	0.83
	Rolling	0.66	0.70	0.75	0.91	0.99
	Mountainous	0.88	0.93	0.99	0.99	0.99

Step 6: Risk Calculation

Annual Owner Risk

Owner consequences anticipated from flood events affecting the roadway prism is based on the defined WRC for the owner and it is estimated based on 100% of the ARC of the roadway prism overtopped plus $5,000 in cleanup costs of debris. Annual owner risk is calculated for each event utilizing the owner consequence (Step 3), vulnerability (Step 5), and threat likelihood (Step 1) multiplying all factors as described in Equation 3.9.

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ \boldsymbol{R}isk_i = Owner\ \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n = number of events

Annual User Risk

User consequences anticipated from a flood event affecting the roadway prims is based on the defined WRC for roadway users. The annual user risk is calculated for each event magnitude (100-yr and 500-yr flood events) utilizing the user consequence (Step

4), vulnerability (Step 5), and threat likelihood (Step 1) multiplying all factors as described in Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ \boldsymbol{R}isk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n = number of events

Total Annual Risk

The total annual risk is the sum of the annual owner risk and the annual user risk calculated using Equation 3.13.

EQUATION 3.13

$$Total\ Annual\ Risk\ = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

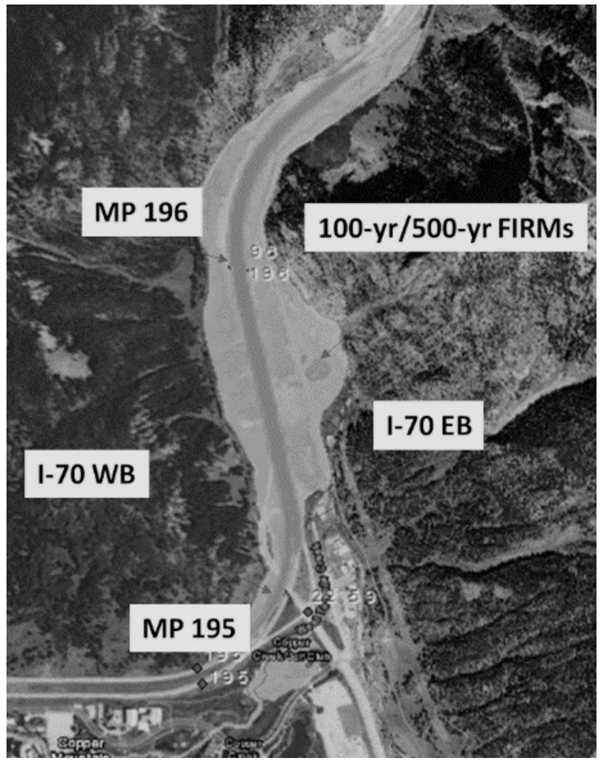
Where n= number of events

An example problem demonstrating the use of this approach is provided next.

Example Problem – Flood-Roadway Prism Assessment

This example demonstrates the risk assessment methodology developed for flood-roadway prism presented in Exhibit 4.2.1.2. The task is to calculate the annual owner risk, user risk, and total risk from flood for the roadway prism section between milepost 195.8 and milepost 197.1 on I-70 in Summit County as shown in Exhibit 4.2.1.14.

EXHIBIT 4.2.1.14 EXAMPLE FLOOD SITE, I-70, MP 195.8-197.0 SUMMIT COUNTY



Site Overview

- Location: I-70, MP 195.8 – MP 197.1, Summit County
- Four-lane freeway (two-lanes in each direction)
- Surface roadway material = Asphalt

Eastbound:

- Overtopping between MP 195.92 - MP 197.0
- Overtopping length ≈ 5,914 ft
- Area overtopped at 100-yr flood event ≈ 22,587 sq yds
- Area overtopped at 500-yr flood event ≈ 22,587 sq yds

Westbound:

- Overtopping between MP 195.8 - MP 197.1
- Overtopping length ≈ 6,758 ft
- Area overtopped at 100-yr flood event ≈ 25,615 sq yds
- Area overtopped at 500-yr flood event ≈ 25,615 sq yds

- Unit cost for roadway prism (AC-Asphalt Concrete (bituminous)) = $150/sq yd
- AASHTO soil classification: A1-A3
- Frost action = Moderate
- Terrain = Mountainous
- Total I-70 $AADT_{Vehicle}$ = 20,490 vehicles
- Total I-70 $AADT_{Truck}$ = 2,510 trucks
- Detour length = 98 miles
- Extra travel time on detour = 126 minutes
- Number of days of full closure = 3 days (both traffic directions overtopped by FIRMs)
- Number of days of partial closure = 0 days (both traffic directions overtopped by FIRMs)

Following the flood-roadway prism methodology presented in Exhibit 4.2.1.2:

Step 1: Threat Data Collection

The annual threat likelihoods for a 100 and 500-yr flood event are found in Exhibit 4.2.1.15

EXHIBIT 4.2.1.15 FLOOD/RAINFALL ANNUAL THREAT LIKELIHOOD

Recurrence Interval* (Year)	Annual Threat Likelihood
1	1/1
2	1/2
5	1/5
10	1/10
25	1/25
50	1/50
100	1/100
500	1/500

*Flood/Rain recurrence intervals do not necessarily constitute the same flow rate.

Step 2: Asset Data Collection

Exhibit 4.2.1.5 describes the data needs and sources to perform the risk assessment. Actual values are listed in the "Site Overview" section.

Step 3: Owner Consequence

The WRC for a flood-roadway prism event is calculated as 100% of roadway prism ARC plus $5,000 in cleanup cost, as shown in Exhibit 4.2.1.16. For this guide, CDOT has established a unit cost of $150/sq yd for Asphalt Concrete (bituminous) as shown in Exhibit 4.2.1.17.

EXHIBIT 4.2.1.16 SUMMARY OF WRC FOR OWNER CONSEQUENCE

		Threat			
		Debris Flow	Flood	Scour	Rockfall
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

EXHIBIT 4.2.1.17 UNIT COSTS

Asset	Units	Unit Cost
Bridge Approach**	sq ft	$350
Bridge*	sq ft	$600
Culvert***	cu ft	$55
PTCS**	sq ft	$550
Road Prism (Asphalt)**	sq yds	$150
Road Prism (Concrete)**	sq yds	$350

* Bridge area is defined as deck length multiplied by deck width, derived from NBI Items 49 and 52, respectively.

**Bridge approach, roadway and PTCS width are derived from CDOT OTIS Highways feature class using fields for lane width, lane count, and shoulder width.

***For culvert (CBC), the volume, in cubic feet, is calculated by multiplying the box height by the box width by the length. These values are derived from the culverts feature class maintained by C-PLAN, CDOT's interactive online mapping platform.

The site includes a divided roadway section, as a result, the owner consequences for each direction of I-70 (EB and WB) that is overtopped by FEMA FIRMs should be calculated as shown here:

<u>Eastbound:</u>

- Area overtopped at 100-yr flood event ≈ 22,587 sq yds
- Area overtopped at 500-yr flood event ≈ 22,587 sq yds

Since FIRM areas for 100-yr and 500-yr flood events cover the same area, the owner consequence for 100-yr and 500-yr food events is estimated to be the same for each event.

$$Owner\ Consequence\ = \left(100\%\ x\ (22{,}587\ sq\ yds\ x\ \frac{\$150}{sq\ yd})\right) + \$5{,}000$$

$$Owner\ Consequence\ = \$3{,}388{,}050 + \$5{,}000$$

$$\boldsymbol{Owner\ Consequence = \$3,393,050\ for\ Eastbound}$$

(for both the 100-yr and 500-yr events)

<u>Westbound:</u>

- Area overtopped at 100-yr flood event ≈ 25,615 sq yds
- Area overtopped at 500-yr flood event ≈ 25,615 sq yds

$$Owner\ Consequence\ = \left(100\%\ x\ (25{,}615\ sq\ yds\ x\ \frac{\$150}{sq\ yd})\right) + \$5{,}000$$

$$Owner\ Consequence\ = \$3{,}842{,}250 + \$5{,}000$$

$$\boldsymbol{Owner\ Consequence = \$3,847,250\ for\ Westbound}$$

(for both the 100-yr and 500-yr events)

Step 4: User Consequence

Calculating user consequence for flooding to the roadway prism requires calculating vehicle and truck operating costs (VOC), as well as the value of lost wages and freight revenue (LW), for both full and partial closure (if applicable) as described here.

$$Total\ User\ Consequence = User\ Consequence_{FC} +\ User\ Consequence_{PC}$$

$$User\ Consequence_{FC} = VOC_{FC} +\ LW_{FC}$$

$$User\ Consequence_{PC} = VOC_{PC} +\ LW_{PC}$$

User Consequence for Full Closure (FC)

As presented in Equations 3.3 and 3.4 user consequence is based on the calculation of VOC_{FC} and LW_{FC}. The OTIS database provides the total average annual daily traffic (AADT) data for roadways, half of the AADT has been assigned to each direction of travel for the purposes of this analysis.

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

Where:

VOC_{FC} = Vehicle operating costs incurred due to full closure
LW_{FC} = Lost wages/truck revenue incurred due to full closure

EQUATION 3.4

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

Where:

VOC_{PC} = Vehicle operating costs incurred due to partial closure
LW_{PC} = Lost wages/truck revenue incurred due to partial closure

Utilizing Equation 3.5 along with User Consequences variables provided in Exhibit 4.2.1.9 and anticipated days of closure from Exhibit 4.2.1.10, the VOC_{FC} for full closure for the roadway prism during a flood event is calculated as follows:

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$ = 10,245 average annual daily traffic (non-truck)
$AADT_{Truck}$ = 1,255 average annual daily truck traffic
$C2$ = \$0.59 vehicle running cost (\$/vehicle-mile)
$C3$ = \$0.96 freight running cost (\$/truck-mile)
d_{FC} = 3 days of full closure
$C7$ = 98 miles difference in distance between detour and original route

$$VOC_{FC} = \left(\left(\frac{\$0.59}{vehicle - mile}\ x\ 10{,}245\frac{vehicle}{day}\right) + \left(\frac{\$0.96}{truck - mile}\ x\ 1{,}255\frac{truck}{day}\right)\right)\ x\ 3\ days\ x\ 98\ miles$$

$$\boldsymbol{VOC_{FC} = \$2,131,309\ per\ traffic\ direction = \$4,262,618\ site}$$

Next, Equation 3.6 is used to calculate lost wages and truck revenue for full closures:

EQUATION 3.6

$$LW_{FC} = \left((C4\ x\ O\ x\ AADT_{Vehicle}) + (C5\ x\ AADT_{Truck})\right) x\ d_{FC}\ x\ \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$ = 10,245 average annual daily traffic (non-truck)

$AADT_{Truck}$ = 1,255 average annual daily truck traffic

$C4$ = \$10.62 average value of time (\$/hour-adult)

O = 1.77 average occupancy (adult/vehicle)

$C5$ = \$25.31 average value of freight time(\$/hour-truck)

d_{FC} = 3 days of full closure

Dt = 126 minutes of extra travel time on detour

$$LW_{FC} = \left(\left(\frac{\$10.62}{adult - hour}\ x\ 1.77\frac{adult}{vehicle}\ x\ 10{,}245\frac{vehicle}{day}\right) + \left(\frac{\$25.31}{truck - hour}\ x\ 1{,}255\frac{truck}{day}\right)\right) x\ 3\ days\ x\ \frac{126\ min}{60\ \frac{min}{hour}}$$

$$\boldsymbol{LW_{FC} = \$1,413,364\ per\ traffic\ direction = \$\ 2,826,728\ site}$$

Equation 3.3 sums the vehicle operating costs incurred due to travel on detour and the lost wages and truck revenue due to travel on the detour:

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

$$User\ Consequence_{FC} = \$2{,}131{,}309 + \$1{,}413{,}364$$

$$\boldsymbol{User\ Consequence_{FC} = \$3,544,673\ per\ traffic\ direction = \$7,089,346\ site}$$

User Consequence for Partial Closure (PC):

Since partial closure is not applicable at this site, VOC_{PC} and LW_{PC} for partial closures are estimated to be \$0.

$$VOC_{PC} = \$0$$

$$LW_{PC} = \$0$$

$$\boldsymbol{User\ Consequence_{PC} = \$0}$$

Total User Consequence:

Total user consequences include the sum of user consequence due to full partial closures as shown in Equation 3.2.

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + \ User\ Consequence_{PC}$$

$$Total\ User\ Consequence = \$3{,}544{,}673 + \$0$$

$$\boldsymbol{Total\ User\ Consequence = \$3,544,673\ per\ Traffic\ Direction}$$

$$\boldsymbol{Total\ User\ Consequence = \$7,089,346\ site}$$

Step 5: Vulnerability Assessment.

Next, vulnerability is determined. First, the embankment erodibility of the site during a flood event is determined using Exhibit 4.2.1.18 based on the provided data.

EXHIBIT 4.2.1.18 EMBANKMENT ERODIBILITY TABLE

AASHTO Soil Classification	Frost Action			
	None	Low	Moderate	High
A1 - A3	Very Low	Low	Moderate	High
A4 - A8	Moderate	High	Very High	Very High

Utilizing Exhibit 4.2.1.18 it is determined that the embankment erodibility is estimated to be "Moderate". Based on the embankment erodibility along with the roadway prism characteristics provided in the "Site Overview", the vulnerability of the roadway prism can be obtained from Exhibit 4.2.1.19.

EXHIBIT 4.2.1.19 FLOOD-ROADWAY PRISM VULNERABILITY FOR 100-YR AND 500-YR FLOOD EVENTS MAGNITUDES

Flood Event Magnitude	Terrain	Embankment Erodibility Potential				
		Very Low	Low	Moderate	High	Very High
100-yr	Level	0.22	0.23	0.25	0.31	0.33
	Rolling	0.26	0.28	0.30	0.36	0.39
	Mountainous	0.35	0.37	0.40	0.48	0.52
500-yr	Level	0.55	0.59	0.63	0.77	0.83
	Rolling	0.66	0.70	0.75	0.91	0.99
	Mountainous	0.88	0.93	0.99	0.99	0.99

Using Exhibit 4.2.1.19, the vulnerability of the roadway prism for 100-yr and 500-yr flood events is estimated to be $V_{100\text{-yr}}$ = 0.40 (for both traffic directions) and $V_{500\text{-yr}}$ = 0.99 (for both traffic directions).

Step 6: Risk Assessment

Annual Owner Risk Calculation

Total annual owner risk is calculated for 100-yr and 500-yr flood threat likelihood by multiplying each threat likelihood by owner consequences by vulnerability for each magnitude of event analyzed, then summing the annual owner risk for all events, utilizing Equation 3.9:

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ Risk_i = Owner\ Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

Exhibits 4.2.1.20 and 4.2.1.21 include the annual owner risk calculations for the roadway prism from flood events for the example location.

EXHIBIT 4.2.1.20 ANNUAL OWNER RISK DETAILED CALCULATIONS

Roadway Traffic Direction	Flood Event Magnitude	Owner Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual Owner Risk ($)
Eastbound	100-yr	$3,393,050	0.40	1/100	$13,572
Westbound		$3,847,250	0.40		$15,389
Eastbound	500-yr	$3,393,050	0.99	1/500	$6,718
Westbound		$3,847,250	0.99		$7,618
				Total	**$43,297**

EXHIBIT 4.2.1.21 ANNUAL OWNER RISK CALCULATIONS

Roadway Traffic Direction	Annual Owner Risk 100-yr ($)	Annual Owner Risk 500-yr ($)	Total Annual Owner Risk ($)
Eastbound	$13,572	$6,718	$20,290
Westbound	$15,389	$7,618	$23,007
		Total	**$43,297**

Annual User Risk Calculation

Total user risk is calculated by multiplying each threat likelihood by user consequences by vulnerability for each magnitude of event analyzed, utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ Risk_i = Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

Exhibits 4.2.1.22 and 4.2.1.23 presents the annual user risk calculations for flood risk.

EXHIBIT 4.2.1.22 ANNUAL USER RISK DETAILED CALCULATIONS

Roadway Traffic Direction	Flood Event Magnitude	User Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual User Risk ($)
Eastbound	100-yr	$3,544,673	0.40	1/100	$14,179
Westbound		$3,544,673	0.40		$14,179
Eastbound	500-yr	$3,544,673	0.99	1/500	$7,018
Westbound		$3,544,673	0.99		$7,018
				TOTAL	**$42,394**

EXHIBIT 4.2.1.23 ANNUAL USER RISK CALCULATIONS

Roadway Traffic Direction	Annual User Risk 100-yr ($)	Annual User Risk 500-yr ($)	Total Annual User Risk ($)
Eastbound	$14,179	$7,018	$21,197
Westbound	$14,179	$7,018	$21,197
		TOTAL	**$42,394**

Total Annual Risk:

Calculate total annual risk by summing total annual owner risk and total annual user risk utilizing Equation 3.13 and shown in Exhibit 4.2.1.24:

EQUATION 3.13

$$Total\ Annual\ Risk\ = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

Where n= number of events

EXHIBIT 4.2.1.24 ANNUAL TOTAL RISK CALCULATIONS

Roadway Traffic Direction	Annual Owner Risk ($)	Annual User Risk ($)	Total Annual Risk ($)
Eastbound	$20,290	$21,197	$41,487
Westbound	$23,007	$21,197	$44,204
		TOTAL	**$85,691**

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4.2.2 Flood-Bridge Risk Assessment

CDOT maintains and repairs over 23,000 total lane miles of highway including approximately 3,500 vehicular bridges. Some of these bridges may be vulnerable to flooding and damage as shown in 4.2.2.1.

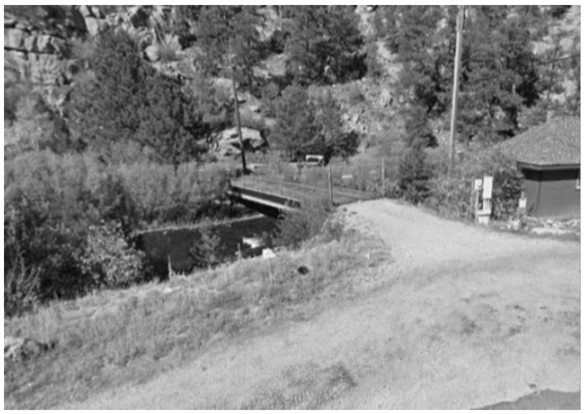


EXHIBIT 4.2.2.1 DAMAGE TO LOCAL ACCESS BRIDGE ON US-34 AT MP 66.15 DURING 2013 FLOOD EVENT

Exhibit 4.2.2.2 illustrates the basic methodology used in risk analysis of flood to bridges.

EXHIBIT 4.2.2.2 FLOOD-BRIDGE RISK ASSESSMENT METHODOLOGY

Step 1: Threat Data Collection
Flood Annual Likelihood (Exhibit 4.2.2.4)

↓

Step 2: Asset Data Collection
Asset (Bridge) Data Needs (Exhibit 4.2.2.5)

↓

Step 3: Owner Consequence Calculation
Owner Worst Reasonable Case (WRC) for Flood-Bridge (Exhibit 4.2.2.6)
Bridge Unit Cost Estimation (Exhibit 4.2.2.7)

↓

Step 4: User Consequence Calculation
User Worst Reasonable Case (WRC) for Flood-Bridge (Exhibit 4.2.2.6)
Vehicle Operating Cost (VOC) and Lost of Wages (LW) (Exhibit 4.2.2.8)
Detour Estimation (Extra Travel Length and Time) (Exhibits 4.2.2.9 and 4.2.2.10)
Calculations (Equations 3.5 through 3.8)
Total User Consequence (Equation 3.2)

↓

Step 5: Vulnerability Assessment
Flood-Bridge Vulnerability
(Exhibits 4.2.2.19 through 4.2.2.20)

↓

Step 6: Risk Assessment
Annual Owner Risk Calculation (Equation 3.9)
Annual User Risk Calculation (Equations 3.2 through 3.8 and 3.11)
Annual Total Risk (Equation 3.13)

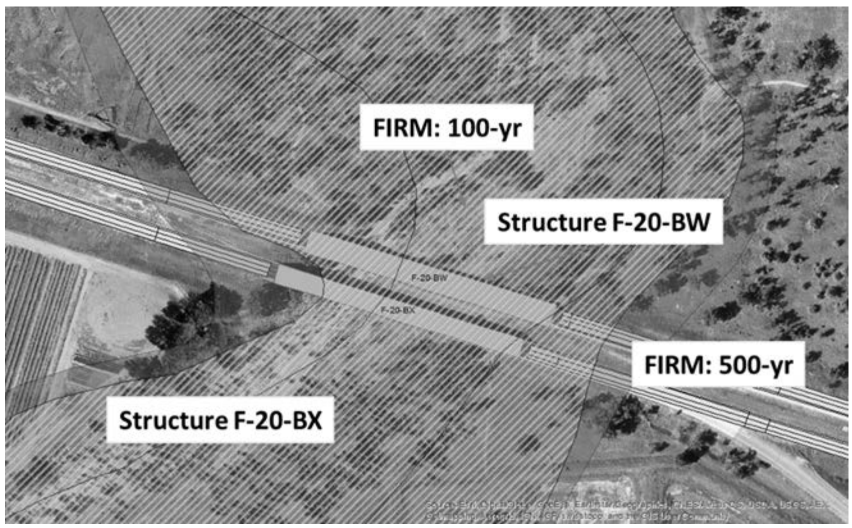
Computational Steps

Step 1: Threat Data Collection

The traditional method for conducting flood frequency (threat likelihood) analysis is to use historical records of peak flows to estimate the expected behavior of future flooding. This information is used to estimate the frequency of occurrence of various magnitude

floods at specific locations (e.g. 100-yr flood events). FEMA Flood Insurance Rate Maps are also utilized when available to generate information for 100-yr and 500-yr events. In this document, the identification of bridges to be considered for flood risk is based on estimated bridge overtopping by FEMA FIRMs. Exhibit 4.2.2.3 includes an example of potential flood-bridge threat based on overtopping by 100-yr and 500-yr FIRMs. Visual inspection is utilized for this planning-level analysis; however, more detailed hydraulic analysis is typically utilized when determining potential mitigation to reduce the threat to specific bridges in the field. Ideally, characteristics like hydraulic capacity would be available, however, given the age and lack of consistent data collection over the lifespan of highway bridges, this information is often not readily available. The approach provided here to estimate hydraulic capacity and the potential threat from flooding has been vetted by CDOT staff for planning-level analysis of the flood-bridge threat.

EXHIBIT 4.2.2.3 POTENTIAL FLOOD-BRIDGE THREAT



The corresponding annual threat likelihoods for 100-yr and 500-yr flood events are presented in Exhibit 4.2.2.4. Note, this approach does not consider increases in threat likelihood due to climate change

EXHIBIT 4.2.2.4 FLOOD/RAINFALL ANNUAL THREAT LIKELIHOOD

Recurrence Interval* (Year)	Annual Threat Likelihood
1	1/1
2	1/2
5	1/5
10	1/10
25	1/25
50	1/50
100	1/100
500	1/500

*Flood/Rain recurrence intervals do not necessarily constitute the same flow rate.

Step 2: Asset Data Collection

Data needed to assess the annual risk from flood events includes asset replacement cost (ARC), user costs, and vulnerability. The FHWA National Bridge Inventory (NBI) database as well as CDOT bridge inspection reports supply the bridge identification number (Structure ID) and dimensions to calculate ARC and determine bridge vulnerability. The OTIS Highways feature class provides traffic volumes and site characteristics for calculating user consequences. Exhibit 4.2.2.5 provides a summary of the data needs and sources to assess risk for flood-bridge conditions and as repeated here:

EXHIBIT 4.2.2.5 DATA NEEDS FOR FLOOD-BRIDGE RISK ANALYSIS

	Data Needs	Data Source
Asset Replacement Cost	**Milepost (beginning and end)**	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Bridge Length (NBI 49)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm CDOT Bridge Inspection Report
	Bridge Width (NBI 52)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm CDOT Bridge Inspection Report
Vulnerability	**Structure ID (NBI 8)**	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm CDOT Bridge Inspection Report
	Span Length (NBI 48)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm CDOT Bridge Inspection Report
	Superstructure Condition (NBI 59)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm CDOT Bridge Inspection Report
	Substructure Condition (NBI 60)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm CDOT Bridge Inspection Report
	Bridge Hydraulic Capacity	CDOT Construction Manuals If bridge overtops at 100-yr flood events, **assume 50-yr capacity.** If bridge overtops at 500-yr but not 100-yr flood events, **assume 100-yr capacity.**
	Scour Condition (NBI 113)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm CDOT Bridge Inspection Report
	Drainage Basin Landcover Type	USGS National Map https://www.mrlc.gov/data/nlcd-2016-land-cover-conus
	Mean Basin Slope	Stream Stats https://streamstats.usgs.gov/ss/
User Consequences	**AADT Vehicles**	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	AADT Trucks	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Roadway Damaged	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Detour	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Detour Distance	CDOT Operations
	Detour Time	CDOT Operations
	Number of Closure Days	See Exhibit 4.2.2.9
	Number of Partial Closure Days	See Exhibit 4.2.2.9
	Average Vehicle Occupancy	FHWA https://www.fhwa.dot.gov/tpm/guidance/avo_factors.pdf
	Car Running Costs	(RITA)/Texas A&M Transportation Institute
	Truck Running Costs	American Transportation Research Institute
	Average Value of Time	(RITA)/Texas A&M Transportation Institute

Step 3: Owner Consequence

Owner consequence measures the impact to the owner (CDOT) in terms of cost of repairs, cleanup, maintenance, and related agency operational costs. The most severe but credible consequence Worst Reasonable Consequence (WRC) for flood-bridge, based on past emergency repair projects, is estimated as 100% the replacement cost of the bridge overtopped by a FIRM plus $5,000 in cleanup costs to remove debris. The ARC unit cost from bridges along with the method to calculate WRC can be found in Exhibits 4.2.2.6 and 4.2.2.7 respectively.

EXHIBIT 4.2.2.6 SUMMARY OF WRC FOR OWNER CONSEQUENCE

		Threat			
		Debris Flow	Flood	Scour	Rockfall
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

EXHIBIT 4.2.2.7 UNIT COSTS

Asset	Units	Unit Cost
Bridge Approach**	sq ft	$350
Bridge*	sq ft	$600
Culvert***	cu ft	$55
PTCS**	sq ft	$550
Road Prism (Asphalt)**	sq yds	$150
Road Prism (Concrete)**	sq yds	$350

* Bridge area is defined as deck length multiplied by deck width, derived from NBI Items 49 and 52, respectively.

**Bridge approach, roadway, and PTCS width are derived from CDOT OTIS Highways feature class using fields for lane width, lane count, and shoulder width.

***For culvert (CBC), the volume, in cubic feet, is calculated by multiplying the box height by the box width by the length. These values are derived from the culverts feature class maintained by C-PLAN, CDOT's interactive online mapping platform.

Step 4: User Consequence

User consequences measure the impact to the public in terms of lost wages and increased vehicle operating costs due to delays, detours, and longer drive times. Required inputs to calculate user consequences include AADT, percent truck traffic, average vehicle occupancy, average hourly wage, detour length, work zone length, speed on detour, number of days of closure, and number of days of partial closure. For user consequences, the estimated WRC from flood on a bridge is considered failure if the bridge is overtopped by a FIRM and it is based on the cost of the user due to 180 days of full closure with no days of partial closure. For further explanation on how to calculate user consequences, see Exhibits 4.2.2.8 through 4.2.2.10 and Equations 3.2 through 3.8 and 3.11.

Exhibit 4.2.2.8 provides default values for a range of factors associated with the cost associated with operating vehicles, value of time, and occupancy that are updated annually by the various federal government agencies. Note the values included in Exhibit 4.2.2.8 were gathered in June of 2019 and will vary in future years.

EXHIBIT 4.2.2.8 CONSTANTS USED IN USER CONSEQUENCE CALCULATIONS

User Cost Terms	Variable	Value	Year Published
Average Vehicle Occupancy	*O*	1.77	2019
Car Running Cost per Mile	*C2*	$0.59	2019
Truck Running Cost per Mile	*C3*	$0.96	2015
Average Value of Time per Adult per Hour	*C4*	$10.62	2015
Average Value of Freight Driver Cost per Hour	*C5*	$25.31	2015
Car Running Cost per Hour	*C8*	$26.52	2015
Truck Running Cost per Hour	*C9*	$44.24	2015

The suggested number of full and partial closure days, derived from the I-70 Pilot, are provided in Exhibit 4.2.2.9. It is suggested that this table be used as guidance for all other corridor's for estimating closures days, both full and partial.

EXHIBIT 4.2.2.9 I-70 RISK AND RESILIENCE PILOT NUMBER OF FULL CLOSURE AND PARTIAL CLOSURE DAYS FOR WRC

Asset	Threat	Full Closure Days (d_{FC})	Partial Closure Days (d_{PC})
Bridge Approach	All	2	0
Bridge	Flood	180	0
Bridge	Debris Flow	2	0
Bridge	Rockfall	4	14
Culvert	Debris Flow	1	0
Culvert	Flood	3	0
PTCS	Rockfall	4	14
Roadway (<=% Width)	Flood	1	0
Roadway (> 50% Width)	Flood	3	0
Roadway (2 Directions)	Flood	3	0
Roadway	Rockfall	4	14

Example detours used for the I-70 Risk and Resilience Pilot and the worked examples in this document are listed in Exhibit 4.2.2.10. Note that *Additional Travel Distance* refers to the additional miles a traveler must travel on detour in comparison to the original route, and *Additional Travel Time* is the additional time a traveler must travel on detour in comparison to the original route. CDOT Operations can provide further guidance on estimating detours from closures for highways other than I-70.

EXHIBIT 4.2.2.10 I-70 RISK AND RESILIENCE PILOT DETOUR TABLE

Starting Milepost	Ending Milepost	Additional Travel Distance (miles) (*C7*)	Additional Travel Time (minutes) (*Dt*)
1	14	146	189
14	90	90	112
90	155	140	167
155	205	98	126
205	231	83	109
231	245	49	77
245	288	3	7
288	353	15	24
353	360	71	96
360	404	76	73
404	438	69	70
438	450	63	77

Total User Consequences is the sum of user consequence due to full and partial closures as shown in Equation 3.2.

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

Where:

$User\ Consequence_{FC}$ = User consequences due to full closure
$User\ Consequence_{PC}$ = User consequences due to partial closure

User consequences for full closure are the sum of vehicle operating costs incurred due to travel on detour, lost wages, and truck revenue due to travel on detour as shown in Equation 3.3.

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

Where:

VOC_{FC} = Vehicle operating costs incurred due to full closure
LW_{FC} = Lost wages/truck revenue incurred due to full closure

User consequences for partial closures are the sum of vehicle operating costs incurred due to traffic delays, lost wages, and truck revenue due to delays incurred while driving through a partial closure as shown in Equation 3.4.

EQUATION 3.4

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

Where:

VOC_{PC} = Vehicle operating costs incurred due to partial closure
LW_{PC} = Lost wages/truck revenue incurred due to partial closure

Equation 3.5 is the equation for calculating vehicle operating costs for full closures.

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$ = Average annual daily traffic (non-truck)

$AADT_{Truck}$ = Average annual daily truck traffic
$C2$ = Vehicle running cost ($/vehicle-mile)
$C3$ = Freight running cost ($/truck-mile)
d_{FC} = Number of full closure days (days)
$C7$ = Difference in distance between detour and original route (mile)

Equation 3.6 is used for calculating lost wages and truck revenue for full closures.

EQUATION 3.6

$$LW_{FC} = \left((C4 \ x \ O \ x \ AADT_{Vehicle}) + (C5 \ x \ AADT_{Truck})\right) x \ d_{FC} \ x \ \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$ = Average annual daily traffic (non-truck)
$AADT_{Truck}$ = Average annual daily truck traffic
$C4$ = Average value of time ($/adult-hour)
O = Average occupancy (adult/vehicle)
$C5$ = Average value of freight time($/truck-hour)
d_{FC} = Number of full closure days (days)
Dt = Extra travel time on detour (minutes)

Equation 3.7 is used for calculating vehicle operating costs due to partial closures.

EQUATION 3.7

$$VOC_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x \ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x \ WZS}\right) x \left((C8 \ x \ AADT_{Vehicle}) + (C9 \ x \ AADT_{Truck})\right) x \ d_{PC}$$

Where:

WL = Work zone length (miles)
WZS = Work zone speed limit (mph)
$WZSR$ = Work zone speed limit reduction (mph)
$AADT_{Vehicle}$ = Average annual daily traffic (non-truck)
$AADT_{Truck}$ = Average annual daily truck traffic
$C8$ = Vehicle running cost ($/vehicle-hour)
$C9$ = Freight running cost ($/truck-hour)
d_{PC} = Number of days of partial closure (days)

Equation 3.8 is used for calculating lost wages and truck revenue due to partial closures.

EQUATION 3.8

$$LW_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x\ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x\ WZS} \right) x\ ((C4\ x\ AADT_{Vehicle}\ x\ O) + (C5\ x\ AADT_{Truck}))\ x\ d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C4$	=	Average value of time ($/adult-hour)
O	=	Average occupancy (adult/vehicle)
$C5$	=	Average value of freight time($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Calculate total annual user risk by multiplying the owner consequences by the vulnerability for each magnitude of event the threat likelihood then summing the annual user risk for all events, utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ \boldsymbol{R}isk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n = number of events

Step 5: Vulnerability Assessment

Vulnerability of bridges from flood events is dependent on multiple factors. Literature sources provided some input as to how bridges perform when exposed to flood that were taken into consideration when developing vulnerability factors. In addition, CDOT Staff Bridge and Maintenance Staff provided opinions and input as to which factors, they deemed contributed most to damage to bridges from flooding. The factors identified for the vulnerability assessment include: 1) hydraulic capacity; 2) scour condition; 3) superstructure condition; 4) substructure conditions; 5) span length; and 6) debris potential for the site. The debris potential of the site during a flood event is determined based on the landcover of the surrounding drainage area and the slope of the surrounding drainage area. Exhibit 4.2.2.11 is the debris potential table needed to determine bridge vulnerability.

Utilizing the debris potential factor obtained with Exhibit 4.2.2.11 along with the bridge characteristics mentioned previously, the vulnerability of bridges can be obtained for either 100-yr flood events or 500-yr flood events using Exhibits 4.2.2.12 and 4.2.2.13.

EXHIBIT 4.2.2.11 DEBRIS POTENTIAL TABLE

	Landcover of Drainage Area			
Mean Basin Site Slope	**Water and Snow**	**Urban**	**Shrubs**	**Trees**
Low (0-8%)	Very Low	Low	Moderate	Moderate
Moderate (9-16%)	Very Low	Moderate	High	High
High (>16%)	Very Low	High	High	Very High

EXHIBIT 4.2.2.12 FLOOD-BRIDGE VULNERABILITY FOR 100-YR EVENT MAGNITUDE

				Superstructure Condition								
				7-9			5-6			0-4		
				Substructure Condition			Substructure Condition			Substructure Condition		
Hydraulic Capacity	**Debris Potential**	**Scour Condition**	**Span Length**	**7-9**	**5-6**	**0-4**	**7-9**	**5-6**	**0-4**	**7-9**	**5-6**	**0-4**
100-yr	**Very Low**	4-9	> 30 ft	0.001	0.003	0.015	0.002	0.005	0.028	0.006	0.016	0.085
			≤ 30 ft	0.001	0.004	0.020	0.003	0.007	0.038	0.008	0.021	0.117
		0-3	> 30 ft	0.206	0.500	0.500	0.386	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.282	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Low	4-9	> 30 ft	0.001	0.003	0.017	0.002	0.006	0.031	0.007	0.018	0.097
			≤ 30 ft	0.002	0.004	0.023	0.003	0.008	0.043	0.009	0.024	0.133
		0-3	> 30 ft	0.233	0.500	0.500	0.437	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.320	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Moderate	4-9	> 30 ft	0.001	0.003	0.019	0.003	0.007	0.035	0.008	0.020	0.110
			≤ 30 ft	0.002	0.005	0.026	0.003	0.009	0.049	0.011	0.028	0.150
		0-3	> 30 ft	0.265	0.500	0.500	0.496	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.362	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	High	4-9	> 30 ft	0.002	0.004	0.021	0.003	0.007	0.040	0.009	0.023	0.125
			≤ 30 ft	0.002	0.005	0.029	0.004	0.010	0.055	0.012	0.031	0.171
		0-3	> 30 ft	0.300	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.411	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Very High	4-9	> 30 ft	0.002	0.005	0.028	0.004	0.009	0.052	0.011	0.029	0.160
			≤ 30 ft	0.003	0.007	0.038	0.005	0.013	0.071	0.016	0.040	0.219
		0-3	> 30 ft	0.386	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
50-yr	**Very Low**	4-9	> 30 ft	0.004	0.010	0.055	0.007	0.019	0.103	0.023	0.059	0.320
			≤ 30 ft	0.005	0.014	0.075	0.010	0.026	0.141	0.031	0.080	0.437
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Low	4-9	> 30 ft	0.004	0.011	0.062	0.008	0.021	0.117	0.026	0.066	0.362
			≤ 30 ft	0.006	0.016	0.085	0.011	0.029	0.160	0.035	0.091	0.496
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Moderate	4-9	> 30 ft	0.005	0.013	0.071	0.009	0.024	0.133	0.029	0.075	0.411
			≤ 30 ft	0.007	0.018	0.097	0.013	0.033	0.182	0.040	0.103	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	High	4-9	> 30 ft	0.006	0.015	0.080	0.011	0.028	0.150	0.033	0.085	0.466
			≤ 30 ft	0.008	0.020	0.110	0.015	0.038	0.206	0.046	0.117	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Very High	4-9	> 30 ft	0.007	0.019	0.103	0.014	0.035	0.193	0.043	0.110	0.500
			≤ 30 ft	0.010	0.026	0.141	0.019	0.049	0.265	0.059	0.150	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500

Exhibit 4.2.2.13 Flood-Bridge Vulnerability for 500-yr Event Magnitude

				Superstructure Condition								
				7-9			5-6			0-4		
				Substructure Condition			Substructure Condition			Substructure Condition		
Hydraulic Capacity	**Debris Potential**	**Scour Condition**	**Span Length**	**7-9**	**5-6**	**0-4**	**7-9**	**5-6**	**0-4**	**7-9**	**5-6**	**0-4**
100-yr	Very Low	4-9	> 30 ft	0.015	0.038	0.206	0.028	0.071	0.386	0.085	0.219	0.500
			≤ 30 ft	0.020	0.052	0.282	0.038	0.097	0.500	0.117	0.300	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Low	4-9	> 30 ft	0.017	0.043	0.233	0.031	0.080	0.437	0.097	0.249	0.500
			≤ 30 ft	0.023	0.059	0.320	0.043	0.110	0.500	0.133	0.340	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Moderate	4-9	> 30 ft	0.019	0.049	0.265	0.035	0.091	0.496	0.110	0.282	0.500
			≤ 30 ft	0.026	0.066	0.362	0.049	0.125	0.500	0.150	0.386	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	High	4-9	> 30 ft	0.021	0.055	0.300	0.040	0.103	0.500	0.125	0.320	0.500
			≤ 30 ft	0.029	0.075	0.411	0.055	0.141	0.500	0.171	0.437	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Very High	4-9	> 30 ft	0.028	0.071	0.386	0.052	0.133	0.500	0.160	0.411	0.500
			≤ 30 ft	0.038	0.097	0.500	0.071	0.182	0.500	0.219	0.500	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
50-yr	Very Low	4-9	> 30 ft	0.055	0.141	0.500	0.103	0.265	0.500	0.320	0.500	0.500
			≤ 30 ft	0.075	0.193	0.500	0.141	0.362	0.500	0.437	0.500	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Low	4-9	> 30 ft	0.062	0.160	0.500	0.117	0.300	0.500	0.362	0.500	0.500
			≤ 30 ft	0.085	0.219	0.500	0.160	0.411	0.500	0.496	0.500	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Moderate	4-9	> 30 ft	0.071	0.182	0.500	0.133	0.340	0.500	0.411	0.500	0.500
			≤ 30 ft	0.097	0.249	0.500	0.182	0.466	0.500	0.500	0.500	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	High	4-9	> 30 ft	0.080	0.206	0.500	0.150	0.386	0.500	0.466	0.500	0.500
			≤ 30 ft	0.110	0.282	0.500	0.206	0.500	0.500	0.500	0.500	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Very High	4-9	> 30 ft	0.103	0.265	0.500	0.193	0.496	0.500	0.500	0.500	0.500
			≤ 30 ft	0.141	0.362	0.500	0.265	0.500	0.500	0.500	0.500	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500

Step 6: Risk Calculation

Annual Owner Risk

The owner consequence for a flood-bridge event is based on the defined WRC for the owner and is estimated based on 100% of the ARC of the bridge plus $5,000 in cleanup costs. Annual owner risk is calculated for each event analyzed utilizing the owner consequence (Step 3), vulnerability (Step 5), and threat likelihood (Step 1) multiplying all factors and utilizing Equation 3.9.

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ Risk_i = Owner\ \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n= number of events

Annual User Risk

The user consequence for a flood event in bridges is based on the defined WRC for roadway users. As presented in Step 4, the estimated WRC for a flood-bridge event is considered failure if the bridge is overtopped by a FIRM. The annual user risk is calculated for each event magnitude of event analyzed (100-yr and 500-yr flood events) utilizing the user consequence (Step 4), vulnerability (Step 5), and threat likelihood (Step 1) multiplying all factors and utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ Risk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n= number of events

Total Annual Risk

The total annual risk for flood for bridges accounts for the annual owner risk as well as for the annual user risk from all flood event magnitudes. Equation 3.13 includes the calculation for total annual risk.

EQUATION 3.13

$$Total\ Annual\ Risk = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

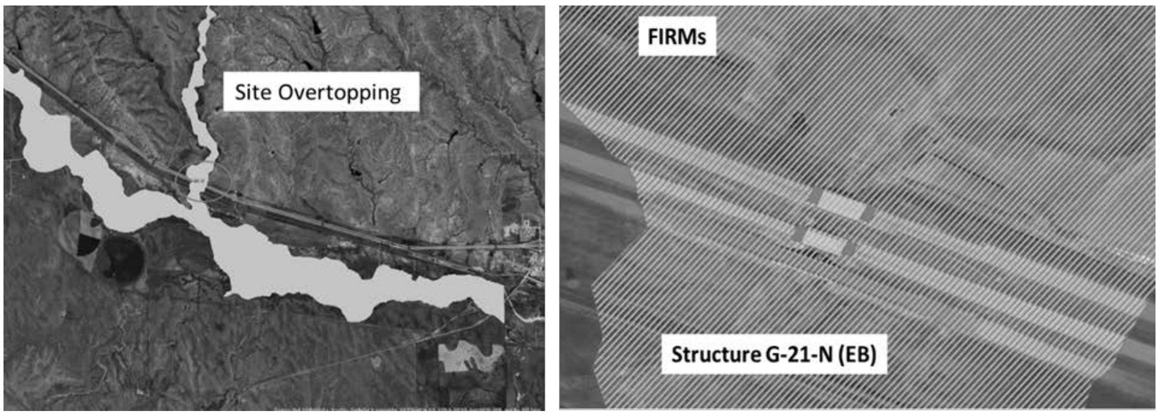
Where n= number of events

An example problem demonstrating the use of this approach is provided next.

Example Problem – Flood-Bridge Risk Assessment

This example demonstrates the risk assessment methodology developed for flood-bridge as included in Exhibit 4.2.2.2. The task is to calculate the annual owner risk, user risk, and total risk to flood for a bridge at milepost 356 onI-70 in Elbert County as shown in Exhibit 4.2.2.14. As shown in Exhibit 4.2.2.14, the bridge is anticipated to overtop during a 100-yr or 500-yr flood event. For this example, only Structure G-21-N (eastbound) is analyzed, however, the calculations are similar for the westbound structure.

EXHIBIT 4.2.2.14 EXAMPLE FLOOD SITE, I-70, MP 356 IN ELBERT COUNTY



Site Overview

- Location: I-70, MP 356, Elbert County
- Four-lane freeway (two-lanes in each direction)
- Full roadway width, each direction = 37 ft
- Unit cost for bridges= $600/sq ft
- Eastbound bridge characteristics:
  - Structure ID = G-21-N
  - Length = 83 ft
  - Width = 42 ft
  - Span length = 38 ft
  - Superstructure condition = 6
  - Substructure condition = 7
  - Scour condition = 5
  - Hydraulic capacity = 50-yr (based on default value, Exhibit 4.2.2.5)
- Mean Basin Slope: Low
- Landcover of Drainage Area: Shrubs
- Total I-70 $AADT_{Vehicle}$ = 8,200 vehicles
- Total I-70 $AADT_{Truck}$ = 2,800 trucks
- Detour length = 71 miles
- Detour time = 96 minutes
- Number of days of full closure = 180 days
- Number of days of partial closure = 0 days

Following the flood-bridge methodology presented in Exhibit 4.2.2.2:

Step 1: Threat Data Collection

The annual threat likelihoods are found in here, Exhibit 4.2.2.15.

EXHIBIT 4.2.2.15 FLOOD/RAINFALL ANNUAL THREAT LIKELIHOOD

Recurrence Interval (years)	Annual Threat Likelihood
1	1/1
2	1/2
5	1/5
10	1/10
25	1/25
50	1/50
100	1/100
500	1/500

*Flood/Rain recurrence intervals do not necessarily constitute the same flow rate.

Step 2: Asset Data Collection

Exhibit 4.2.2.5 describes the data needs and sources to perform the risk assessment. Actual values are listed in the "Site Overview" section.

Step 3: Owner Consequence

For this procedure, CDOT has established a unit cost for bridges at $600/sq ft as shown in Exhibit 4.2.2.16. To calculate area, multiply the full width by the length of the bridge. The WRC for a flood-bridge event is estimated as 100% of bridge ARC plus $5,000 in cleanup cost, Exhibit 4.2.2.17.

EXHIBIT 4.2.2.16 UNIT COSTS

Asset	Units	Unit Cost
Bridge Approach**	sq ft	$350
Bridge*	sq ft	$600
Culvert***	cu ft	$55
PTCS**	sq ft	$550
Road Prism (Asphalt)**	sq yds	$150
Road Prism (Concrete)**	sq yds	$350

* Bridge area is defined as deck length multiplied by deck width, derived from NBI Items 49 and 52, respectively.

**Bridge approach, roadway, and PTCS width are derived from CDOT OTIS Highways feature class using fields for lane width, lane count, and shoulder width.
***For culvert (CBC), the volume, in cubic feet, is calculated by multiplying the box height by the box width by the length. These values are derived from the culverts feature class maintained by C-PLAN, CDOT's interactive online mapping platform.

EXHIBIT 4.2.2.17 SUMMARY OF WRC FOR OWNER CONSEQUENCE

		Threat			
		Debris Flow	**Flood**	**Scour**	**Rockfall**
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

$$Owner\ Consequence = \left(100\%\ x\ \left((42\ ft\ x\ 83\ ft)\ x\ \frac{\$600}{sq\ ft}\right)\right) + \$5{,}000$$

$$Owner\ Consequence = \$2{,}091{,}600 + \$5{,}000$$

$$\boldsymbol{Owner\ Consequence = \$2,096,600}$$

Step 4: User Consequence

Calculating user consequence for flood-bridge events requires calculating vehicle and truck operating costs (VOC), as well as the value of lost wages and freight revenue (LW), for both full and partial closure (if applicable) as shown in Equations 3.2 through 3.8 and 3.11.

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

User Consequence for Full Closure (FC):

As presented in Equations 3.3 and 3.4 user consequence is based on the calculation of VOC_{FC} and LW_{FC}. The OTIS database provides total average annual daily traffic (AADT) data for the I-70 facility, half of the AADT has been assigned to each direction of travel for the purposes of this analysis.

Utilizing Equation 3.5 along with User Consequence variables provided in Exhibit 4.2.2.8 and anticipated days of closure from Exhibit 4.2.2.9, the VOC_{FC} for full closure for bridges during a flood event is calculated as follows:

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$	=	4,100 average annual daily traffic (non-truck)
$AADT_{Truck}$	=	1,400 average annual daily truck traffic
$C2$	=	\$0.59 vehicle running cost (\$/vehicle-mile)
$C3$	=	\$0.96 freight running cost (\$/truck-mile)
d_{FC}	=	180 days of full closure
$C7$	=	71 miles difference between detour and original route

$$VOC_{FC} = \left(\left(\frac{\$0.59}{vehicle - mile}\ x\ 4{,}100\frac{vehicle}{day}\right) + \left(\frac{\$0.96}{truck - mile}\ x\ 1{,}400\frac{truck}{day}\right)\right)\ x\ 180\ days\ x\ 71\ miles$$

$$\boldsymbol{VOC_{FC} = \$48,091,140}$$

Next use Equation 3.6 to calculate lost wages and truck revenue for full closures:

EQUATION 3.6

$$LW_{FC} = \left((C4\ x\ O\ x\ AADT_{Vehicle}) + (C5\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$	=	4,100 average annual daily traffic (non-truck)
$AADT_{Truck}$	=	1,400 average annual daily truck traffic
$C4$	=	\$10.62 average value of time (\$/hour-adult)
O	=	1.77 average occupancy (adult/vehicle)

$C5$	=	\$25.31 average value of freight time(\$/hour-truck)
d_{FC}	=	180 days of full closure
Dt	=	96 minutes of extra travel time on detour

$$LW_{FC} = \left(\left(\frac{\$10.62}{adult-hour}\ x\ 1.77\frac{adult}{vehicle}\ x\ 4{,}100\frac{vehicle}{day}\right) + \left(\frac{\$25.31}{truck-hour}\ x\ 1{,}400\frac{truck}{day}\right)\right)\ x\ 180\ days\ x\ \frac{96\ mins}{60\ \frac{mins}{hour}}$$

$$\boldsymbol{LF_{FC} = \$32,400,962}$$

User consequences for full closure are the sum of vehicle operating costs incurred due to vehicle travel on detour and the lost wages and truck revenue due to travel on detour as shown in Equation 3.3:

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

$$User\ Consequence_{FC} = \$48{,}091{,}140 + \$32{,}400{,}962$$

$$\boldsymbol{User\ Consequence_{FC} = \$80,492,102}$$

User Consequence for Partial Closure (PC):

Since partial closure are not anticipated at this site, VOC_{PC} and LW_{PC} for partial closures are estimated to be \$0:

$$VOC_{PC} = \$0$$

$$LW_{PC} = \$0$$

$$\boldsymbol{User\ Consequence_{PC} = \$0}$$

Total User Consequence:

Total user consequences include the sum of user consequence due to full and partial closures as shown in Equation 3.2:

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

$$Total\ User\ Consequence = \$80{,}492{,}102 + \$0$$

$$\textit{Total User Consequence} = \$\mathbf{80,492,102}$$

Step 5: Vulnerability Assessment

The debris potential factor of the site during a flood event is determined using Exhibit 4.2.2.18 based on the provided data for low slope and shrubs as drainage basin landcover type and repeated here for this specific example:

EXHIBIT 4.2.2.18 DEBRIS POTENTIAL TABLE

Mean Basin Site Slope	Landcover of Drainage Area			
	Water and Snow	**Urban**	**Shrubs**	**Trees**
Low (0-8%)	Very Low	Low	Moderate	Moderate
Moderate (9-16%)	Very Low	Moderate	High	High
High (>16%)	Very Low	High	High	Very High

The debris potential is determined to be "Moderate". Based on a low debris potential along with bridge characteristics provided in the "Site Overview", the vulnerability of the bridge can be obtained from Exhibits 4.2.2.19 and 4.2.2.20. The bridge characteristics needed to determine bridge vulnerability include:

- Span length (NBI 48) = 38 ft
- Superstructure condition (NBI 59) = 6
- Substructure condition (NBI 60) = 7
- Scour condition (NBI 113) = 5
- Hydraulic capacity = 50-yr (based on default value, Exhibit 4.2.2.5)
- Debris potential (from Exhibit 4.2.2.18) = moderate

EXHIBIT 4.2.2.19 FLOOD-BRIDGE VULNERABILITY FOR 100-YR EVENT MAGNITUDE

				Superstructure Condition								
				7-9			5-6			0-4		
				Substructure Condition			Substructure Condition			Substructure Condition		
Hydraulic Capacity	Debris Potential	Scour Condition	Span Length	7-9	5-6	0-4	7-9	5-6	0-4	7-9	5-6	0-4
100-yr	Very Low	4-9	> 30 ft	0.001	0.003	0.015	0.002	0.005	0.028	0.006	0.016	0.085
			≤ 30 ft	0.001	0.004	0.020	0.003	0.007	0.038	0.008	0.021	0.117
		0-3	> 30 ft	0.206	0.500	0.500	0.386	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.282	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Low	4-9	> 30 ft	0.001	0.003	0.017	0.002	0.006	0.031	0.007	0.018	0.097
			≤ 30 ft	0.002	0.004	0.023	0.003	0.008	0.043	0.009	0.024	0.133
		0-3	> 30 ft	0.233	0.500	0.500	0.437	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.320	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Moderate	4-9	> 30 ft	0.001	0.003	0.019	0.003	0.007	0.035	0.008	0.020	0.110
			≤ 30 ft	0.002	0.005	0.026	0.003	0.009	0.049	0.011	0.028	0.150
		0-3	> 30 ft	0.265	0.500	0.500	0.496	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.362	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	High	4-9	> 30 ft	0.002	0.004	0.021	0.003	0.007	0.040	0.009	0.023	0.125
			≤ 30 ft	0.002	0.005	0.029	0.004	0.010	0.055	0.012	0.031	0.171
		0-3	> 30 ft	0.300	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.411	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Very High	4-9	> 30 ft	0.002	0.005	0.028	0.004	0.009	0.052	0.011	0.029	0.160
			≤ 30 ft	0.003	0.007	0.038	0.005	0.013	0.071	0.016	0.040	0.219
		0-3	> 30 ft	0.386	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
50-yr	Very Low	4-9	> 30 ft	0.004	0.010	0.055	0.007	0.019	0.103	0.023	0.059	0.320
			≤ 30 ft	0.005	0.014	0.075	0.010	0.026	0.141	0.031	0.080	0.437
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Low	4-9	> 30 ft	0.004	0.011	0.062	0.008	0.021	0.117	0.026	0.066	0.362
			≤ 30 ft	0.006	0.016	0.085	0.011	0.029	0.160	0.035	0.091	0.496
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Moderate	4-9	> 30 ft	0.005	0.013	0.071	0.009	0.024	0.133	0.029	0.075	0.411
			≤ 30 ft	0.007	0.018	0.097	0.013	0.033	0.182	0.040	0.103	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	High	4-9	> 30 ft	0.006	0.015	0.080	0.011	0.028	0.150	0.033	0.085	0.466
			≤ 30 ft	0.008	0.020	0.110	0.015	0.038	0.206	0.046	0.117	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Very High	4-9	> 30 ft	0.007	0.019	0.103	0.014	0.035	0.193	0.043	0.110	0.500
			≤ 30 ft	0.010	0.026	0.141	0.019	0.049	0.265	0.059	0.150	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500

EXHIBIT 4.2.2.20 FLOOD-BRIDGE VULNERABILITY FOR 500-YR EVENT MAGNITUDE

				Superstructure Condition								
				7-9			5-6			0-4		
				Substructure Condition			Substructure Condition			Substructure Condition		
Hydraulic Capacity	Debris Potential	Scour Condition	Span Length	7-9	5-6	0-4	7-9	5-6	0-4	7-9	5-6	0-4
100-yr	Very Low	4-9	> 30 ft	0.015	0.038	0.206	0.028	0.071	0.386	0.085	0.219	0.500
			≤ 30 ft	0.020	0.052	0.282	0.038	0.097	0.500	0.117	0.300	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Low	4-9	> 30 ft	0.017	0.043	0.233	0.031	0.080	0.437	0.097	0.249	0.500
			≤ 30 ft	0.023	0.059	0.320	0.043	0.110	0.500	0.133	0.340	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Moderate	4-9	> 30 ft	0.019	0.049	0.265	0.035	0.091	0.496	0.110	0.282	0.500
			≤ 30 ft	0.026	0.066	0.362	0.049	0.125	0.500	0.150	0.386	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	High	4-9	> 30 ft	0.021	0.055	0.300	0.040	0.103	0.500	0.125	0.320	0.500
			≤ 30 ft	0.029	0.075	0.411	0.055	0.141	0.500	0.171	0.437	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Very High	4-9	> 30 ft	0.028	0.071	0.386	0.052	0.133	0.500	0.160	0.411	0.500
			≤ 30 ft	0.038	0.097	0.500	0.071	0.182	0.500	0.219	0.500	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
50-yr	Very Low	4-9	> 30 ft	0.055	0.141	0.500	0.103	0.265	0.500	0.320	0.500	0.500
			≤ 30 ft	0.075	0.193	0.500	0.141	0.362	0.500	0.437	0.500	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Low	4-9	> 30 ft	0.062	0.160	0.500	0.117	0.300	0.500	0.362	0.500	0.500
			≤ 30 ft	0.085	0.219	0.500	0.160	0.411	0.500	0.496	0.500	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Moderate	4-9	> 30 ft	0.071	0.182	0.500	0.133	0.340	0.500	0.411	0.500	0.500
			≤ 30 ft	0.097	0.249	0.500	0.182	0.466	0.500	0.500	0.500	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	High	4-9	> 30 ft	0.080	0.206	0.500	0.150	0.386	0.500	0.466	0.500	0.500
			≤ 30 ft	0.110	0.282	0.500	0.206	0.500	0.500	0.500	0.500	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Very High	4-9	> 30 ft	0.103	0.265	0.500	0.193	0.496	0.500	0.500	0.500	0.500
			≤ 30 ft	0.141	0.362	0.500	0.265	0.500	0.500	0.500	0.500	0.500
		0-3	> 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
			≤ 30 ft	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500

Using Exhibits 4.2.2.19 and 4.2.2.20 it was determined the vulnerability of the bridge for a 100-yr flood event to be $V_{100\text{-yr}} = 0.009$ and for a 500-yr flood event to be $V_{500\text{-yr}} = 0.133$.

Step 6. Risk Assessment

Annual Owner Risk

Total annual owner risk is calculated for 100-yr and 500-yr flood threat likelihood by multiplying each threat likelihood by owner consequences by vulnerability for each magnitude of event analyzed then summing the annual owner risk for all events utilizing Equation 3.9:

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ Risk_i = Owner\ Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

Exhibit 4.2.2.21 presents the annual owner risk calculations for flood-bridge events.

EXHIBIT 4.2.2.21 ANNUAL OWNER RISK CALCULATIONS

Flood Event Magnitude	Owner Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual Owner Risk ($)
100-yr	$2,096,600	0.009	1/100	$189
500-yr	$2,096,600	0.133	1/500	$558
			TOTAL	**$747**

Annual User Risk

Total user risk is calculated for 100-yr and 500-yr flood events by multiplying each threat likelihood by user consequences by vulnerability for each magnitude of event, then summing the annual user risk for all events utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ Risk_i = \ Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

Exhibit 4.2.2.22 presents the annual user risk calculations for flood risk.

EXHIBIT 4.2.2.22 ANNUAL USER RISK CALCULATIONS

Flood Event Magnitude	User Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual User Risk ($)
100-yr	$80,492,102	0.009	1/100	$7,244
500-yr	$80,492,102	0.133	1/500	$21,411
			TOTAL	**$28,655**

Total Annual Risk

Calculate total annual risk by adding total annual owner risk to total annual user risk, utilizing Equation 3.13:

EQUATION 3.13

$$Total\ Annual\ Risk\ = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

Where n= number of events

$$Total\ Annual\ Risk = (\$189 + \$558) + (\$7{,}244 + \$21{,}411)$$

$$\boldsymbol{Total\ Annual\ Risk} = \$\mathbf{747} + \$\mathbf{28,655} = \$\mathbf{29,402}$$

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4.2.3 Flood-Bridge Approach Risk Assessment

The recent 2013 flood event revealed that often the most vulnerable section of a bridge to flood risk are bridge approaches and not the actual structure

EXHIBIT 4.2.3.1 EXAMPLES OF DAMAGE FROM FLOOD TO A BRIDGE APPROACH

Exhibit 4.2.3.2 illustrates the basic methodology and steps used in risk analysis of flood to bridge approaches.

EXHIBIT 4.2.3.2 FLOOD-BRIDGE APPROACH RISK ASSESSMENT METHODOLOGY

Step 1: Threat Data Collection
Flood Annual Likelihood (Exhibit 4.2.3.3)

↓

Step 2: Asset Data Collection
Asset (Bridge Approach) Data Needs (Exhibit 4.2.3.4)

↓

Step 3: Owner Consequence Calculation
Owner Worst Reasonable Case (WRC) for Flood-Bridge Approach (Exhibit 4.2.3.5)
Bridge Approach Unit Cost Estimation (Exhibit 4.2.3.6)

↓

Step 4: User Consequence Calculation
User Worst Reasonable Case (WRC) for Flood-Bridge Approach (Exhibit 4.2.3.5)
Vehicle Operating Cost (VOC) and Lost of Wages (LW) (Exhibit 4.2.3.7)
Detour Estimation (Extra Travel Length and Time) (Exhibits 4.2.3.8 and 4.2.3.9)
Calculations (Equations 3.5 through 3.8)
Total User Consequence (Equation 3.2)

↓

Step 5: Vulnerability Assessment
Flood-Bridge Approach Vulnerability (Exhibits 4.2.3.14 through 4.2.3.16)

↓

Step 6: Risk Assessment
Annual Owner Risk Calculation (Equation 3.9)
Annual User Risk Calculation (Equations 3.2 through 3.8 and 3.11)
Annual Total Risk (Equation 3.13)

Computational Steps

Step 1: Threat Data Collection

As discussed in Section 4.2.1, for planning level analyses FEMA FIRMS are used to determine likelihood of overtopping from flood events. In addition, more robust hydraulic analyses are utilized when determining specific mitigation design to reduce risk from flooding. For flood-bridge approach analysis, FEMA FIRMs are utilized to estimate the likelihood of overtopping from flood events similar to the method taken for flood-bridge analysis.

EXHIBIT 4.2.3.3 FLOOD/RAINFALL ANNUAL THREAT LIKELIHOOD

Recurrence Interval* (Year)	Annual Threat Likelihood
1	1/1
2	1/2
5	1/5
10	1/10
25	1/25
50	1/50
100	1/100
500	1/500

*Flood/Rain recurrence intervals do not necessarily constitute the same flow rate.

Step 2: Asset Data Collection

Data needed to assess the annual risk from flood events includes asset replacement costs (ARC), user costs, and vulnerability. The FHWA National Bridge Inventory (NBI) database, PONTIS database as well as CDOT bridge inspection reports provide the bridge identification number (Structure ID) and dimensions to calculate ARC and bridge approach(s) vulnerabilities. In addition, the OTIS Highways feature class provides traffic volumes and site characteristics for calculating user consequences. Exhibit 4.2.3.4 provides a summary of the data needs and sources to assess risk for flood-bridge approach.

EXHIBIT 4.2.3.4 DATA NEEDS FOR FLOOD-BRIDGE APPROACH RISK ANALYSIS

	Data Needs	Data Source
Asset Replacement Cost	**Milepost (beginning and end)**	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Roadway Geometry	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Bridge Approach Length	Default to be 20 feet
Vulnerability	**Structure ID (NBI 8)**	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm
	Superstructure Condition (NBI 59)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm
	Substructure Condition (NBI 60)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm
	Slope Protection Condition (Element 325)	CDOT Bridge Inspection Report
	Type of Slope Protection (Element 326)	CDOT Bridge Inspection Report
	Scour Condition (NBI 113)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm
	Drainage Basin Landcover Type	USGS National Map https://www.mrlc.gov/data/nlcd-2016-land-cover-conus
	Mean Basin Slope	Stream Stats https://streamstats.usgs.gov/ss/
User Consequences	**AADT Vehicles**	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	AADT Trucks	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Roadway Damaged	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Detour	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Detour Distance	CDOT Operations
	Detour Time	CDOT Operations
	Number of Closure Days	See Exhibit 4.2.3.8
	Number of Partial Closure Days	See Exhibit 4.2.3.8
	Average Vehicle Occupancy	FHWA https://www.fhwa.dot.gov/tpm/guidance/avo_factors.pdf
	Car Running Costs	(RITA)/Texas A&M Transportation Institute
	Truck Running Costs	American Transportation Research Institute
	Average Value of Time	(RITA)/Texas A&M Transportation Institute

Step 3: Owner Consequence Assessment

Owner consequence measures the impact to the owner (CDOT) in terms of cost of repairs, cleanup, maintenance, and related agency operational costs. The most severe but credible consequence Worst Reasonable Consequence (WRC) for flood-bridge approach, based on past emergency repair projects, is estimated as 100% the ARC of the bridge approach(s) overtopped by a FIRM plus $5,000 in cleanup costs to remove debris.

The asset replacement unit cost from bridge approaches along with the method to calculate WRC can be found in Exhibit 4.2.3.5 and Exhibit 4.2.3.6 respectively.

EXHIBIT 4.2.3.5 SUMMARY OF WRC FOR OWNER CONSEQUENCE

		Threat			
		Debris Flow	Flood	Scour	Rockfall
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
Asset	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
Asset	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
Asset	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
Asset	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

EXHIBIT 4.2.3.6 UNIT COSTS

Asset	Units	Unit Cost
Bridge Approach**	sq ft	$350
Bridge*	sq ft	$600
Culvert***	cu ft	$55
PTCS**	sq ft	$550
Road Prism (Asphalt)**	sq yds	$150
Road Prism (Concrete)**	sq yds	$350

* Bridge area is defined as deck length multiplied by deck width, derived from NBI Items 49 and 52, respectively.
**Bridge approach, roadway and PTCS width are derived from CDOT OTIS Highways feature class using fields for lane width, lane count, and shoulder width.
***For culvert (CBC), the volume, in cubic feet, is calculated by multiplying the box height by the box width by the length. These values are derived from the culverts feature class maintained by C-PLAN, CDOT's interactive online mapping platform.

Step 4: User Consequence Assessment

User consequences measure the impact to the public in terms of lost wages and increased vehicle operating costs due to delays, detours, and drive times. Required inputs include AADT, percent truck traffic, average vehicle occupancy, average hourly wage, detour length, work zone length, speed on detour, number of days of closure, and number of days of partial closure. For user consequences, the estimated WRC from flood-bridge approach events is considered bridge approach failure if the bridge approach is overtopped by a FIRMs and it is based on the cost of the user due to full closure for two days. For further explanation on how to calculate user consequences, see Exhibits 4.2.3.7 through 4.2.3.9 and Equations 3.2 through 3.8 and 3.11.

Exhibit 4.2.3.7 provides default values for a range of factors associated with the cost associated with operating vehicles, value of time, and occupancy that are updated annually by the various federal government agencies. Note the values included in Exhibit 4.2.3.7 were gathered in June of 2019 and will vary in future years.

EXHIBIT 4.2.3.7 CONSTANTS USED IN USER CONSEQUENCE CALCULATIONS

User Cost Terms	Variable	Value	Year Published
Average Vehicle Occupancy	*O*	1.77	2019
Car Running Cost per Mile	*C2*	$0.59	2019
Truck Running Cost per Mile	*C3*	$0.96	2015
Average Value of Time per Adult per Hour	*C4*	$10.62	2015
Average Value of Freight Driver Cost per Hour	*C5*	$25.31	2015
Car Running Cost per Hour	*C8*	$26.52	2015
Truck Running Cost per Hour	*C9*	$44.24	2015

The suggested number of full and partial closure days, derived from the I-70 Pilot, are provided in Exhibit 4.2.3.8. It is suggested that this table be used as guidance for all other corridor's for estimating closures days, both full and partial.

EXHIBIT 4.2.3.8 I-70 RISK AND RESILIENCE PILOT NUMBER OF FULL CLOSURE AND PARTIAL CLOSURE DAYS FOR WRC

Asset	Threat	Full Closure Days (d_{FC})	Partial Closure Days (d_{PC})
Bridge Approach	All	2	0
Bridge	Flood	180	0
Bridge	Debris Flow	2	0
Bridge	Rockfall	4	14
Culvert	Debris Flow	1	0
Culvert	Flood	3	0
PTCS	Rockfall	4	14
Roadway (<=% Width)	Flood	1	0
Roadway (> 50% Width)	Flood	3	0
Roadway (2 Directions)	Flood	3	0
Roadway	Rockfall	4	14

Example detours used for the I-70 Risk and Resilience Pilot and the worked examples in this document are listed in Exhibit 4.2.3.9. Note that *Additional Travel Distance* refers to the additional miles a traveler must travel on detour in comparison to the original route, and *Additional Travel Time* is the additional time a traveler must travel on detour in comparison to the original route. CDOT Operations can provide further guidance on estimating detours from closures for highways other than I-70.

EXHIBIT 4.2.3.9 I-70 RISK AND RESILIENCE PILOT DETOUR TABLE

Starting Milepost	Ending Milepost	Additional Travel Distance (miles) (*C7*)	Additional Travel Time (minutes) (*Dt*)
1	14	146	189
14	90	90	112
90	155	140	167
155	205	98	126
205	231	83	109
231	245	49	77
245	288	3	7
288	353	15	24
353	360	71	96
360	404	76	73
404	438	69	70
438	450	63	77

Total User Consequences is the sum of user consequence due to full and partial closures as shown in Equation 3.2.

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

Where:

$User\ Consequence_{FC}$ = User consequences due to full closure
$User\ Consequence_{PC}$ = User consequences due to partial closure

User consequences for full closure are the sum of vehicle operating costs incurred due to travel on detour, lost wages, and truck revenue due to travel on detour as shown in Equation 3.3.

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

Where:

VOC_{FC} = Vehicle operating costs incurred due to full closure
LW_{FC} = Lost wages/truck revenue incurred due to full closure

User consequences for partial closures are the sum of vehicle operating costs incurred due to traffic delays, lost wages, and truck revenue due to delays incurred while driving through a partial closure as shown in Equation 3.4.

EQUATION 3.4

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

Where:

VOC_{PC} = Vehicle operating costs incurred due to partial closure
LW_{PC} = Lost wages/truck revenue incurred due to partial closure

Equation 3.5 is the equation for calculating vehicle operating costs for full closures.

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right) x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$ = Average annual daily traffic (non-truck)

$AADT_{Truck}$ = Average annual daily truck traffic
$C2$ = Vehicle running cost ($/vehicle-mile)
$C3$ = Freight running cost ($/truck-mile)
d_{FC} = Number of full closure days (days)
$C7$ = Difference in distance between detour and original route (mile)

Equation 3.6 is used for calculating lost wages and truck revenue for full closures.

EQUATION 3.6

$$LW_{FC} = \left((C4 \; x \; O \; x \; AADT_{Vehicle}) + (C5 \; x \; AADT_{Truck}) \right) x \; d_{FC} \; x \; \left(\frac{Dt}{60} \right)$$

Where:

$AADT_{Vehicle}$ = Average annual daily traffic (non-truck)
$AADT_{Truck}$ = Average annual daily truck traffic
$C4$ = Average value of time ($/adult-hour)
O = Average occupancy (adult/vehicle)
$C5$ = Average value of freight time($/truck-hour)
d_{FC} = Number of full closure days (days)
Dt = Extra travel time on detour (minutes)

Equation 3.7 is used for calculating vehicle operating costs due to partial closures.

EQUATION 3.7

$$VOC_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x \; (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x \; WZS} \right) x \; \left((C8 \; x \; AADT_{Vehicle}) + (C9 \; x \; AADT_{Truck}) \right) x \; d_{PC}$$

Where:

WL = Work zone length (miles)
WZS = Work zone speed limit (mph)
$WZSR$ = Work zone speed limit reduction (mph)
$AADT_{Vehicle}$ = Average annual daily traffic (non-truck)
$AADT_{Truck}$ = Average annual daily truck traffic
$C8$ = Vehicle running cost ($/vehicle-hour)
$C9$ = Freight running cost ($/truck-hour)
d_{PC} = Number of days of partial closure (days)

Equation 3.8 is used for calculating lost wages and truck revenue due to partial closures.

EQUATION 3.8

$$LW_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x\ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x\ WZS}\right) x\ ((C4\ x\ AADT_{Vehicle}\ x\ O) + (C5\ x\ AADT_{Truck}))\ x\ d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C4$	=	Average value of time ($/adult-hour)
O	=	Average occupancy (adult/vehicle)
$C5$	=	Average value of freight time($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Calculate total annual user risk by multiplying the owner consequences by the vulnerability for each magnitude of event the threat likelihood then summing the annual user risk for all events, utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ \boldsymbol{R}isk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n = number of events

Step 5: Vulnerability Assessment

Vulnerability of bridge approaches from flood events is dependent on multiple factors. Literature sources provided some input as to how bridges perform when exposed to flood that were taken into consideration when developing vulnerability factors. In addition, CDOT Staff Bridge and Maintenance Staff provided opinions and input as to which factors, they deemed contributed most to damage to bridges from flooding. The factors identified for the vulnerability assessment include: 1) hydraulic capacity of the bridge; 2) type of slope protection; 3) slope protection condition and 4) debris potential for the site. The debris potential of the site during a flood event is determined based on the landcover of the surrounding drainage area and the slope of the surrounding drainage area. Exhibit 3.21 (introduced in the flood-bridge section) presents the debris potential table to determine bridge approach vulnerability.

Utilizing the debris potential factor obtained with Exhibit 4.2.3.10 along with the bridge characteristics mentioned above, the vulnerability of bridges can be obtained for either 100-yr flood events or 500-yr flood events as shown in Exhibits 4.2.3.11 and 4.2.3.12.

EXHIBIT 4.2.3.10 DEBRIS POTENTIAL TABLE

	Landcover of Drainage Area			
Mean Basin Site Slope	**Water and Snow**	**Urban**	**Shrubs**	**Trees**
Low (0-8%)	Very Low	Low	Moderate	Moderate
Moderate (9-16%)	Very Low	Moderate	High	High
High (>16%)	Very Low	High	High	Very High

EXHIBIT 4.2.3.11 FLOOD-BRIDGE APPROACH VULNERABILITY RATINGS 100-YR FLOOD EVENT MAGNITUDE

Flood Event Magnitude	Hydraulic Capacity	Slope Type	Slope Protection Condition	Debris Potential				
				Very Low	Low	Moderate	High	Very High
100-yr	100-yr	Wingwalls + Riprap	State 1	0.0008	0.0011	0.0036	0.0121	0.0221
			State 2	0.0015	0.0020	0.0066	0.0221	0.0403
			State 3	0.0040	0.0054	0.0181	0.0601	0.1096
		Wingwalls	State 1	0.0009	0.0012	0.0040	0.0134	0.0244
			State 2	0.0016	0.0022	0.0073	0.0244	0.0445
			State 3	0.0045	0.0060	0.0200	0.0664	0.1211
		Riprap	State 1	0.0010	0.0013	0.0045	0.0148	0.0270
			State 2	0.0018	0.0024	0.0081	0.0270	0.0492
			State 3	0.0049	0.0066	0.0221	0.0734	0.1339
		None	State 1	0.0045	0.0060	0.0200	0.0664	0.1211
			State 2	0.0081	0.0110	0.0364	0.1211	0.2209
			State 3	0.0221	0.0298	0.0992	0.3296	0.6010
	50-yr	Wingwalls + Riprap	State 1	0.0270	0.0364	0.1211	0.4027	0.7342
			State 2	0.0492	0.0664	0.2209	0.7342	0.9900
			State 3	0.1339	0.1808	0.6010	0.9900	0.9900
		Wingwalls	State 1	0.0298	0.0403	0.1339	0.4451	0.8115
			State 2	0.0544	0.0734	0.2441	0.8115	0.9900
			State 3	0.1480	0.1998	0.6643	0.9900	0.9900
		Riprap	State 1	0.0330	0.0445	0.1480	0.4919	0.8969
			State 2	0.0601	0.0812	0.2698	0.8969	0.9900
			State 3	0.1636	0.2209	0.7342	0.9900	0.9900
		None	State 1	0.1480	0.1998	0.6643	0.9900	0.9900
			State 2	0.2698	0.3643	0.9900	0.9900	0.9900
			State 3	0.7342	0.9900	0.9900	0.9900	0.9900

EXHIBIT 4.2.3.12 FLOOD-APPROACH VULNERABILITY RATINGS 500-YR FLOOD EVENT MAGNITUDE

Flood Event Magnitude	Hydraulic Capacity	Slope Type	Slope Protection Condition	Debris Potential				
				Very Low	Low	Moderate	High	Very High
500-yr	100-yr	Wingwalls + Riprap	State 1	0.0221	0.0298	0.0992	0.3296	0.6010
			State 2	0.0403	0.0544	0.1808	0.6010	0.9900
			State 3	0.1096	0.1480	0.4919	0.9900	0.9900
		Wingwalls	State 1	0.0244	0.0330	0.1096	0.3643	0.6643
			State 2	0.0445	0.0601	0.1998	0.6643	0.9900
			State 3	0.1211	0.1636	0.5437	0.9900	0.9900
		Riprap	State 1	0.0270	0.0364	0.1211	0.4027	0.7342
			State 2	0.0492	0.0664	0.2209	0.7342	0.9900
			State 3	0.1339	0.1808	0.6010	0.9900	0.9900
		None	State 1	0.1211	0.1636	0.5437	0.9900	0.9900
			State 2	0.2209	0.2982	0.9900	0.9900	0.9900
			State 3	0.6010	0.8115	0.9900	0.9900	0.9900
	50-yr	Wingwalls + Riprap	State 1	0.7342	0.9900	0.9900	0.9900	0.9900
			State 2	0.9900	0.9900	0.9900	0.9900	0.9900
			State 3	0.9900	0.9900	0.9900	0.9900	0.9900
		Wingwalls	State 1	0.8115	0.9900	0.9900	0.9900	0.9900
			State 2	0.9900	0.9900	0.9900	0.9900	0.9900
			State 3	0.9900	0.9900	0.9900	0.9900	0.9900
		Riprap	State 1	0.8969	0.9900	0.9900	0.9900	0.9900
			State 2	0.9900	0.9900	0.9900	0.9900	0.9900
			State 3	0.9900	0.9900	0.9900	0.9900	0.9900
		None	State 1	0.9900	0.9900	0.9900	0.9900	0.9900
			State 2	0.9900	0.9900	0.9900	0.9900	0.9900
			State 3	0.9900	0.9900	0.9900	0.9900	0.9900

Step 6: Risk Calculation

Annual Owner Risk

The owner consequence for a flood-bridge approach event is based on the defined WRC for the owner and it is estimated based on 100% of the ARC of the bridge approach(s) overtopped plus $5,000 in cleanup costs of debris. Annual owner risk is calculated for each event magnitude (100-yr and 500-yr flood events) utilizing the owner consequence (Step 3), vulnerability (Step 5), and threat likelihood (Step 1) multiplying all factors and utilizing Equation 3.9.

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ Risk_i = Owner\ \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n= number of events

Annual User Risk

The annual user risk for a flood event in bridges approach is accounted for in the annual user risk for flood-bridge.

Total Annual Risk

The total annual risk for flood for bridges approach accounts for the annual owner risk, as the annual user risk has been accounted for in flood-bridge from all flood event magnitudes. Equation 3.13 includes the calculation for total annual risk.

EQUATION 3.13

$$Total\ Annual\ Risk\ = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

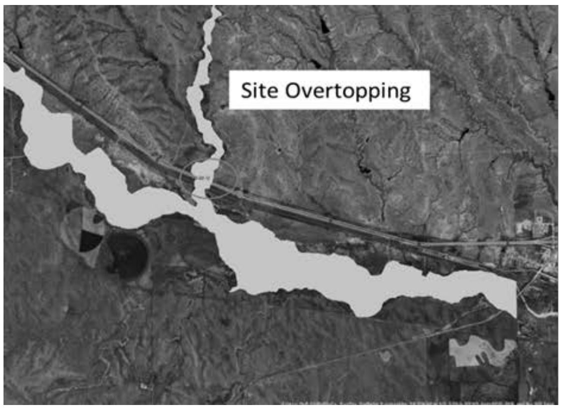
Where n= number of events

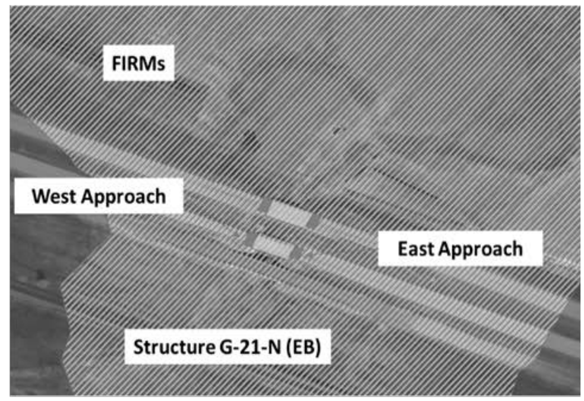
An example problem demonstrating the use of this approach is provided next.

Example Problem - Flood-Bridge Approach Risk Assessment

This example demonstrates the risk assessment methodology developed for flood-bridge approach presented in Exhibit 4.2.3.2. The task is to calculate the annual owner risk, user risk, and total risk from flood for the bridge approaches of one of the bridges at milepost 356 on I-70 in Elbert County as shown in Exhibit 4.2.3.13. As shown in Exhibit 4.2.3.13, both bridge approaches for Structure G-21-N are anticipated to overtop based on the 100-yr and 500-yr FIRMs. For demonstration purposes, only risk of Structure G-21-N bridge approaches will be analyzed.

EXHIBIT 4.2.3.13 EXAMPLE FLOOD SITE, I-70, MP 356 IN ELBERT COUNTY





Site Overview

- Location: I-70, MP 356, Elbert County
- Four-lane freeway (two-lanes in each direction)
- Full roadway width, each direction = 37 ft
- Unit cost for bridge approach= $350/sq ft
- Eastbound bridge/approach characteristics:
  - Structure ID = G-21-N
  - Hydraulic capacity = 50-yr (based on default value, Exhibit 4.2.3.4)

  East Bridge Approach:
  - Bridge Approach(s) length = 20 ft (based on default value, Exhibit 4.2.3.4)
  - Bridge Approach width= 38 ft
  - Type of slope protection = Riprap
  - Slope protection condition = Condition 2

  West Bridge Approach:
  - Bridge Approach(s) length = 20 ft (based on default value, Exhibit 4.2.3.4)
  - Bridge Approach width = 38 ft
  - Type of slope protection = Riprap
  - Slope protection condition = Condition 1
- Slope: Low
- Landcover of Drainage Area: Shrubs
- Total I-70 $AADT_{Vehicle}$ = 8,200 vehicles
- Total I-70 $AADT_{Truck}$ = 2,800 trucks
- Detour length = 71 miles

- Detour time = 96 minutes
- Number of days of full closure = 2 days
- Number of days of partial closure = 0 days

Following the flood-bridge approach methodology presented in Exhibit 4.2.3.2:

Step 1: Threat Data Collection

The annual threat likelihoods for a 100 and 500-yr flood event are found in Exhibit 4.2.3.14.

EXHIBIT 4.2.3.14 FLOOD/RAINFALL ANNUAL THREAT LIKELIHOOD

Recurrence Interval (years)	Annual Threat Likelihood
1	1/1
2	1/2
5	1/5
10	1/10
25	1/25
50	1/50
100	1/100
500	1/500

*Flood/Rain recurrence intervals do not necessarily constitute the same flow rate.

Step 2: Asset Data Collection

Exhibit 4.2.3.4 describes the data needs and sources to perform the risk assessment and values for this example are listed in the "Site Overview" section.

Step 3: Owner Consequence

The WRC for a flood-bridge approach event is estimated as 100% of bridge approach ARC plus $5,000 in cleanup costs, Exhibit 4.2.3.15. For this procedure, CDOT has defined the unit cost for bridge approaches to be $350/sq ft, Exhibit 4.2.3.16. To calculate area of bridge approaches, multiply the full width by the length of the bridge approach. Since both bridge approaches of Structure G-21-N are overtopped by 100-yr and 500-yr flood events, the owner consequence for each end of the structure are calculated:

EXHIBIT 4.2.3.15 SUMMARY OF WRC FOR OWNER CONSEQUENCE

		Threat			
		Debris Flow	Flood	Scour	Rockfall
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

EXHIBIT 4.2.3.16 UNIT COSTS

Asset	Units	Unit Cost
Bridge Approach**	sq ft	$350
Bridge*	sq ft	$600
Culvert***	cu ft	$55
PTCS**	sq ft	$550
Road Prism (Asphalt)**	sq yds	$150
Road Prism (Concrete)**	sq yds	$350

* Bridge area is defined as deck length multiplied by deck width, derived from NBI Items 49 and 52, respectively.

**Bridge approach, roadway and PTCS width are derived from CDOT OTIS Highways feature class using fields for lane width, lane count, and shoulder width.

***For culvert (CBC), the volume, in cubic feet, is calculated by multiplying the box height by the box width by the length. These values are derived from the culverts feature class maintained by C-PLAN, CDOT's interactive online mapping platform.

$$Owner\ Consequence = \left(100\%\ x \left((38ft\ x\ 20\ ft)\ x\ \frac{\$350}{sq\ ft}\right)\right) + \$5,000$$

$$Owner\ Consequence = \$266,000 + \$5,000$$

$$Owner\ Consequence = \$271{,}000$$

$$\boldsymbol{Owner\ Consequence = \$271{,}000\ per\ approach = \$542{,}000\ bridge}$$

Step 4: User Consequence

Calculating user consequence for flood-bridges approach events requires calculating vehicle and truck operating costs (VOC), as well as the value of lost wages and freight revenue (LW), for both full and partial closure (if applicable) as shown in Equations 3.2 through 3.8 and Equation 3.11.

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

User Consequence for Full Closure (FC)

As presented in Equations 3.3 and 3.4 user consequence is based on the calculation of VOC_{FC} and LW_{FC}. OTIS provides total average annual daily traffic (AADT) data for the I-70 facility, half of the AADT has been assigned to each direction of travel for the purposes of this analysis.

Utilizing Equation 3.5 along with User Consequences variables provided in Exhibit 4.2.3.7 and anticipated days of closure from Exhibit 4.2.3.8, the VOC_{FC} for full closure of bridge approaches during a flood event is calculated as follows:

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$ = 4,100 average annual daily traffic (non-truck)
$AADT_{Truck}$ = 1,400 average annual daily truck traffic
$C2$ = \$0.59 vehicle running cost (\$/vehicle-mile)
$C3$ = \$0.96 freight running cost (\$/truck-mile)
d_{FC} = 2 days of full closure
$C7$ = 71 miles difference between detour and original route

$$VOC_{FC} = \left(\left(\frac{\$0.59}{vehicle - mile}\ x\ 4{,}100\frac{vehicle}{day}\right) + \left(\frac{\$0.96}{truck - mile}\ x\ 1{,}400\frac{truck}{day}\right)\right)\ x\ 2\ days\ x\ 71\ miles$$

$$\boldsymbol{VOC_{FC} = \$534{,}346\ bridge = \$267{,}173\ per\ approach}$$

Next use Equation 3.6 to calculate lost wages and truck revenue for full closures:

EQUATION 3.6

$$LW_{FC} = \left((C4\ x\ O\ x\ AADT_{Vehicle}) + (C5\ x\ AADT_{Truck})\right) x\ d_{FC}\ x\ \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$	=	4,100 average annual daily traffic (non-truck)
$AADT_{Truck}$	=	1,400 average annual daily truck traffic
$C4$	=	\$10.62 average value of time (\$/hour-adult)
O	=	1.77 average occupancy (adult/vehicle)
$C5$	=	\$25.31 average value of freight time(\$/hour-truck)
d_{FC}	=	2 days of full closure
Dt	=	96 minutes of extra travel time on detour

$$LW_{FC} = \left(\left(\frac{\$10.62}{adult - hour}\ x\ 1.77\frac{adult}{vehicle}\ x\ 4{,}100\frac{vehicle}{day}\right) + \left(\frac{\$25.31}{truck - hour}\ x\ 1{,}400\frac{truck}{day}\right)\right) x\ 2\ days\ x\ \frac{96\ min}{60\ \frac{min}{hour}}$$

$$\boldsymbol{LF_{FC} = \$360{,}011\ bridge = \$\ 180{,}006\ per\ approach}$$

Finally, sum of vehicle operating costs incurred due to vehicle travel on detour and the lost wages and truck revenue due to travel on detour using Equation 3.3:

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

$$User\ Consequence_{FC} = \$534{,}346 + \$360{,}011$$

$$\boldsymbol{User\ Consequence_{FC} = \$894{,}357\ bridge = \$447{,}179\ per\ approach}$$

User Consequence for Partial Closure (PC):

Since partial closures are not anticipated at this site, VOC_{PC} and LW_{PC} for partial closure is estimated to be \$0:

$$VOC_{PC} = \$0$$

$$LW_{PC} = \$0$$

$$\boldsymbol{User\ Consequence_{PC} = \$0}$$

Total User Consequence:

Total user consequences include the sum of user consequence due to full and partial closures as shown in Equation 3.2.

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

$$Total\ User\ Consequence = \$894{,}357 + \$0$$

$$\boldsymbol{Total\ User\ Consequence = \$894,357\ bridge = \$447,179\ per\ approach}$$

Step 5: Vulnerability Assessment

The debris potential factor of the site during a flood event is determined using Exhibit 4.2.3.14 based on the provided data for low slope and shrubs as drainage basin landcover type. Based on a moderate debris potential, the vulnerability of each bridge approach can be obtained using Exhibits 4.2.3.15 and 4.2.3.16 and the following:

Bridge Characteristics:

- Hydraulic capacity = 50-yr (based on default value, Exhibit 4.2.3.4)

East Bridge Approach:

- Bridge Approach(s) length = 20 ft (based on default value, Exhibit 4.2.3.4)
- Bridge Approach width (NBI 32) = 38 ft
- Type of slope protection (PONTIS 326) = Riprap
- Slope protection condition (PONTIS 325) = Condition 2

West Bridge Approach:

- Bridge Approach(s) length = 20 ft (based on default value, Exhibit 4.2.3.4)
- Bridge Approach width (NBI 32) = 38 ft
- Type of slope protection (PONTIS 326) = Riprap
- Slope protection condition (PONTIS 325) = Condition 1

EXHIBIT 4.2.3.17 DEBRIS POTENTIAL TABLE

Mean Basin Site Slope	Landcover of Drainage Area: Water and Snow	Urban	Shrubs	Trees
Low (0-8%)	Very Low	Low	Moderate	Moderate
Moderate (9-16%)	Very Low	Moderate	High	High
High (>16%)	Very Low	High	High	Very High

The provided data is used in Exhibits 4.2.3.18 and 4.2.3.19 to determine the vulnerability of the bridge approaches for 100-yr and 500-yr flood events as shown here:

EXHIBIT 4.2.3.18 FLOOD-BRIDGE APPROACH VULNERABILITY FOR 100-YR EVENT MAGNITUDE

Flood Event Magnitude	Hydraulic Capacity	Slope Type	Slope Protection Condition	Debris Potential: Very Low	Low	Moderate	High	Very High
100-yr	100-yr	Wingwalls + Riprap	State 1	0.0008	0.0011	0.0036	0.0121	0.0221
			State 2	0.0015	0.0020	0.0066	0.0221	0.0403
			State 3	0.0040	0.0054	0.0181	0.0601	0.1096
		Wingwalls	State 1	0.0009	0.0012	0.0040	0.0134	0.0244
			State 2	0.0016	0.0022	0.0073	0.0244	0.0445
			State 3	0.0045	0.0060	0.0200	0.0664	0.1211
		Riprap	State 1	0.0010	0.0013	0.0045	0.0148	0.0270
			State 2	0.0018	0.0024	0.0081	0.0270	0.0492
			State 3	0.0049	0.0066	0.0221	0.0734	0.1339
		None	State 1	0.0045	0.0060	0.0200	0.0664	0.1211
			State 2	0.0081	0.0110	0.0364	0.1211	0.2209
			State 3	0.0221	0.0298	0.0992	0.3296	0.6010
	50-yr	Wingwalls + Riprap	State 1	0.0270	0.0364	0.1211	0.4027	0.7342
			State 2	0.0492	0.0664	0.2209	0.7342	0.9900
			State 3	0.1339	0.1808	0.6010	0.9900	0.9900
		Wingwalls	State 1	0.0298	0.0403	0.1339	0.4451	0.8115
			State 2	0.0544	0.0734	0.2441	0.8115	0.9900
			State 3	0.1480	0.1998	0.6643	0.9900	0.9900
		Riprap	State 1	0.0330	0.0445	0.1480	0.4919	0.8969
			State 2	0.0601	0.0812	0.2698	0.8969	0.9900
			State 3	0.1636	0.2209	0.7342	0.9900	0.9900
		None	State 1	0.1480	0.1998	0.6643	0.9900	0.9900
			State 2	0.2698	0.3643	0.9900	0.9900	0.9900
			State 3	0.7342	0.9900	0.9900	0.9900	0.9900

EXHIBIT 4.2.3.16 FLOOD-BRIDGE VULNERABILITY FOR 500-YR EVENT MAGNITUDE

Flood Event Magnitude	Hydraulic Capacity	Slope Type	Slope Protection Condition	Debris Potential: Very Low	Low	Moderate	High	Very High
500-yr	100-yr	Wingwalls + Riprap	State 1	0.0221	0.0298	0.0992	0.3296	0.6010
			State 2	0.0403	0.0544	0.1808	0.6010	0.9900
			State 3	0.1096	0.1480	0.4919	0.9900	0.9900
		Wingwalls	State 1	0.0244	0.0330	0.1096	0.3643	0.6643
			State 2	0.0445	0.0601	0.1998	0.6643	0.9900
			State 3	0.1211	0.1636	0.5437	0.9900	0.9900
		Riprap	State 1	0.0270	0.0364	0.1211	0.4027	0.7342
			State 2	0.0492	0.0664	0.2209	0.7342	0.9900
			State 3	0.1339	0.1808	0.6010	0.9900	0.9900
		None	State 1	0.1211	0.1636	0.5437	0.9900	0.9900
			State 2	0.2209	0.2982	0.9900	0.9900	0.9900
			State 3	0.6010	0.8115	0.9900	0.9900	0.9900
	50-yr	Wingwalls + Riprap	State 1	0.7342	0.9900	0.9900	0.9900	0.9900
			State 2	0.9900	0.9900	0.9900	0.9900	0.9900
			State 3	0.9900	0.9900	0.9900	0.9900	0.9900
		Wingwalls	State 1	0.8115	0.9900	0.9900	0.9900	0.9900
			State 2	0.9900	0.9900	0.9900	0.9900	0.9900
			State 3	0.9900	0.9900	0.9900	0.9900	0.9900
		Riprap	State 1	0.8969	0.9900	0.9900	0.9900	0.9900
			State 2	0.9900	0.9900	0.9900	0.9900	0.9900
			State 3	0.9900	0.9900	0.9900	0.9900	0.9900
		None	State 1	0.9900	0.9900	0.9900	0.9900	0.9900
			State 2	0.9900	0.9900	0.9900	0.9900	0.9900
			State 3	0.9900	0.9900	0.9900	0.9900	0.9900

Using Exhibits 4.2.3.18 and 4.2.3.18 vulnerability of the bridge approaches for a 100-yr flood event is $V_{100\text{-yr}}$ = 0.2698 (east bridge approach) and $V_{100\text{-yr}}$ = 0.1480 (west bridge approach) and for a 500-yr flood event to be $V_{500\text{-yr}}$ = 0.9900 (east bridge approach) and $V_{500\text{-yr}}$ = 0.9900 (west bridge approach).

Step 6. Risk Assessment

Annual Owner Risk Calculation

Calculate total annual owner risk by multiplying the threat likelihood by the owner consequences by the vulnerability for each event magnitude studied, then sum the annual owner risk for all events utilizing Equation 3.9:

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ Risk_i = Owner\ Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

Exhibit 4.2.3.20 includes the annual owner risk for each bridge approach:

EXHIBIT 4.2.3.20 ANNUAL OWNER RISK DETAIL CALCULATIONS

Bridge Approach Location	Flood Event Magnitude	Owner Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual Owner Risk ($)
East	100-yr	$271,000	0.1480	1/100	$401
West		$271,000	0.2698		$731
East	500-yr	$271,000	0.99	1/500	$537
West		$271,000	0.99		$537
				TOTAL	**$2,206**

Exhibit 4.2.3.21 includes the annual owner risk for the site:

EXHIBIT 4.2.3.21 ANNUAL OWNER RISK CALCULATIONS

Bridge Approach Location	Annual Owner Risk 100-yr ($)	Annual Owner Risk 500-yr ($)	Total Annual Owner Risk ($)
East	$401	$537	$938
West	$731	$537	$1,268
		TOTAL	**$2,206**

Annual User Risk Calculation

Calculate total annual user risk by multiplying the threat likelihood by the user consequences by the vulnerability for each event magnitude analyzed, then sum the annual owner risk for all events utilizing Equation 3.11:

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ Risk_i = Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

Exhibits 4.2.3.22 includes the annual user for each bridge approach:

EXHIBIT 4.2.3.22 ANNUAL USER RISK DETAIL CALCULATIONS

Bridge Approach Location	Flood Event Magnitude	User Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual User Risk ($)
East	100-yr	$447,179	0.1480	1/100	$662
West		$447,179	0.2698		$1,206
East	500-yr	$447,179	0.9900	1/500	$885
West		$447,179	0.9900		$885
				TOTAL	**$3,638**

Exhibit 4.2.3.23 includes the annual user risk for the site:

EXHIBIT 4.2.3.23 ANNUAL USER RISK CALCULATIONS

Bridge Approach Location	Annual User Risk 100-yr ($)	Annual User Risk 500-yr ($)	Total Annual User Risk ($)
East	$662	$885	$1,547
West	$1,206	$885	$2,091
		TOTAL	**$3,638**

Total Annual Risk Calculation

Calculate total annual risk by adding total annual owner risk to total annual user risk utilizing Equation 3.13:

EQUATION 3.13

$$Total\ Annual\ Risk\ = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

Where n= number of events

Exhibit 4.2.3.24 presents the total annual risk for the site:

EXHIBIT 4.2.3.24 TOTAL ANNUAL RISK CALCULATIONS

Bridge Approach Location	Annual Owner Risk ($)	Annual User Risk ($)	Total Annual Risk ($)
East	$938	$1,547	$2,485
West	$1,268	$2,091	$3,359
		TOTAL	$5,844

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4.2.4 Flood Minor Culvert Risk Assessment

A *culvert* is defined as "a structure used to convey surface runoff through embankment" and as "a structure, as distinguished from bridges, that is usually covered with embankment and is composed of structural material around the entire perimeter…" (Colorado Department of Transportation - CDOT, 2004).

For purposes of this procedure, culverts are divided in minor and major culverts. *Minor culverts* are considered structures with 20 feet or less in centerline span width between extreme ends of openings and major culverts are greater than 20 feet in span width. Minor culverts include concrete, metal, and plastic pipes. Some of these culverts might be potentially vulnerable to multiple threat including flooding.

Exhibit 4.2.4.1 includes examples of damage from flood to minor culverts.

EXHIBIT 4.2.4.1 DAMAGE TO MINOR CULVERTS DURING 2013 FLOOD EVENT

Exhibit 4.2.4.2 illustrates the basic methodology and steps used in risk analysis of flooding to minor culvert.

EXHIBIT 4.2.4.2 FLOOD-MINOR CULVERT RISK ASSESSMENT METHODOLOGY

Step 1: Threat Data Collection
Flood Annual Likelihood (Exhibit 4.2.4.4)

↓

Step 2: Asset Data Collection
Asset (Minor Culvert) Data Needs (Exhibit 4.2.4.5)

↓

Step 3: Owner Consequence Calculation
Owner Worst Reasonable Case (WRC) for Flood-Minor Culvert (Exhibit 4.2.4.6)
Minor Culvert Unit Cost Estimation (Exhibit 4.2.4.7)

↓

Step 4: User Consequence Calculation
User Worst Reasonable Case (WRC) for Threat-Asset Pair (Exhibit 4.2.4.6)
Vehicle Operating Cost (VOC) and Lost of Wages (LW) (Exhibit 4.2.4.8)
Detour Estimation (Extra Travel Length and Time) (Exhibits 4.2.4.9 and 4.2.4.10)
Calculations (Equations 3.5 through 3.8)

↓

Step 5: Vulnerability Assessment
Flood-Minor Culvert Vulnerability (Exhibits 4.2.4.8 and 4.2.4.9)

↓

Step 6: Risk Assessment
Annual Owner Risk Calculation (Equation 3.9)
Annual User Risk Calculation (Equations 3.2 through 3.8 and 3.11)
Annual Total Risk (Equation 3.13)

Computational Steps

Step 1: Threat Data Collection

The traditional method for conducting flood frequency (threat likelihood) analysis is to use historical records of peak flows to estimate the expected behavior of future flooding. This information is used to estimate the frequency of occurrence of various magnitude

floods at specific locations (e.g. 100-yr flood events). Peak flows can either be determined by CDOT Hydraulic Staff or by Stream Stats, which has been deemed acceptable by the CDOT subject matter experts for this procedure.

In order to determine if a minor culvert may be at risk to flooding, it is necessary to determine if the culvert flow capacity is exceeded by the anticipated flow of a specific rain event. For example, if the peak flow (**Q_{EVENT}**) for a 100-yr rain event is greater than the design flow (**Q_{DESIGN}**) of the culvert, a risk analysis should be performed. If the peak flow is less than that of the design flow of the culvert, it is assumed that the culvert passes the flow with no damage and no analysis will be performed. Note, this approach is acceptable for planning level analysis of risk to minor culverts from flooding, however, more detailed hydraulic analysis is typically utilized when determining specific mitigation required for project level culvert design.

EXHIBIT 4.2.4.3 EXAMPLE Q_{EVENT}/Q_{DESIGN} RATIO CALCULATIONS

Rainfall Event Magnitude	Q_{EVENT} (cfs)	Q_{DESIGN} (cfs)	Q_{EVENT}/Q_{DESIGN}
25-yr	33	55	0.60*
50-yr	44	55	0.80*
100-yr	56	55	1.02

* Q_{EVENT}/Q_{DESIGN} is less than or equal to one anticipated risk is negligible .

The corresponding annual threat likelihood for different flood events are included in Exhibit 4.2.4.4. Note, this approach does not consider increases in threat likelihood due to climate change.

EXHIBIT 4.2.4.4 FLOOD/RAINFALL ANNUAL THREAT LIKELIHOOD

Recurrence Interval (years)	Annual Threat Likelihood
1	1/1
2	1/2
5	1/5
10	1/10
25	1/25
50	1/50
100	1/100
500	1/500

*Flood/Rain recurrence intervals do not necessarily constitute the same flow rate.

Step 2: Asset Data Collection

Data needed to assess the annual risk from flood events includes asset replacement costs (ARC), user costs, and vulnerability. The CDOT Authoritative Culvert ArcGIS Online (C-Plan), USGS National Map, and USDA Natural Resources Conservation Services provides the necessary information to calculate the minor culvert ARC and vulnerability. The OTIS Highways feature class provides traffic volumes and site characteristics for calculating user consequences. Exhibit 4.2.4.5 provides a summary of the data needed and sources to assess risk for flood-minor culvert.

EXHIBIT 4.2.4.5 DATA NEEDS FOR FLOOD-MINOR CULVERT RISK ANALYSIS

	Data Needs	Data Source
Asset Replacement Cost	**Culvert Identification Number (ID)**	CDOT Authoritative Culvert ArcGIS Online (C-Plan) https://cdot.maps.arcgis.com/home/index.html
	Culvert Dimensions	CDOT Authoritative Culvert ArcGIS Online (C-Plan) https://cdot.maps.arcgis.com/home/index.html
Vulnerability	**Culvert Condition**	CDOT Authoritative Culvert ArcGIS Online (C-Plan) https://cdot.maps.arcgis.com/home/index.html
	Peak Flow Culvert Design (Q_{DESIGN})	CDOT Design Plans or FHWA Hydraulic Design of Highway Culverts (HDSN 5)
	Peak Flow at Different Rain Events at the Culvert Under Analysis (Q_{EVENT})	CDOT Hydraulic Staff or Stream Stats https://streamstats.usgs.gov/ss/
	Drainage Basin Landcover Type	National Landcover Data Base https://www.mrlc.gov/data/nlcd-2016-land-cover-conus
	Mean Basin Slope	Stream Stats https://streamstats.usgs.gov/ss/
User Consequences	**AADT Vehicles**	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	AADT Trucks	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Roadway Damaged	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Detour	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Detour Distance	CDOT Operations
	Detour Time	CDOT Operations
	Number of Closure Days	See Exhibit 4.2.4.9
	Number of Partial Closure Days	See Exhibit 4.2.4.9
	Average Vehicle Occupancy	FHWA https://www.fhwa.dot.gov/tpm/guidance/avo_factors.pdf
	Car Running Costs	(RITA)/Texas A&M Transportation Institute
	Truck Running Costs	American Transportation Research Institute
	Average Value of Time	(RITA)/Texas A&M Transportation Institute

Step 3: Owner Consequence Assessment

Owner consequence measures the impact to the owner (CDOT) in terms of cost of repairs, cleanup, maintenance, and related agency operational costs. The most severe but credible consequence Worst Reasonable Consequence (WRC) for flood-minor culvert, based on past emergency repair projects, is estimated as 100% the asset replacement cost, which includes the items necessary to replace culvert, including the roadway prism costs, of the culvert where the peak flow of the rain event is greater than the peak flow design of the culvert plus $5,000 in cleanup costs.

EXHIBIT 4.2.4.6 SUMMARY OF WRC FOR OWNER CONSEQUENCE

		Threat			
		Debris Flow	**Flood**	**Scour**	**Rockfall**
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

EXHIBIT 4.2.4.7 UNIT COSTS FOR MINOR CULVERTS

Pipe Diameter (in)	**Unit Cost ($/lin ft)**
<48	2,205
48	2,225
54	2,660
60	3,135
66	3,660
72	4,235
78	4,865
84	5,550
90	10,325
96	11,690
102	13,160
108	14,770
120	18,325
138	24,695

Step 4: User Consequence Assessment

User consequences measure the impact to the public in terms of lost wages and increased vehicle operating costs due to delays, detours, and longer drive times. Required inputs include AADT, percent truck traffic, average vehicle occupancy, average hourly wage, detour length, work zone length, speed on detour, number of days of closure, and number of days of partial closure. For user consequences, the estimated WRC from flood on a minor culvert is considered failure of the culvert and is based on full closures to traffic. For further explanation on how to calculate user consequences see Equations 3.2 through 3.8 and 3.11.

Exhibit 4.2.4.8 provides default values for a range of factors associated with the cost associated with operating vehicles, value of time, and occupancy that are updated annually by the various federal government agencies. Note the values included in Exhibit 4.2.4.8 were gathered in June of 2019 and will vary in future years.

EXHIBIT 4.2.4.8 CONSTANTS USED IN USER CONSEQUENCE CALCULATIONS

User Cost Terms	Variable	Value	Year Published
Average Vehicle Occupancy	*O*	1.77	2019
Car Running Cost per Mile	*C2*	$0.59	2019
Truck Running Cost per Mile	*C3*	$0.96	2015
Average Value of Time per Adult per Hour	*C4*	$10.62	2015
Average Value of Freight Driver Cost per Hour	*C5*	$25.31	2015
Car Running Cost per Hour	*C8*	$26.52	2015
Truck Running Cost per Hour	*C9*	$44.24	2015

The suggested number of full and partial closure days, derived from the I-70 Pilot, are provided in Exhibit 4.2.4.9. It is suggested that this table be used as guidance for all other corridor's for estimating closures days, both full and partial.

EXHIBIT 4.2.4.9 I-70 RISK AND RESILIENCE PILOT NUMBER OF FULL CLOSURE AND PARTIAL CLOSURE DAYS FOR WRC

Asset	Threat	Full Closure Days (d_{FC})	Partial Closure Days (d_{PC})
Bridge Approach	All	2	0
Bridge	Flood	180	0
Bridge	Debris Flow	2	0
Bridge	Rockfall	4	14
Culvert	Debris Flow	1	0
Culvert	Flood	3	0
PTCS	Rockfall	4	14
Roadway (<=% Width)	Flood	1	0
Roadway (> 50% Width)	Flood	3	0
Roadway (2 Directions)	Flood	3	0
Roadway	Rockfall	4	14

Example detours used for the I-70 Risk and Resilience Pilot and the worked examples in this document are listed in Exhibit 4.2.4.10. Note that *Additional Travel Distance* refers to the additional miles a traveler must travel on detour in comparison to the original route, and *Additional Travel Time* is the additional time a traveler must travel on detour in comparison to the original route. CDOT Operations can provide further guidance on estimating detours from closures for highways other than I-70.

EXHIBIT 4.2.4.10 I-70 RISK AND RESILIENCE PILOT DETOUR TABLE

Starting Milepost	Ending Milepost	Additional Travel Distance (miles) (*C7*)	Additional Travel Time (minutes) (*Dt*)
1	14	146	189
14	90	90	112
90	155	140	167
155	205	98	126
205	231	83	109
231	245	49	77
245	288	3	7
288	353	15	24
353	360	71	96
360	404	76	73
404	438	69	70
438	450	63	77

Total User Consequences is the sum of user consequence due to full and partial closures as shown in Equation 3.2.

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

Where:

User Consequence$_{FC}$	=	User consequences due to full closure
User Consequence$_{PC}$	=	User consequences due to partial closure

User consequences for full closure are the sum of vehicle operating costs incurred due to travel on detour, lost wages, and truck revenue due to travel on detour as shown in Equation 3.3.

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

Where:

VOC_{FC}	=	Vehicle operating costs incurred due to full closure
LW_{FC}	=	Lost wages/truck revenue incurred due to full closure

User consequences for partial closures are the sum of vehicle operating costs incurred due to traffic delays, lost wages, and truck revenue due to delays incurred while driving through a partial closure as shown in Equation 3.4.

EQUATION 3.4

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

Where:

VOC_{PC}	=	Vehicle operating costs incurred due to partial closure
LW_{PC}	=	Lost wages/truck revenue incurred due to partial closure

Equation 3.5 is the equation for calculating vehicle operating costs for full closures.

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C2$	=	Vehicle running cost ($/vehicle-mile)
$C3$	=	Freight running cost ($/truck-mile)
d_{FC}	=	Number of full closure days (days)
$C7$	=	Difference in distance between detour and original route (mile)

Equation 3.6 is used for calculating lost wages and truck revenue for full closures.

EQUATION 3.6

$$LW_{FC} = \left(\left(C4\ x\ O\ x\ AADT_{Vehicle}\right) + \left(C5\ x\ AADT_{Truck}\right)\right)\ x\ d_{FC}\ x\ \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C4$	=	Average value of time ($/adult-hour)
O	=	Average occupancy (adult/vehicle)
$C5$	=	Average value of freight time($/truck-hour)
d_{FC}	=	Number of full closure days (days)
Dt	=	Extra travel time on detour (minutes)

Equation 3.7 is used for calculating vehicle operating costs due to partial closures.

EQUATION 3.7

$$VOC_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right)\ x\ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right)x\ WZS}\right)\ x\ \left(\left(C8\ x\ AADT_{Vehicle}\right) + \left(C9\ x\ AADT_{Truck}\right)\right)\ x\ d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C8$	=	Vehicle running cost ($/vehicle-hour)
$C9$	=	Freight running cost ($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Equation 3.8 is used for calculating lost wages and truck revenue due to partial closures.

EQUATION 3.8

$$LW_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x\ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x\ WZS}\right) x\ ((C4\ x\ AADT_{Vehicle}\ x\ O) + (C5\ x\ AADT_{Truck}))\ x\ d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C4$	=	Average value of time ($/adult-hour)
O	=	Average occupancy (adult/vehicle)
$C5$	=	Average value of freight time($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Calculate total annual user risk by multiplying the owner consequences by the vulnerability for each magnitude of event the threat likelihood then summing the annual user risk for all events, utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ \boldsymbol{R}isk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n = number of events

Step 5. Vulnerability Assessment

Vulnerability of minor culverts from flood events is based on multiple factors. For this procedure, the vulnerability table for minor culverts for flood risk was developed based on CDOT hydraulic and maintenance staff expert opinion and empirical data gathered from recent flood events. The factors identified include: terrain and debris potential. The debris potential of the site during a flood event is determined based on the landcover of the drainage basin area and the slope of the surrounding drainage area. Exhibit 4.2.4.11 (introduced in the flood-bridge section) presents the debris potential table to determine minor culvert vulnerability.

Utilizing the debris potential factor obtained with Exhibit 4.2.4.11 along with the Q_{EVENT}/Q_{DESIGN} ratio and culvert condition, the vulnerability of minor culverts can be obtained using Exhibit 4.2.4.12.

EXHIBIT 4.2.4.11 DEBRIS POTENTIAL TABLE

Mean Basin Site Slope	Landcover of Drainage Area: Water and Snow	Urban	Shrubs	Trees
Low (0-8%)	Very Low	Low	Moderate	Moderate
Moderate (9-16%)	Very Low	Moderate	High	High
High (>16%)	Very Low	High	High	Very High

EXHIBIT 4.2.4.12 FLOOD-MINOR CULVERT VULNERABILITY

Q_{EVENT}/Q_{DESIGN}	Culvert Condition	Debris Potential: Very Low	Low	Moderate	High	Very High
1 - 2	Good	0.05	0.06	0.08	0.13	0.30
	Fair	0.07	0.08	0.12	0.18	0.42
	Poor	0.25	0.30	0.42	0.64	0.99
2.1 - 3	Good	0.08	0.09	0.13	0.20	0.47
	Fair	0.10	0.13	0.18	0.27	0.64
	Poor	0.38	0.47	0.64	0.99	0.99
3.1 - 4	Good	0.18	0.22	0.30	0.47	0.99
	Fair	0.25	0.30	0.42	0.64	0.99
	Poor	0.89	0.99	0.99	0.99	0.99
> 4	Good	0.64	0.80	0.99	0.99	0.99
	Fair	0.89	0.99	0.99	0.99	0.99
	Poor	0.99	0.99	0.99	0.99	0.99

Step 6. Risk Calculation

Annual Owner Risk

As noted in Step 3, the owner consequence for flood-minor culvert events is based on the defined WRC for the owner. Annual owner risk is calculated for each rain event magnitude where the Q_{EVENT} is greater than the Q_{DESIGN} utilizing the owner consequence (Step 3), vulnerability (Step 5), and threat likelihood (Step 1) multiplying all factors and utilizing Equation 3.9.

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ \boldsymbol{R}isk_i = Owner\ \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n = number of events

Annual User Risk

The user consequence for flood-minor culvert events is based on the defined WRC for roadway users. The annual user risk is calculated for each rain event magnitude where the Q_{EVENT} is greater than the Q_{DESIGN} utilizing the user consequence (from Step 4), vulnerability (from Step 5), and threat likelihood (from Step 1) multiplying all factors and utilizing to Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ \boldsymbol{R}isk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n = number of events

Total Annual Risk

The total annual risk for flood-minor culvert events includes annual owner risk and annual user risk from all relevant rain event magnitudes where the Q_{EVENT} is greater than Q_{DESIGN}. Equation 3.13 can be used to estimate total annual risk.

EQUATION 3.13

$$Total\ Annual\ Risk = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

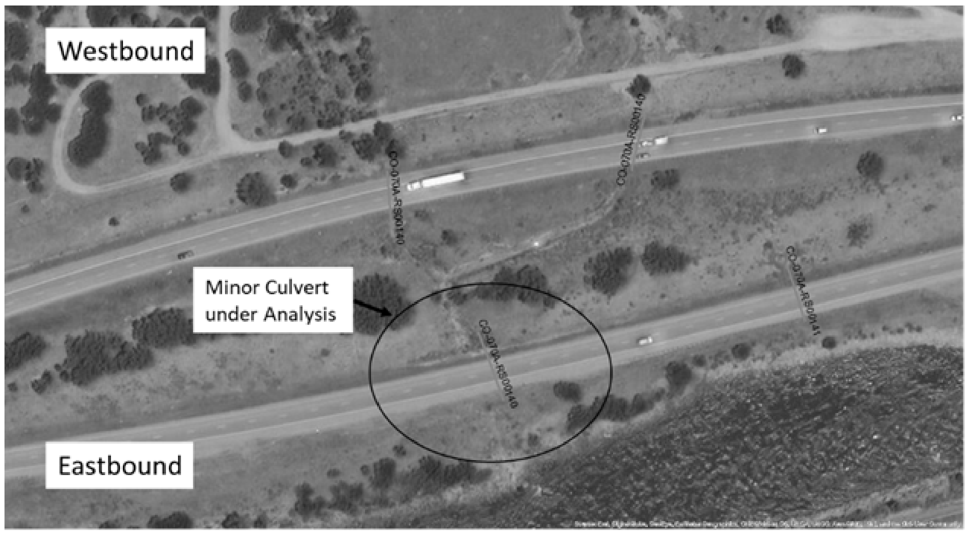
Where n= number of events

An example problem demonstrating the use of this approach is provided next.

Example Problem – Flood-Minor Culvert Risk Assessment

This example demonstrates the risk assessment methodology developed for flood-minor culvert events presented in Exhibit 4.2.4.2. The task is to calculate the annual owner risk, user risk, and total risk from flooding to a minor culvert at milepost 112.9 (eastbound) on I-70 in Garfield County as shown in Exhibit 4.2.4.13. As shown in Exhibit 4.2.4.13, there is a series of three minor culverts in this location. For demonstration purposes, only the minor culvert located in the eastbound lanes will be analyzed.

EXHIBIT 4.2.4.13 EXAMPLE FLOOD-MINOR CULVERT SITE, I-70, MP 112.9 GARFIELD COUNTY



Site Overview

- Location: I-70, MP 112.9 Garfield County
- Four-lane freeway (two-lanes in each direction)
- <u>Eastbound culvert</u>:
    - Culvert ID: 070AA112930EL (GIS Link CUL070A395268112)
    - Culvert type: corrugated metal pipe (CMP)
    - Culvert diameter: <48-inch (36-inch)
    - Culvert length = 78 ft
    - Culvert condition: Fair
    - Unit cost for 54-inch, minor culvert = $2,205/lin ft
    - Peak flow culvert design = 55 cfs
    - Peak flow 25-yr rain event = 33 cfs
    - Peak flow 50-yr rain event = 44 cfs
    - Peak flow 100-yr rain event = 56 cfs
- Mean basin slope: 49% (high)
- Drainage basin landcover type: Trees
- Total I-70 $AADT_{Vehicle}$ = 20,928 vehicles
- Total I-70 $AADT_{Truck}$ = 3,072 trucks
- Detour length = 140 miles
- Extra travel time on detour = 167 minutes
- Number of days of full closure = 3 days
- Number of days of partial closure = 0 days

Following the flood-minor culvert methodology presented in Exhibit 4.2.4.2:

Step 1: Threat Data Collection

In order to identify the annual threat likelihoods to be used in the analysis, the Q_{EVENT}/Q_{DESIGN} ratios for the rain events must be determined as follows:

EXHIBIT 4.2.4.14 Q_{EVENT}/Q_{ESIGN} RATIO CALCULATIONS

Rainfall Event Magnitude	Q_{EVENT} (cfs)	Q_{DESIGN} (cfs)	Q_{EVENT}/Q_{DESIGN}
25-yr	33	55	0.60
50-yr	44	55	0.80
100-yr	56	55	1.02

Since the peak flows for both the 25-yr and 50-yr events are less than that of the design flow of the culvert, it is assumed that the culvert passes the flow with no damage and no analysis will be performed

The rain event magnitudes that generate Q_{EVENT}/Q_{DESIGN} greater than or equal 1.0 will be used in the analysis based on Exhibit 4.2.4.14. It is assumed that the culvert, Q_{DESIGN}, passes the Q_{EVENT}. Annual treat likelihood for these events are estimated using Exhibit 4.2.4.15.

EXHIBIT 4.2.4.15 FLOOD/RAINFALL ANNUAL THREAT LIKELIHOOD

Recurrence Interval (years)	Annual Threat Likelihood
1	1/1
2	1/2
5	1/5
10	1/10
25	1/25
50	1/50
100	1/100
500	1/500

*Flood/Rain recurrence intervals do not necessarily constitute the same flow rate.

Step 2: Asset Data Collection

Exhibit 4.2.4.2 describes the data needs and sources to perform the risk assessment. Actual values are listed in the "Site Overview" section.

Step 3: Owner Consequence

For this procedure, CDOT has established the unit cost of minor culverts based on culvert diameter. The culvert under analysis has a diameter of <48 inch. From Exhibit 4.2.4.16, the unit cost for the pipe is $2,205/lin ft. The unit cost includes all necessary items to replace the asset.

EXHIBIT 4.2.4.16 UNIT COSTS FOR MINOR CULVERTS

Pipe Diameter (in)	Unit Cost ($/lin ft)
<48	2,205
48	2,225
54	2,660
60	3,135
66	3,660
72	4,235
78	4,865
84	5,550
90	10,325
96	11,690
102	13,160
108	14,770
120	18,325
138	24,695

EXHIBIT 4.2.4.17 SUMMARY OF WRC FOR OWNER CONSEQUENCE

		Threat			
		Debris Flow	**Flood**	**Scour**	**Rockfall**
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

The owner consequence can be calculated, from Exhibit 4.2.4.17, as follows:

$$Owner\ Consequence = \left(100\%\ x\ (\frac{\$2{,}205}{lin\ ft}\ \ x\ 78\ lin\ ft)\right) + \$5{,}000$$

$$Owner\ Consequence = \$171{,}990 + \$5{,}000$$

$$\boldsymbol{Owner\ Consequence} = \$\mathbf{176,990}$$

Step 4: User Consequence

Calculating user consequence for flood-minor culvert events requires calculating vehicle and truck operating costs (VOC), as well as the value of lost wages and freight revenue (LW), for both full and partial closure (if applicable) as shown in Exhibits 4.2.4.8 through 4.2.4.10 and Equations 3.2 through 3.8 and Equation 3.11.

$$Total\ User\ Consequence = User\ Consequence_{FC} +\ User\ Consequence_{PC}$$

$$User\ Consequence_{FC} = VOC_{FC} +\ LW_{FC}$$

$$User\ Consequence_{PC} = VOC_{PC} +\ LW_{PC}$$

Total User Consequences is the sum of user consequence due to full and partial closures as shown in Equation 3.2.

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} +\ User\ Consequence_{PC}$$

Where:

$User\ Consequence_{FC}$	=	User consequences due to full closure
$User\ Consequence_{PC}$	=	User consequences due to partial closure

User consequences for full closure are the sum of vehicle operating costs incurred due to travel on detour, lost wages, and truck revenue due to travel on detour as shown in Equation 3.3.

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} +\ LW_{FC}$$

Where:

VOC_{FC}	=	Vehicle operating costs incurred due to full closure
LW_{FC}	=	Lost wages/truck revenue incurred due to full closure

User consequences for partial closures are the sum of vehicle operating costs incurred due to traffic delays, lost wages, and truck revenue due to delays incurred while driving through a partial closure as shown in Equation 3.4.

EQUATION 3.4

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

Where:

VOC_{PC} = Vehicle operating costs incurred due to partial closure
LW_{PC} = Lost wages/truck revenue incurred due to partial closure

Equation 3.5 is the equation for calculating vehicle operating costs for full closures.

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$ = Average annual daily traffic (non-truck)
$AADT_{Truck}$ = Average annual daily truck traffic
$C2$ = Vehicle running cost ($/vehicle-mile)
$C3$ = Freight running cost ($/truck-mile)
d_{FC} = Number of full closure days (days)
$C7$ = Difference in distance between detour and original route (mile)

Equation 3.6 is used for calculating lost wages and truck revenue for full closures.

EQUATION 3.6

$$LW_{FC} = \left((C4\ x\ O\ x\ AADT_{Vehicle}) + (C5\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$ = Average annual daily traffic (non-truck)
$AADT_{Truck}$ = Average annual daily truck traffic
$C4$ = Average value of time ($/adult-hour)
O = Average occupancy (adult/vehicle)
$C5$ = Average value of freight time($/truck-hour)
d_{FC} = Number of full closure days (days)
Dt = Extra travel time on detour (minutes)

Equation 3.7 is used for calculating vehicle operating costs due to partial closures.

EQUATION 3.7

$$VOC_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x \, (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x \, WZS} \right) x \left((C8 \; x \; AADT_{Vehicle}) + (C9 \; x \; AADT_{Truck}) \right) x \; d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C8$	=	Vehicle running cost ($/vehicle-hour)
$C9$	=	Freight running cost ($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Equation 3.8 is used for calculating lost wages and truck revenue due to partial closures.

EQUATION 3.8

$$LW_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x \, (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x \, WZS} \right) x \left((C4 \; x \; AADT_{Vehicle} \; x \; O) + (C5 \; x \; AADT_{Truck}) \right) x \; d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C4$	=	Average value of time ($/adult-hour)
O	=	Average occupancy (adult/vehicle)
$C5$	=	Average value of freight time($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Calculate total annual user risk by multiplying the owner consequences by the vulnerability for each magnitude of event the threat likelihood then summing the annual user risk for all events, utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ \boldsymbol{R}isk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n = number of events

User Consequence for Full Closure (FC)

As presented in Equations 3.3 and 3.4, user consequence is based on the calculation of VOC_{FC} and LW_{FC}. Given the OTIS database provides total average annual daily traffic (AADT) data for the entire facility, half of the AADT has been assigned to each direction of travel for the purposes of this analysis.

Utilizing Equation 3.5, parameters presented in Exhibit 4.2.4.8 and closure days presented in Exhibit 4.2.4.9, the VOC_{FC} for full closure for the roadway during a flood event is calculated:

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$	=	10,464 average annual daily traffic (non-truck)
$AADT_{Truck}$	=	1,536 average annual daily truck traffic
$C2$	=	$0.59vehicle running cost ($/vehicle-mile)
$C3$	=	$0.96 freight running cost ($/truck-mile)
d_{FC}	=	3 days of full closure
$C7$	=	140 miles difference in distance between detour and original route

$$VOC_{FC} = \left(\left(\frac{\$0.59}{vehicle - mile}\ x\ 10{,}464\frac{vehicle}{day}\right) + \left(\frac{\$0.96}{truck - mile}\ x\ 1{,}536\frac{truck}{day}\right)\right)\ x\ 3\ days\ x\ 140\ miles$$

$$\boldsymbol{VOC_{FC}} = \$\mathbf{3,212,294}$$

Next use Equation 3.6 to calculate lost wages and truck revenue for full closures:

EQUATION 3.6

$$LW_{FC} = \left((C4 \ x \ O \ x \ AADT_{Vehicle}) + (C5 \ x \ AADT_{Truck})\right) x \ d_{FC} \ x \ \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$	=	10,464 average annual daily traffic (non-truck)
$AADT_{Truck}$	=	1,536 average annual daily truck traffic
$C4$	=	\$10.62 average value of time (\$/hour-adult)
O	=	1.77 average occupancy (adult/vehicle)
$C5$	=	\$25.31 average value of freight time(\$/hour-truck)
d_{FC}	=	3 days of full closure
Dt	=	167 minutes of extra travel time on detour

$$LW_{FC} = \left(\left(\frac{\$10.62}{adult - hour} \ x \ 1.77 \frac{adult}{vehicle} \ x \ 10{,}464 \frac{vehicle}{day}\right) + \left(\frac{\$25.31}{truck - hour} \ x \ 1{,}536 \frac{truck}{day}\right)\right) x \ 3 \ days \ x \ \frac{167 \ min}{60 \ \frac{min}{hour}}$$

$$\boldsymbol{LW_{FC} = \$1,967,027}$$

Finally, sum of vehicle operating costs incurred due to vehicle travel on the detour and the lost wages and truck revenue due to travel on the detour utilizing Equation 3.3:

EQUATION 3.3

$$User \ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

$$User \ Consequence_{FC} = \$3{,}212{,}294 + \$1{,}967{,}027$$

$$\boldsymbol{User \ Consequence_{FC} = \$5,179,321}$$

User Consequence for Partial Closure (PC):

Since partial closure is not applicable on this site, VOC_{PC} and LW_{PC} for partial closure is estimated to be \$0:

$$VOC_{PC} = \$0$$

$$LW_{PC} = \$0$$

$$\boldsymbol{User \ Consequence_{PC} = \$0}$$

Total User Consequence:

Total user consequences include the sum of user consequence due to full closure and user consequence due to partial closures as shown in Equation 3.2:

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + \ User\ Consequence_{PC}$$

$$Total\ User\ Consequence = \$5{,}179{,}321 + \$0$$

$$\boldsymbol{Total\ User\ Consequence} = \$\mathbf{5{,}179{,}321}$$

Step 5: Vulnerability Assessment

The debris potential factor of the site during a flood event is determined using Exhibit 4.2.4.18 and with the provided data, high slope and trees as drainage basin landcover type:

EXHIBIT 4.2.4.18 DEBRIS POTENTIAL TABLE

Mean Basin Site Slope	Landcover of Drainage Area: Water and Snow	Urban	Shrubs	Trees
Low (0-8%)	Very Low	Low	Moderate	Moderate
Moderate (9-16%)	Very Low	Moderate	High	High
High (>16%)	Very Low	High	High	Very High

It is determined that the debris potential factor of the site is “Very High”. Exhibit 4.2.4.19 is used to determine the minor culvert vulnerability. In addition, the Q_{EVENT}/Q_{DESIGN} ratios for the 25-yr and 50-yr events that were calculated in Step 1 mandate that risk not be analyzed for rain events as Q_{DESIGN} passes the Q_{EVENT}.

EXHIBIT 4.2.4.19 FLOOD-MINOR CULVERT VULNERABILITY

Q_{EVENT}/Q_{DESIGN}	Culvert Condition	Debris Potential				
		Very Low	Low	Moderate	High	Very High
1 - 2	Good	0.05	0.06	0.08	0.13	0.30
	Fair	0.07	0.08	0.12	0.18	0.42
	Poor	0.25	0.30	0.42	0.64	0.99
2.1 - 3	Good	0.08	0.09	0.13	0.20	0.47
	Fair	0.10	0.13	0.18	0.27	0.64
	Poor	0.38	0.47	0.64	0.99	0.99
3.1 - 4	Good	0.18	0.22	0.30	0.47	0.99
	Fair	0.25	0.30	0.42	0.64	0.99
	Poor	0.89	0.99	0.99	0.99	0.99
> 4	Good	0.64	0.80	0.99	0.99	0.99
	Fair	0.89	0.99	0.99	0.99	0.99
	Poor	0.99	0.99	0.99	0.99	0.99

The Q_{EVENT}/Q_{DESIGN} ratios calculated in Step 1 for the 25-yr and 50-yr events are less than 1, the vulnerabilities are $V_{25\text{-}yr} = 0$ and $V_{50\text{-}yr} = 0$. Using Exhibit 4.2.4.19, the vulnerability of the minor culvert for the100-yr rain events is found to be: $V_{100\text{-}yr} = 0.42$.

Step 6: Risk Assessment

Annual Owner Risk Calculation

Calculate total annual owner risk by multiplying the threat likelihood by the owner consequences by the vulnerability for each event, then summing the annual owner risk for all events analyzed utilizing Equation 3.9:

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ Risk_i = Owner\ Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

Exhibit 4.2.4.20 includes the annual owner risk findings for rain events analyzed:

EXHIBIT 4.2.4.20 ANNUAL OWNER RISK CALCULATIONS

Rain Event Magnitude	Owner Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual Owner Risk ($)
25-yr	$212,480	0	1/25	$0
50-yr	$212,480	0	1/50	$0
100-yr	$176,990	0.42	1/100	$743
			TOTAL	**$743**

Annual User Risk Calculation

Calculate total annual user risk by multiplying the threat likelihood by the owner consequences by the vulnerability for each magnitude of event, then sum to determine the annual user risk for all events analyzed utilizing Equation 3.11:

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ Risk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n= number of events

Exhibit 4.2.4.21 includes the annual user risk findings.

EXHIBIT 4.2.4.21 ANNUAL USER RISK CALCULATIONS

Rain Event Magnitude	User Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual User Risk ($)
25-yr	$5,179,321	0	1/25	$0
50-yr	$5,179,321	0	1/50	$0
100-yr	$5,179,321	0.99	1/100	$21,753
			TOTAL	**$21,753**

Total Annual Risk Calculation

Calculate total annual risk by adding total annual owner risk to total annual user risk utilizing Equation 3.13:

EQUATION 3.13

$$Total\ Annual\ Risk\ = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

Where n= number of events

Exhibit 4.2.4.22 includes the total annual risk results for each rain event analyzed:

EXHIBIT 4.2.4.22 ANNUAL TOTAL RISK CALCULATIONS

Rain Event Magnitude	Annual Owner Risk ($)	Annual User Risk ($)	Total Annual Risk ($)
25-yr	$0	$0	$0
50-yr	$0	$0	$0
100-yr	$743	$21,753	$22,496
TOTAL	**$743**	**$21,753**	**$22,496**

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4.2.5 Flood-Major Culvert Risk Assessment

For purposes of this procedure, culverts are divided into minor and major culvert categories. *Major culverts* are considered structures with greater than 20 feet in centerline span width between extreme ends of openings. In addition, major culverts include concrete boxes. Exhibit 4.2.5.1 includes an example of damage from flooding to major culverts.

EXHIBIT 4.2.5.1 DAMAGE TO MAJOR CULVERTS DURING 2013 FLOOD EVENT

Exhibit 4.2.5.2 illustrates the basic methodology and steps used in risk analysis of flood to major culverts.

EXHIBIT 4.2.5.2 FLOOD-MAJOR CULVERT RISK ASSESSMENT METHODOLOGY

Step 1: Threat Data Collection
Flood Annual Likelihood (Exhibit 4.2.5.4)

↓

Step 2: Asset Data Collection
Asset (Major Culvert) Data Needs (Exhibit 4.2.5.5)

↓

Step 3: Owner Consequence Calculation
Owner Worst Reasonable Case (WRC) for Flood-Major Culvert (Exhibit 4.2.5.6)
Major Culvert Unit Cost Estimation (Exhibits 4.2.5.7)

↓

Step 4: User Consequence Calculation
User Worst Reasonable Case (WRC) for Flood-Major Culvert (Exhibit 4.2.5.6)
Vehicle Operating Cost (VOC) and Lost of Wages (LW) (Exhibit 4.2.5.8)
Detour Estimation (Extra Travel Length and Time) (Exhibits 4.2.5.8and 4.2.5.9)
Calculations (Equations 3.5 through 3.8)
Total User Consequence (Equation 3.2)

↓

Step 5: Vulnerability Assessment
Flood-Major Culvert Vulnerability (Exhibit 4.2.5.12)

↓

Step 6: Risk Assessment
Annual Owner Risk Calculation (Equation 3.9)
Annual User Risk Calculation (Equations 3.2 through 3.8 and 3.11)
Annual Total Risk (Equation 3.13)

Computational Steps

Step 1: Threat Data Collection

Section 4.2.1 includes an overview of the methods used to estimate threat likelihood for flood events. Note, this approach is acceptable for planning level analysis of risk to major culverts from flooding, however, more detailed hydraulic analysis is typically utilized when determining specific mitigation required for project level culvert designs. Exhibit 4.2.5.3 includes an example of a major culvert overtopped by potential 100-yr flood event.

EXHIBIT 4.2.5.3 MAJOR CULVERTS OVERTOPPED BY POTENTIAL 100-YR FLOOD EVENT (100-YR FEMA FIRM)

The corresponding annual threat likelihoods for different 100-yr and 500-yr flood events are presented in Exhibit 4.2.5.4. Note, this approach does not consider increases in threat likelihood due to climate change.

EXHIBIT 4.2.5.4 FLOOD/RAINFALL ANNUAL THREAT LIKELIHOOD

Recurrence Interval* (Year)	Annual Threat Likelihood
1	1/1
2	1/2
5	1/5
10	1/10
25	1/25
50	1/50
100	1/100
500	1/500

*Flood/Rain recurrence intervals do not necessarily constitute the same flow rate.

Step 2: Asset Data Collection

Data needed to assess the annual risk from flood events includes asset replacement costs (ARC), user costs, and vulnerability. The FHWA National Bridge Inventory (NBI) and the CDOT Authoritative Culvert ArcGIS Online (C-Plan) databases provides culvert characteristics to calculate ARC and culvert vulnerability. In addition, the USGS National Map and the USDA Natural Resources Conservation Services provide information to estimate the debris potential of the site. The OTIS Highways feature class provides traffic volumes and site characteristics for calculating user consequences. Exhibit 4.2.5.5 provides a summary of the data needs and sources to assess risk for flood-major culverts.

EXHIBIT 4.2.5.5 DATA NEEDS FOR FLOOD-MAJOR CULVERTS RISK ANALYSIS

	Data Needs	Data Source
Asset Replacement Cost	**Culvert Identification Number (ID)**	CDOT Authoritative Culvert ArcGIS Online (C-Plan) https://cdot.maps.arcgis.com/home/index.html
	Culvert Dimensions	CDOT Authoritative Culvert ArcGIS Online (C-Plan) https://cdot.maps.arcgis.com/home/index.html
	Number of Cells	CDOT Authoritative Culvert ArcGIS Online (C-Plan) https://cdot.maps.arcgis.com/home/index.html
Vulnerability	**Culvert Condition**	CDOT Authoritative Culvert ArcGIS Online (C-Plan) https://cdot.maps.arcgis.com/home/index.html
	Culvert Hydraulic Capacity	If overtops at 100-yr event, **assume 50-yr capacity**; if overtops at 500-yr **assume 100-yr capacity**
	Channel and Channel Protection Condition (NBI 61)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm CDOT Culvert Inspection Report
	Drainage Basin	USGS National Map
	Landcover Type	https://www.mrlc.gov/data/nlcd-2016-land-cover-conus
	Mean Basin Slope	Stream Stats https://streamstats.usgs.gov/ss/
User Consequences	**AADT Vehicles**	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	AADT Trucks	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Roadway Damaged	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Detour	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Detour Distance	CDOT Operations
	Detour Time	CDOT Operations
	Number of Closure Days	See Exhibit 4.2.5.9
	Number of Partial Closure Days	See Exhibit 4.2.5.9
	Average Vehicle Occupancy	FHWA https://www.fhwa.dot.gov/tpm/guidance/avo_factors.pdf
	Car Running Costs	(RITA)/Texas A&M Transportation Institute
	Truck Running Costs	American Transportation Research Institute
	Average Value of Time	(RITA)/Texas A&M Transportation Institute

Step 3: Owner Consequence Assessment

Owner consequence measures the impact to the owner (CDOT) in terms of cost of repairs, cleanup, maintenance, and related agency operational cost. The most severe but credible consequence Worst Reasonable Consequence (WRC) for flood-major culvert, based on past emergency repair projects, is estimated as 100% the replacement cost of the culvert if overtopped by either a 100-yr or 500-yr FEMA FIRM plus $5,000 in cleanup costs to remove debris. The ARC unit cost from major culverts along with the method to calculate WRC can be found in Exhibits 4.2.5.6 through 4.2.5.7.

EXHIBIT 4.2.5.6 SUMMARY OF WRC FOR OWNER CONSEQUENCE

		Threat			
		Debris Flow	**Flood**	**Scour**	**Rockfall**
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

EXHIBIT 4.2.5.7
UNIT COSTS

Asset	Units	Unit Cost
Bridge Approach**	sq ft	$350
Bridge*	sq ft	$600
Culvert***	cu ft	$55
PTCS**	sq ft	$550
Road Prism (Asphalt)**	sq yds	$150
Road Prism (Concrete)**	sq yds	$350

* Bridge area is defined as deck length multiplied by deck width, derived from NBI Items 49 and 52, respectively.
**Bridge approach, roadway and PTCS width are derived from CDOT OTIS Highways feature class using fields for lane width, lane count, and shoulder width.
***For culvert (CBC), the volume, in cubic feet, is calculated by multiplying the box height by the box width by the length. These values are derived from the culverts feature class maintained by C-PLAN, CDOT's interactive online mapping platform.

Step 4: User Consequence Assessment

User consequences measure the impact to the public in terms of lost wages and increased vehicle operating costs due to delays, detours, and longer drive times. Required inputs include AADT, percent truck traffic, average vehicle occupancy, average hourly wage, detour length, work zone length, speed on detour, number of days of closure, and number of days of partial closure. For user consequences, the estimated WRC from flood-major culvert events is considered failure if overtopped by a FIRM and it is based on the cost to the user due to full closures. For further explanation on how to calculate user consequences Equations 3.2 through 3.8 and 3.11.

Exhibit 4.2.5.8 provides default values for a range of factors associated with the cost associated with operating vehicles, value of time, and occupancy that are updated annually by the various federal government agencies. Note the values included in Exhibit 4.2.5.8 were gathered in June of 2019 and will vary in future years.

EXHIBIT 4.2.5.8 CONSTANTS USED IN USER CONSEQUENCE CALCULATIONS

User Cost Terms	Variable	Value	Year Published
Average Vehicle Occupancy	*O*	1.77	2019
Car Running Cost per Mile	*C2*	$0.59	2019
Truck Running Cost per Mile	*C3*	$0.96	2015
Average Value of Time per Adult per Hour	*C4*	$10.62	2015
Average Value of Freight Driver Cost per Hour	*C5*	$25.31	2015
Car Running Cost per Hour	*C8*	$26.52	2015
Truck Running Cost per Hour	*C9*	$44.24	2015

The suggested number of full and partial closure days, derived from the I-70 Pilot, are provided in Exhibit 4.2.5.9 It is suggested that this table be used as guidance for all other corridor's for estimating closures days, both full and partial.

EXHIBIT 4.2.5.9 I-70 RISK AND RESILIENCE PILOT NUMBER OF FULL CLOSURE AND PARTIAL CLOSURE DAYS FOR WRC

Asset	Threat	Full Closure Days (d_{FC})	Partial Closure Days (d_{PC})
Bridge Approach	All	2	0
Bridge	Flood	180	0
Bridge	Debris Flow	2	0
Bridge	Rockfall	4	14
Culvert	Debris Flow	1	0
Culvert	Flood	3	0
PTCS	Rockfall	4	14
Roadway (<=% Width)	Flood	1	0
Roadway (> 50% Width)	Flood	3	0
Roadway (2 Directions)	Flood	3	0
Roadway	Rockfall	4	14

Example detours used for the I-70 Risk and Resilience Pilot and the worked examples in this document are listed in Exhibit 4.2.5.10. Note that *Additional Travel Distance* refers to the additional miles a traveler must travel on detour in comparison to the original route, and *Additional Travel Time* is the additional time a traveler must travel on detour in comparison to the original route. CDOT Operations can provide further guidance on estimating detours from closures for highways other than I-70.

EXHIBIT 4.2.5.10 I-70 RISK AND RESILIENCE PILOT DETOUR TABLE

Starting Milepost	Ending Milepost	Additional Travel Distance (miles) *(C7)*	Additional Travel Time (minutes) *(Dt)*
1	14	146	189
14	90	90	112
90	155	140	167
155	205	98	126
205	231	83	109
231	245	49	77
245	288	3	7
288	353	15	24
353	360	71	96
360	404	76	73
404	438	69	70
438	450	63	77

Total User Consequences is the sum of user consequence due to full and partial closures as shown in Equation 3.2.

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

Where:

$User\ Consequence_{FC}$ = User consequences due to full closure
$User\ Consequence_{PC}$ = User consequences due to partial closure

User consequences for full closure are the sum of vehicle operating costs incurred due to travel on detour, lost wages, and truck revenue due to travel on detour as shown in Equation 3.3.

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

Where:

VOC_{FC} = Vehicle operating costs incurred due to full closure
LW_{FC} = Lost wages/truck revenue incurred due to full closure

User consequences for partial closures are the sum of vehicle operating costs incurred due to traffic delays, lost wages, and truck revenue due to delays incurred while driving through a partial closure as shown in Equation 3.4.

EQUATION 3.4

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

Where:

VOC_{PC} = Vehicle operating costs incurred due to partial closure

LW_{PC} = Lost wages/truck revenue incurred due to partial closure

Equation 3.5 is the equation for calculating vehicle operating costs for full closures.

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$ = Average annual daily traffic (non-truck)

$AADT_{Truck}$ = Average annual daily truck traffic

$C2$ = Vehicle running cost ($/vehicle-mile)

$C3$ = Freight running cost ($/truck-mile)

d_{FC} = Number of full closure days (days)

$C7$ = Difference in distance between detour and original route (mile)

Equation 3.6 is used for calculating lost wages and truck revenue for full closures.

EQUATION 3.6

$$LW_{FC} = \left((C4\ x\ O\ x\ AADT_{Vehicle}) + (C5\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$ = Average annual daily traffic (non-truck)

$AADT_{Truck}$ = Average annual daily truck traffic

$C4$ = Average value of time ($/adult-hour)

O = Average occupancy (adult/vehicle)

$C5$ = Average value of freight time($/truck-hour)

d_{FC} = Number of full closure days (days)

Dt = Extra travel time on detour (minutes)

Equation 3.7 is used for calculating vehicle operating costs due to partial closures.

EQUATION 3.7

$$VOC_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x\ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x\ WZS}\right) x\ ((C8\ x\ AADT_{Vehicle}) + (C9\ x\ AADT_{Truck}))\ x\ d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C8$	=	Vehicle running cost ($/vehicle-hour)
$C9$	=	Freight running cost ($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Equation 3.8 is used for calculating lost wages and truck revenue due to partial closures.

EQUATION 3.8

$$LW_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x\ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x\ WZS}\right) x\ ((C4\ x\ AADT_{Vehicle}\ x\ O) + (C5\ x\ AADT_{Truck}))\ x\ d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C4$	=	Average value of time ($/adult-hour)
O	=	Average occupancy (adult/vehicle)
$C5$	=	Average value of freight time($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Calculate total annual user risk by multiplying the owner consequences by the vulnerability for each magnitude of event the threat likelihood then summing the annual user risk for all events, utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ \boldsymbol{R}isk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n = number of events

Step 5: Vulnerability Assessment

Vulnerability of a major culvert from flood events is dependent on multiple factors. Literature sources provided some input as to how major culverts perform when exposed to flood were taken into consideration when developing vulnerability factors. In addition, CDOT hydraulic staff and Maintenance Staff provided opinions and input as to which factors contributed most to damage to major culverts from flooding. The main factors identified for the vulnerability assessment include: 1) hydraulic capacity of the culvert; 2) culvert condition; 3) channel and channel protection condition; and 4) debris potential. The debris potential of the site during a flood event is determined based on the landcover of the surrounding drainage area and the slope of the surrounding drainage area.

Utilizing the debris potential factor obtained with Exhibit 4.2.5.11 along with the hydraulic capacity of the culvert, culvert condition and channel and channel protection condition, the vulnerability of major culverts can be obtained for 100-yr and 500-yr flood events using Exhibit 4.2.5.12.

EXHIBIT 4.2.5.11 DEBRIS POTENTIAL TABLE

	Landcover of Drainage Area			
Mean Basin Site Slope	**Water and Snow**	**Urban**	**Shrubs**	**Trees**
Low (0-8%)	Very Low	Low	Moderate	Moderate
Moderate (9-16%)	Very Low	Moderate	High	High
High (>16%)	Very Low	High	High	Very High

EXHIBIT 4.2.5.12 FLOOD-MAJOR CULVERT VULNERABILITY

Flood Event Magnitude	Hydraulic Capacity	Culvert Condition	Channel and Channel Protection	Debris Potential: Very Low	Low	Moderate	High	Very High
100-yr	100-yr	7-9	7-9	0.001	0.001	0.004	0.01	0.02
			4-6	0.001	0.001	0.004	0.01	0.03
			0-3	0.002	0.002	0.007	0.02	0.04
		4-6	7-9	0.001	0.002	0.005	0.02	0.03
			4-6	0.001	0.002	0.007	0.02	0.04
			0-3	0.002	0.003	0.01	0.04	0.07
		0-3	7-9	0.003	0.004	0.01	0.05	0.09
			4-6	0.004	0.005	0.02	0.06	0.11
			0-3	0.007	0.009	0.03	0.10	0.18
	50-yr	7-9	7-9	0.03	0.04	0.12	0.40	0.73
			4-6	0.03	0.04	0.15	0.49	0.90
			0-3	0.05	0.07	0.24	0.81	0.99
		4-6	7-9	0.04	0.05	0.18	0.60	0.99
			4-6	0.05	0.07	0.22	0.73	0.99
			0-3	0.08	0.11	0.36	0.99	0.99
		0-3	7-9	0.11	0.15	0.49	0.99	0.99
			4-6	0.13	0.18	0.60	0.99	0.99
			0-3	0.22	0.30	0.99	0.99	0.99
500-yr	100-yr	7-9	7-9	0.02	0.03	0.10	0.33	0.60
			4-6	0.03	0.04	0.12	0.40	0.73
			0-3	0.04	0.06	0.20	0.66	0.99
		4-6	7-9	0.03	0.04	0.15	0.49	0.90
			4-6	0.04	0.05	0.18	0.60	0.99
			0-3	0.07	0.09	0.30	0.99	0.99
		0-3	7-9	0.09	0.12	0.40	0.99	0.99
			4-6	0.11	0.15	0.49	0.99	0.99
			0-3	0.18	0.24	0.81	0.99	0.99
	50-yr	7-9	7-9	0.73	0.99	0.99	0.99	0.99
			4-6	0.90	0.99	0.99	0.99	0.99
			0-3	0.99	0.99	0.99	0.99	0.99
		4-6	7-9	0.99	0.99	0.99	0.99	0.99
			4-6	0.99	0.99	0.99	0.99	0.99
			0-3	0.99	0.99	0.99	0.99	0.99
		0-3	7-9	0.99	0.99	0.99	0.99	0.99
			4-6	0.99	0.99	0.99	0.99	0.99
			0-3	0.99	0.99	0.99	0.99	0.99

Step 6: Risk Calculation

Annual Owner Risk

The owner consequence for a flood event to a major culvert is based on the defined WRC for the owner. Annual owner risk is calculated for each event magnitude (100-yr and 500-yr flood events) utilizing the owner consequence (Step 3), vulnerability (Step 5), and threat likelihood (Step 1) multiplying all factors and utilizing Equation 3.9.

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ \boldsymbol{R}isk_i = Owner\ \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n = number of events

Annual User Risk

The user consequence for a flood event to major culverts is based on the defined WRC for roadway users. For user consequences, the estimated WRC is based on failure and closure of the highway facility when major culverts are overtopped by FIRMs.

The annual user risk is calculated for each event magnitude (100-yr and 500-yr flood events) utilizing the user consequence (Step 4), vulnerability (Step 5), and threat likelihood (Step 1) multiplying all factors and utilizing Equation 3.11

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ \boldsymbol{R}isk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n = number of events

Total Annual Risk

The total annual risk for flood for major culverts includes annual owner risk and annual user risk from all relevant flood event magnitudes as shown in Equation 3.13.

EQUATION 3.13

$$Total\ Annual\ Risk\ = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

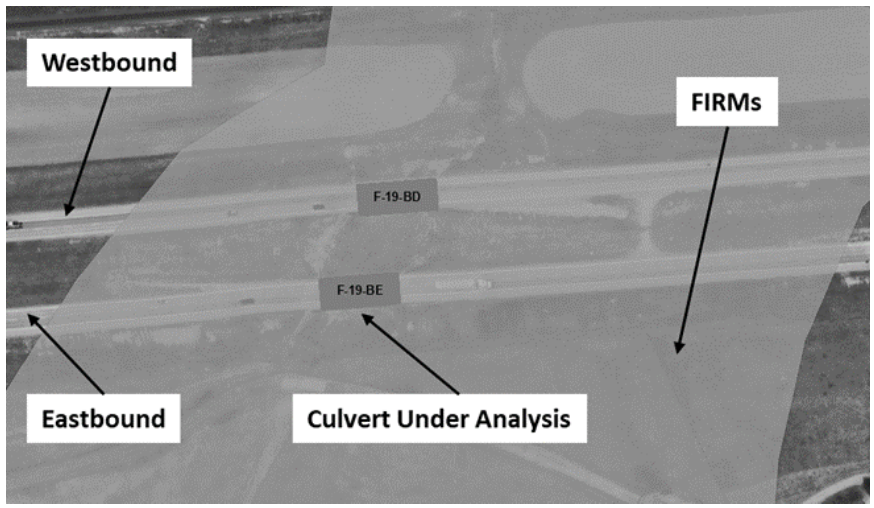
Where n= number of events

An example problem demonstrating the use of this approach is provided next.

Example Problem – Flood-Major Culvert Risk Assessment

This example demonstrates the risk assessment methodology developed for flood-major culvert presented in Exhibit 4.2.5.2. The task is to calculate the annual owner risk, user risk, and total risk from flood-major culvert events at milepost 109.18 on I-70, in Arapahoe County as shown in Exhibit 4.2.5.13. As shown, the major culverts are anticipated to be overtopped based on the 100-yr and 500-yr FIRMs. For demonstration purposes, only the major culvert located on the eastbound direction is analyzed.

EXHIBIT 4.2.5.13 EXAMPLE MAJOR CULVERT FLOOD SITE, I-70, MP 109.18 ARAPAHOE COUNTY



Site Overview

- Location: I-70, MP 109.18, County
- Four-lane freeway (two-lanes in each direction)

- Eastbound culvert:
    - Culvert identification ID (NBI 8) = F-19-BE
    - Type of culvert = culvert (CBC)
    - Culvert width = 25 ft
    - Culvert length = 45 ft
    - Culvert height = 15 ft
    - Number of cells = 4
    - Culvert condition = 7
    - Channel and channel protection condition = 7
    - Culvert hydraulic capacity = 50-yr (based on default value, Exhibit 4.2.5.5)
- Unit cost for major culvert = $55/cu ft
- Drainage basin landcover type: Shrubs
- Slope: 2.25 %
- Total I-70 $AADT_{Vehicle}$ = 10,220 vehicles
- Total I-70 $AADT_{Truck}$ = 3,780 trucks
- Detour length = 140 miles
- Extra travel time on detour = 167 minutes

- Number of days of full closure = 30 day (both traffic directions overtopped by FIRMs)
- Number of days of partial closure = 0 days (both traffic directions overtopped by FIRMs)

Following the flood-major culvert methodology presented in Exhibit 4.2.5.2:

Step 1: Threat Data Collection

The annual threat likelihoods are found in Exhibit 4.2.5.14.

EXHIBIT 4.2.5.14 FLOOD/RAINFALL ANNUAL THREAT LIKELIHOOD

Recurrence Interval (years)	Annual Threat Likelihood
1	1/1
2	1/2
5	1/5
10	1/10
25	1/25
50	1/50
100	1/100
500	1/500

*Flood/Rain recurrence intervals do not necessarily constitute the same flow rate.

Step 2: Asset Data Collection

Exhibit 4.2.5.5 describes the data and sources needed to perform the risk assessment and the actual values are listed in the "Site Overview" section. In addition, constants required for user risk calculations are found in Exhibit 4.2.5.8.

Step 3: Owner Consequence

CDOT has established the unit cost for major culverts at $55/cu ft for this procedure. The owner consequence of the culvert is calculated utilizing Exhibit 4.2.5.15.

EXHIBIT 4.2.5.15 SUMMARY OF WRC FOR OWNER CONSEQUENCE

Asset	Threat: Debris Flow	Threat: Flood	Threat: Scour	Threat: Rockfall
Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

EXHIBIT 4.2.5.16 UNIT COSTS

Asset	Units	Unit Cost
Bridge Approach**	sq ft	$350
Bridge*	sq ft	$600
Culvert***	cu ft	$55
PTCS**	sq ft	$550
Road Prism (Asphalt)**	sq yds	$150
Road Prism (Concrete)**	sq yds	$350

* Bridge area is defined as deck length multiplied by deck width, derived from NBI Items 49 and 52, respectively.

**Bridge approach, roadway and PTCS width are derived from CDOT OTIS Highways feature class using fields for lane width, lane count, and shoulder width.

***For culvert (CBC), the volume, in cubic feet, is calculated by multiplying the box height by the box width by the length. These values are derived from the culverts feature class maintained by C-PLAN, CDOT's interactive online mapping platform.

$$Owner\ Consequence = \left(100\%\ x\left((45\ ft\ x\ 25\ ft\ x\ 15\ ft)\ x\ \frac{\$55}{cu\ ft}\right)\right) + \$5{,}000$$

$$Owner\ Consequence = \$928{,}125 + \$5{,}000$$

$$\boldsymbol{Owner\ Consequence = \$933,125}$$

Step 4: User Consequence

Calculating user consequence for flood-major culvert events requires calculating vehicle and truck operating costs (VOC), as well as the value of lost wages and freight revenue (LW), for both full and partial closures as shown in Equations 3.2 through 3.8 and 3.11.

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

User Consequence for Full Closure (FC)

As presented in Equations 3.5 and 3.6, user consequence is based on the calculation of VOC_{FC} and LW_{FC}. Highway traffic volumes are provided in OTIS for the I-70 facility, half of the AADT has been assigned to each direction of travel for the purpose of this analysis.

Utilizing Equation 3.5, parameters presented in Exhibit 4.2.5.8 and closure days presented in Exhibit 4.2.5.9, the VOC_{FC} for full closure for the roadway during a flood event is calculated:

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$ = 5,110 average annual daily traffic (non-truck)
$AADT_{Truck}$ = 1,890 average annual daily truck traffic
$C2$ = \$0.59 vehicle running cost (\$/vehicle-mile)
$C3$ = \$0.96 freight running cost (\$/truck-mile)
d_{FC} = 30 days of full closure
$C7$ = 140 miles difference in distance between detour and original route

$$VOC_{FC} = \left(\left(\frac{\$0.59}{vehicle - mile}\ x\ 5{,}110\frac{vehicle}{day}\right) + \left(\frac{\$0.96}{truck - mile}\ x\ 1{,}890\frac{truck}{day}\right)\right)\ x\ 30\ days\ x\ 140\ miles$$

$$\boldsymbol{VOC_{FC} = \$20,283,060}$$

Next use Equation 3.6 to calculate lost wages and truck revenue for full closures:

EQUATION 3.6

$$LW_{FC} = \left((C4\ x\ O\ x\ AADT_{Vehicle}) + (C5\ x\ AADT_{Truck})\right) x\ d_{FC}\ x\ \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$	=	5,110 average annual daily traffic (non-truck)
$AADT_{Truck}$	=	1,890 average annual daily truck traffic
$C4$	=	\$10.62 average value of time (\$/hour-adult)
O	=	1.77 average occupancy (adult/vehicle)
$C5$	=	\$25.31 average value of freight time(\$/hour-truck)
d_{FC}	=	30 days of full closure
Dt	=	167 minutes of extra travel time on detour

$$LW_{FC} = \left(\left(\frac{\$10.62}{adult - hour}\ x\ 1.77\frac{adult}{vehicle}\ x\ 5{,}110\frac{vehicle}{day}\right) + \left(\frac{\$25.31}{truck - hour}\ x\ 1{,}890\frac{truck}{day},\right)\right) x\ 30\ days\ x\ \frac{167\ min}{60\ \frac{min}{hour}}$$

$$\boldsymbol{LW_{FC} = \$12{,}014{,}866}$$

Finally, sum of vehicle operating costs incurred due to vehicle travel on the detour and the lost wages and truck revenue due to travel on the detour utilizing Equation 3.3:

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

$$User\ Consequence_{FC} = \$20{,}283{,}060 + \$12{,}014{,}866$$

$$\boldsymbol{Total\ User\ Consequence = \$32{,}297{,}926}$$

User Consequence for Partial Closure (PC):

Since partial closure is not anticipated for this site, VOC_{PC} and LW_{PC} for partial closure is estimated to be \$0:

$$VOC_{PC} = \$0$$

$$LW_{PC} = \$0$$

$$\boldsymbol{User\ Consequence_{PC} = \$0}$$

Total User Consequence:

Total user consequences include the sum of user consequence due to full and partial closures as shown in Equation 3.2:

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + \ User\ Consequence_{PC}$$

$$Total\ User\ Consequence = \$32{,}297{,}926 + \$0$$

$$\boldsymbol{Total\ User\ Consequence} = \$\mathbf{32{,}297{,}926}$$

Step 5.: Vulnerability Assessment.

The debris potential of the site during a flood event is determined using Exhibit 4.2.5.17, and the provided data for the study site:

EXHIBIT 4.2.5.17 DEBRIS POTENTIAL TABLE

	Landcover of Drainage Area			
Mean Basin Site Slope	**Water and Snow**	**Urban**	**Shrubs**	**Trees**
Low (0-8%)	Very Low	Low	Moderate	Moderate
Moderate (9-16%)	Very Low	Moderate	High	High
High (>16%)	Very Low	High	High	Very High

It is determined that the debris potential factor of the site is "Moderate". Based on moderate debris potential along with the hydraulic capacity of the culvert, culvert condition and channel and channel protection condition, the vulnerability of the culvert is obtained using Exhibit 4.2.5.18 for 100-yr and 500-yr flood event magnitudes as shown here:

EXHIBIT 4.2.5.18 FLOOD-MAJOR CULVERT VULNERABILITY

Flood Event Magnitude	Hydraulic Capacity	Culvert Condition	Channel and Channel Protection	Debris Potential				
				Very Low	Low	Moderate	High	Very High
100-yr	100-yr	7-9	7-9	0.001	0.001	0.004	0.01	0.02
			4-6	0.001	0.001	0.004	0.01	0.03
			0-3	0.002	0.002	0.007	0.02	0.04
		4-6	7-9	0.001	0.002	0.005	0.02	0.03
			4-6	0.001	0.002	0.007	0.02	0.04
			0-3	0.002	0.003	0.01	0.04	0.07
		0-3	7-9	0.003	0.004	0.01	0.05	0.09
			4-6	0.004	0.005	0.02	0.06	0.11
			0-3	0.007	0.009	0.03	0.10	0.18
	50-yr	7-9	7-9	0.03	0.04	0.12	0.40	0.73
			4-6	0.03	0.04	0.15	0.49	0.90
			0-3	0.05	0.07	0.24	0.81	0.99
		4-6	7-9	0.04	0.05	0.18	0.60	0.99
			4-6	0.05	0.07	0.22	0.73	0.99
			0-3	0.08	0.11	0.36	0.99	0.99
		0-3	7-9	0.11	0.15	0.49	0.99	0.99
			4-6	0.13	0.18	0.60	0.99	0.99
			0-3	0.22	0.30	0.99	0.99	0.99
500-yr	100-yr	7-9	7-9	0.02	0.03	0.10	0.33	0.60
			4-6	0.03	0.04	0.12	0.40	0.73
			0-3	0.04	0.06	0.20	0.66	0.99
		4-6	7-9	0.03	0.04	0.15	0.49	0.90
			4-6	0.04	0.05	0.18	0.60	0.99
			0-3	0.07	0.09	0.30	0.99	0.99
		0-3	7-9	0.09	0.12	0.40	0.99	0.99
			4-6	0.11	0.15	0.49	0.99	0.99
			0-3	0.18	0.24	0.81	0.99	0.99
	50-yr	7-9	7-9	0.73	0.99	0.99	0.99	0.99
			4-6	0.90	0.99	0.99	0.99	0.99
			0-3	0.99	0.99	0.99	0.99	0.99
		4-6	7-9	0.99	0.99	0.99	0.99	0.99
			4-6	0.99	0.99	0.99	0.99	0.99
			0-3	0.99	0.99	0.99	0.99	0.99
		0-3	7-9	0.99	0.99	0.99	0.99	0.99
			4-6	0.99	0.99	0.99	0.99	0.99
			0-3	0.99	0.99	0.99	0.99	0.99

Using Exhibit 4.2.5.18, the vulnerability of the major culvert is found to be $V_{100\text{-yr}} = 0.12$ and $V_{500\text{-yr}} = 0.99$ for 100-yr and 500-yr events respectively.

Step 6. Risk Assessment

Annual Owner Risk

Next, calculate total annual owner risk by multiplying the threat likelihood by the owner consequences by the vulnerability for the 100-yr and 500-yr flood events, then sum the annual owner risk for all events utilizing Equation 3.9:

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ Risk_i = Owner\ Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

Exhibit 4.2.4.19 includes the annual owner risk for each flood event magnitude and the total site.

EXHIBIT 4.2.5.19 ANNUAL OWNER RISK CALCULATIONS

Flood Event Magnitude	Owner Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual Owner Risk ($)
100-yr	$933,125	0.12	1/100	$1,120
500-yr	$933,125	0.99	1/500	$1,848
			TOTAL	**$2,968**

Annual User Risk

Calculate total annual user risk for 100-yr and 500-yr flood event magnitudes by multiplying the threat likelihood by the owner consequences by the vulnerability for each magnitude of event analyzed then sum the annual user risk for all events utilizing Equation 3.11:

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ Risk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n= number of events

Exhibit 4.2.5.20 includes the annual user risk for each flood event magnitude analyzed and the total site.

EXHIBIT 4.2.5.20 ANNUAL USER RISK CALCULATIONS

Flood Event Magnitude	User Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual User Risk ($)
100-yr	$32,297,926	0.12	1/100	$38,758
500-yr	$32,297,926	0.99	1/500	$63,950
			TOTAL	**$102,707**

Total Annual Risk Calculation

Calculate total annual risk by adding total annual owner risk to total annual user risk utilizing Equation 3.13:

EQUATION 3.13

$$Total\ Annual\ Risk = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

Where n= number of events

The total annual risk is calculated with Equation 3.13 and the results are provided here:

$$Total\ Annual\ Risk = \$2{,}968 + \$102{,}707$$

$$\boldsymbol{Total\ Annual\ Risk = \$105{,}676}$$

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4.2.6 Scour-Bridge Risk Assessment

Bridge scour is considered a leading cause of bridge failure and is defined as "the erosion caused by water of the soil surrounding a bridge foundation (piers and abutments)". (U.S. Department of Transportation. Federal Highway Administration (USDOT-FHWA), 2012). Scour negatively affects transportation infrastructure including bridges. CDOT maintains and repairs approximately 3,500 vehicular bridges and some of these bridges may be vulnerable to scour and possible bridge failure.

CDOT develops Plan of Actions (POAs) for scour critical bridges and bridges with unknown foundations on their system. The POAs help to program and prioritize the installation of scour countermeasures to protect vulnerable bridges and to establish a systematic process of monitoring bridges to ensure public safety, especially during flood events. In August of 2019, 144 bridges were deemed scour critical system wide.

In order to estimate the risk to bridges from scour, a process was developed based on the FHWA HYRISK Model and the adjusted HYRISK model from Georgia DOT (GDOT) research Project RP-11-27, Development of a Risk-Based Scorecard to Assess Scour Vulnerability of Georgia's Bridges (Georgia Department of Transportation, 2013).

HYRISK is a simplified risk-based model developed by FHWA in the late 1990's and modified in 2006 to assess the probability of bridge failure due to scour (Pearson, 2002). Georgia DOT extended this work in the noted project to revised failure probabilities of bridges from the original model.

EXHIBIT 4.2.6.1 BRIDGE SCOUR ON US-36 BRIDGES AT ST. VRAIN AND LEFT-HAND CREEK

Exhibit 4.2.6.2 illustrates the methodology and steps followed to quantify annual risk to bridges from scour.

EXHIBIT 4.2.6.2 SCOUR-BRIDGE RISK ASSESSMENT METHODOLOGY

Step 1: Threat Data Collection
This step is combined into one step, Step 5

↓

Step 2: Asset Data Collection
Asset (Bridge) Data Needs (Exhibit 4.2.6.3)

↓

Step 3: Owner Consequence Calculation
Owner Worst Reasonable Case (WRC) for Scour-Bridge (Exhibit 4.2.6.4)
Bridge Unit Cost Estimation (Exhibit 4.2.6.5)

↓

Step 4: User Consequence Calculation
User Worst Reasonable Case (WRC) for Scour-Bridge (Exhibit 4.2.6.4)
Vehicle Operating Cost (VOC) and Lost of Wages (LW) (Exhibit 4.2.6.6)
Detour Estimation (Extra Travel Length and Time) (Exhibits 4.2.6.7 and 4.2.6.8)
Calculations (Equations 3.5 through 3.8)
Total User Consequence (Equation 3.2)

↓

Step 5: Vulnerability Assessment (Failure Probability Assessment)
Scour-Bridge Failure Probability (Exhibits 4.2.6.10 and 4.2.6.11)

↓

Step 6: Risk Assessment
Annual Owner Risk Calculation (Equation 3.10)
Annual User Risk Calculation (Equations 3.2 through 3.8 and 3.12)
Annual Total Risk (Equation 3.13)

COMPUTATIONAL STEPS

Step 1: Threat Data Collection

This step is combined into one step in order to calculate failure probability, Step 5: Vulnerability Assessment (Failure Probability Assessment). More information is provided in Step 5.

Step 2: Asset Data Collection

Data needed to assess the annual risk from scour on bridges includes ARC, user costs, and vulnerability. The National Bridge Inventory (NBI) database and CDOT bridge inspection reports provide bridge identification numbers (Structure ID) and dimensions to calculate the asset replacement costs (ARC), as well as all the data to calculate bridge failure probabilities. The OTIS Highways database provides traffic volumes and site characteristics for calculating user consequences. Exhibit 4.2.6.3 provides a summary of the data needs and sources to assess the annual risk for of bridges from scour.

EXHIBIT 4.2.6.3 DATA NEEDS FOR SCOUR-BRIDGE RISK ANALYSIS

	Data Needs	Data Source
Asset Replacement Cost	**Milepost (beginning and end)**	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Bridge Length (NBI 49)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm
	Bridge Width (NBI 52)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm
Vulnerability	**Structure ID (NBI 8)**	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm
	Span Length (NBI 48)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm
	Superstructure Condition (NBI 59)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm
	Substructure Condition (NBI 60)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm
	Bridge Hydraulic Capacity	If overtops at 100-yr event, **assume 50-yr capacity**; if overtops at 500-yr **assume 100-yr capacity.**
	Scour Condition (NBI 113)	FHWA National Bridge Inventory (NBI) https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm
	Drainage Basin Landcover Type	USGS National Map https://www.mrlc.gov/data/nlcd-2016-land-cover-conus
	Mean Basin Slope	Stream Stats https://streamstats.usgs.gov/ss/
User Consequences	**AADT Vehicles**	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	AADT Trucks	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Roadway Damaged	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Speed on Detour	Highway Data-OTIS http://dtdapps.coloradodot.info/otis
	Detour Distance	CDOT Operations
	Detour Time	CDOT Operations
	Number of Closure Days	See Exhibit 4.2.6.7
	Number of Partial Closure Days	See Exhibit 4.2.6.7
	Average Vehicle Occupancy	FHWA https://www.fhwa.dot.gov/tpm/guidance/avo_factors.pdf
	Car Running Costs	(RITA)/Texas A&M Transportation Institute
	Truck Running Costs	American Transportation Research Institute
	Average Value of Time	(RITA)/Texas A&M Transportation Institute

Step 3: Owner Consequence Assessment

Owner consequence measures the impact to the owner (CDOT) in terms of cost of repairs, cleanup, maintenance, and related agency operational cost. The most severe but credible consequence (WRC) for scour-bridge is bridge failure. Failure is estimated as 100% the replacement cost of the bridge plus $5,000 in cleanup costs. The ARC unit cost from major culverts along with the method to calculate WRC can be found in Exhibits 4.2.6.4 and Exhibit 4.2.6.5 respectively.

EXHIBIT 4.2.6.4 SUMMARY OF WRC FOR OWNER CONSEQUENCE

		Threat			
		Debris Flow	**Flood**	**Scour**	**Rockfall**
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

EXHIBIT 4.2.6.5 UNIT COSTS

Asset	Units	Unit Cost
Bridge Approach**	sq ft	$350
Bridge*	sq ft	$600
Culvert***	cu ft	$55
PTCS**	sq ft	$550
Road Prism (Asphalt)**	sq yds	$150
Road Prism (Concrete)**	sq yds	$350

Step 4: User Consequence Assessment

User consequences measure the impact to the traveling public in terms of lost wages and increased vehicle operating costs due to delays, detours, and longer travel distances. Required inputs include AADT, percent truck traffic, average vehicle occupancy, average hourly wage, detour length, work zone length, speed on detour, number of days of closure, and number of days of partial closure. For user consequences, the estimated WRC from for scour risk to bridges is bridge failure. For further explanation on how to calculate user consequences, see Equations 3.2 through 3.8 and 3.11.

Exhibit 4.2.6.6 provides default values for a range of factors associated with the cost associated with operating vehicles, value of time, and occupancy that are updated annually by the various federal government agencies. Note the values included in Exhibit 4.2.6.6 were gathered in June of 2019 and will vary in future years.

EXHIBIT 4.2.6.6 CONSTANTS USED IN USER CONSEQUENCE CALCULATIONS

User Cost Terms	Variable	Value	Year Published
Average Vehicle Occupancy	*O*	1.77	2019
Car Running Cost per Mile	*C2*	$0.59	2019
Truck Running Cost per Mile	*C3*	$0.96	2015
Average Value of Time per Adult per Hour	*C4*	$10.62	2015
Average Value of Freight Driver Cost per Hour	*C5*	$25.31	2015
Car Running Cost per Hour	*C8*	$26.52	2015
Truck Running Cost per Hour	*C9*	$44.24	2015

The suggested number of full and partial closure days, derived from the I-70 Pilot, are provided in Exhibit 4.2.6.7. It is suggested that this table be used as guidance for all other corridor's for estimating closures days, both full and partial.

EXHIBIT 4.2.6.7 I-70 RISK AND RESILIENCE PILOT NUMBER OF FULL CLOSURE AND PARTIAL CLOSURE DAYS FOR WRC

Asset	Threat	Full Closure Days (d_{FC})	Partial Closure Days (d_{PC})
Bridge Approach	All	2	0
Bridge	Flood	180	0
Bridge	Debris Flow	2	0
Bridge	Rockfall	4	14
Culvert	Debris Flow	1	0
Culvert	Flood	3	0
PTCS	Rockfall	4	14
Roadway (<=% Width)	Flood	1	0
Roadway (> 50% Width)	Flood	3	0
Roadway (2 Directions)	Flood	3	0
Roadway	Rockfall	4	14

Example detours used for the I-70 Risk and Resilience Pilot and the worked examples in this document are listed in Exhibit 4.2.6.8. Note that *Additional Travel Distance* refers to the additional miles a traveler must travel on detour in comparison to the original route, and *Additional Travel Time* is the additional time a traveler must travel on detour in comparison to the original route. CDOT Operations can provide further guidance on estimating detours from closures for highways other than I-70.

EXHIBIT 4.2.6.8 I-70 RISK AND RESILIENCE PILOT DETOUR TABLE

Starting Milepost	Ending Milepost	Additional Travel Distance (miles) *(C7)*	Additional Travel Time (minutes) *(Dt)*
1	14	146	189
14	90	90	112
90	155	140	167
155	205	98	126
205	231	83	109
231	245	49	77
245	288	3	7
288	353	15	24
353	360	71	96
360	404	76	73
404	438	69	70
438	450	63	77

Total User Consequences is the sum of user consequence due to full and partial closures as shown in Equation 3.2.

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + \ User\ Consequence_{PC}$$

Where:

$User\ Consequence_{FC}$ = User consequences due to full closure
$User\ Consequence_{PC}$ = User consequences due to partial closure

User consequences for full closure are the sum of vehicle operating costs incurred due to travel on detour, lost wages, and truck revenue due to travel on detour as shown in Equation 3.3.

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + \ LW_{FC}$$

Where:

VOC_{FC} = Vehicle operating costs incurred due to full closure
LW_{FC} = Lost wages/truck revenue incurred due to full closure

User consequences for partial closures are the sum of vehicle operating costs incurred due to traffic delays, lost wages, and truck revenue due to delays incurred while driving through a partial closure as shown in Equation 3.4.

EQUATION 3.4

$$User\ Consequence_{PC} = VOC_{PC} + LW_{PC}$$

Where:

VOC_{PC}	=	Vehicle operating costs incurred due to partial closure
LW_{PC}	=	Lost wages/truck revenue incurred due to partial closure

Equation 3.5 is the equation for calculating vehicle operating costs for full closures.

EQUATION 3.5

$$VOC_{FC} = \left((C2\ x\ AADT_{Vehicle}) + (C3\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ C7$$

Where:

$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C2$	=	Vehicle running cost ($/vehicle-mile)
$C3$	=	Freight running cost ($/truck-mile)
d_{FC}	=	Number of full closure days (days)
$C7$	=	Difference in distance between detour and original route (mile)

Equation 3.6 is used for calculating lost wages and truck revenue for full closures.

EQUATION 3.6

$$LW_{FC} = \left((C4\ x\ O\ x\ AADT_{Vehicle}) + (C5\ x\ AADT_{Truck})\right)\ x\ d_{FC}\ x\ \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C4$	=	Average value of time ($/adult-hour)
O	=	Average occupancy (adult/vehicle)
$C5$	=	Average value of freight time($/truck-hour)
d_{FC}	=	Number of full closure days (days)
Dt	=	Extra travel time on detour (minutes)

Equation 3.7 is used for calculating vehicle operating costs due to partial closures.

EQUATION 3.7

$$VOC_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) \ x \ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x \ WZS} \right) x \ ((C8 \ x \ AADT_{Vehicle}) + (C9 \ x \ AADT_{Truck})) \ x \ d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C8$	=	Vehicle running cost ($/vehicle-hour)
$C9$	=	Freight running cost ($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Equation 3.8 is used for calculating lost wages and truck revenue due to partial closures.

EQUATION 3.8

$$LW_{PC} = \left(\frac{1}{\left(\frac{1}{WL}\right) x \ (WZS - WZSR)} - \frac{1}{\left(\frac{1}{WL}\right) x \ WZS} \right) x \ ((C4 \ x \ AADT_{Vehicle} \ x \ O) + (C5 \ x \ AADT_{Truck})) \ x \ d_{PC}$$

Where:

WL	=	Work zone length (miles)
WZS	=	Work zone speed limit (mph)
$WZSR$	=	Work zone speed limit reduction (mph)
$AADT_{Vehicle}$	=	Average annual daily traffic (non-truck)
$AADT_{Truck}$	=	Average annual daily truck traffic
$C4$	=	Average value of time ($/adult-hour)
O	=	Average occupancy (adult/vehicle)
$C5$	=	Average value of freight time($/truck-hour)
d_{PC}	=	Number of days of partial closure (days)

Calculate total annual user risk by multiplying the owner consequences by the vulnerability for each magnitude of event the threat likelihood then summing the annual user risk for all events, utilizing Equation 3.11.

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ \boldsymbol{R}isk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n = number of events

Step 5: Vulnerability Assessment (Failure Probability Assessment)

The Scour-Bridge model combines threat likelihood (T) and vulnerability (V) as one factor (annual probability of failure (PF)) unlike other threat-asset pairs previously presented. For this procedure, multiple tables adopted from the revised FHWA HYRISK Model (Georgia Department of Transportation, 2013) are provided to estimate the failure probability of bridges from scour. The primary factors identified to estimate failure probability can be obtained from the FHWA National Bridge Inventory (NBI) databased and include: 1) functional classification; 2) waterway adequacy; 3) channel protection and 4) substructure condition.

The tables from FHWA HYRISK Model are listed in Exhibits 4.2.6.9 through 4.2.6.10. The tables display the estimated the annual overtopping frequency based on waterway adequacy and functional classification, the estimated the bridge scour vulnerability rating based on substructure condition and channel protection and the estimated annual probability of bridge failure utilizing the overtopping frequency and the scour vulnerability rating.

EXHIBIT 4.2.6.9 ANNUAL OVERTOPPING FREQUENCY

Functional Classification (NBI 26)	Waterway Adequacy (NBI 71)										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**N**
Principal Arterials-Interstates (01,11)	C	C	O	O	O	O	S	S	S	R	N
Freeways or Expressways (12)	C	C	F	O	O	O	S	S	S	R	N
Other Principal Arterials (02,14)	C	C	F	O	O	O	S	S	S	R	N
Minor Arterials (06,16)	C	C	F	O	O	O	S	S	S	R	N
Major Collectors (07,17)	C	C	F	O	O	O	S	S	S	R	N
Minor Collectors (08)	C	C	F	F*	O	O	O	S	S	R	N
Locals (09,19)	C	C	F	F*	O	O	O	S	S	R	N

Key: N = Never; R = Remote (T > 100 yr); S = Slight (T = 11–100 yr); O = Occasional (T = 3–10 yr); F = Frequent (T < 3 yr)

(Source: Federal Highway Administration (FHWA) HYRISK Model (Pearson, 2002))

Note: If overtopping frequency is either C Bridge Closed or N None the HYRISK model is not applicable.

EXHIBIT 4.2.6.10 SCOUR-BRIDGE VULNERABILITY

Channel Protection (NBI 61)	Substructure Condition (NBI 60*)										
	0	1	2	3	4	5	6	7	8	9	N
0 Failure	0	0	0	0	0	0	0	0	0	0	0
1 Failure	0	1	1	1	1	1	1	1	1	1	N
2 Near Collapse	0	1	2	2	2	2	2	2	2	2	N
3 Channel Migration	0	1	2	2	3	4	4	4	4	4	N
4 Undetermined Bank	0	1	2	3	4	4	5	5	6	6	N
5 Eroded Bank	0	1	2	3	4	5	5	6	7	7	N
6 Bed Movement	0	1	2	3	4	5	6	6	7	7	N
7 Minor Drift	0	1	2	3	4	6	6	7	7	8	N
8 Stable Condition	0	1	2	3	4	6	7	7	8	8	N
9 No Deficiencies	0	1	2	3	4	7	7	8	8	9	N
N Not Over Water	0	1	N	N	N	N	N	N	N	N	N

*Codes for Substructure Condition are: 0 failed; 1 bridge closed – imminent failure; 2 critical scour; 3 serious scour; 4 advanced scour; 5 minor scour; 6 minor deterioration; 7 good condition; 8 very good condition; 9 excellent condition; N not applicable.

EXHIBIT 4.2.6.11 ANNUAL PROBABILITY OF BRIDGE FAILURE (PF) FROM SCOUR

Scour Vulnerability (From Exhibit 4.2.6.10)	Overtopping Frequency (From Exhibit 4.2.6.9)			
	Remote (0.01)	Slight (0.02)	Occasional (0.20)	Frequent (0.30)
0 Failed	1.00	1.00	1.00	1.00
1 Imminent Failure	0.01	0.01	0.01	0.01
2 Critical Scour	0.005	0.006	0.008	0.009
3 Serious Scour	0.0011	0.0013	0.0016	0.002
4 Advanced Scour	0.0004	0.0005	0.0006	0.0007
5 Minor Scour	0.0003	0.0004	0.0005	0.0007
6 Minor Deterioration	0.00018	0.00025	0.0004	0.0005
7 Good Condition	0.00018	0.00025	0.0004	0.0005
8 Very Good Condition	0.000004	0.000005	0.00002	0.00004
9 Excellent Condition	0.0000025	0.000003	0.000004	0.000007

(Source: Revised FHWA HYRISK Model (Georgia Department of Transportation, 2013))

Step 6. Risk Calculation

Annual Owner Risk

The owner consequence for scour in bridges is based on the defined WRC. The annual owner risk for bridge scour is calculated utilizing the owner consequence (from Step 3), and annual probability of failure (PF) (from Step 5) multiplying all factors utilizing Equation 3.10.

EQUATION 3.10 (Scour-Bridge)

$$Annual\ Owner\ Risk = Owner\ Consequence\ x\ PF\ x\ K$$

Where $K = K_1 * K_2$
K_1 is a bridge type factor based on NBI data, and K_2 is a foundation type factor based on information.

The values presently recommended for K_1 are 1.0 for spans less than 100 feet long and 0.67 for rigid continuous spans with lengths in excess of 100 feet. This factor adjusts to reflect the benefit of structural continuity which can compensate for loss of intermediate supports.

The values recommended for K_2, given below, should be developed for both abutment and pier condition, selecting the largest value for the analysis:

1.0 - unknown foundations or spread footings on erodible soil above scour depth with pier footing top visible or 1- to 2 ft below stream bed
0.8 - pile foundations when length is unknown, are less than 19 ft, or are all-wood pile foundations
0.2- foundations on massive rock

Annual User Risk

The user consequence for the annual risk of bridge failure from scour is based on the defined WRC. The WRC for user consequences is based on the cost to the user due to 180 days of full closure due to bridge failure. Annual user risk is calculated for each bridge utilizing the user consequence (Step 4) and Annual Probability of Failure (PF) (Step 5) multiplying all factors utilizing Equation 3.12.

EQUATION 3.12 (Scour-Bridge)

$$Annual\ User\ Risk = Owner\ Consequence\ x\ PF$$

Total Annual Risk

The total annual risk for scour for bridges accounts for the annual owner risk as well as for the annual user risk. Equation 3.13 shows the calculation for total annual risk for scour-bridge.

EQUATION 3.13

$$Total\ Annual\ Risk\ = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

Where n= number of events

An example problem demonstrating the use of this approach is provided next.

Example Problem Scour-Bridge Risk Assessment

This example demonstrates the risk assessment methodology developed for scour-bridge. The task is to calculate the annual owner risk, user risk, and total risk from scour for a bridge on I-70 at milepost 356 in Elbert County as shown in Exhibit 4.2.6.12 For demonstration purposes, only the risk of Structure G-21-N (eastbound) will be analyzed.

EXHIBIT 4.2.6.12 EXAMPLE BRIDGE SITE, I-70, MP 356 IN ELBERT COUNTY

Site Overview

- Location: I-70, MP 356, Elbert County
- Four-lane freeway (two-lanes in each direction)
- Full roadway width, each direction = 37 ft
- Unit cost for bridge = $600/sq ft
- Eastbound bridge characteristics:
  - Structure ID = G-21-N
  - Length = 83 ft
  - Width = 42 ft
  - Functional classification = 1
  - Waterway adequacy = 8
  - Channel protection = 8
  - Substructure condition = 7
  - Spans are >100 ft in length
  - Foundation type = unknown
- Total I-70 $AADT_{vehicle}$ = 8,200 vehicles
- Total I-70 $AADT_{truck}$ = 2,800 trucks
- Detour length = 71 miles
- Detour time = 96 minutes
- Number of days of full closure = 180 days
- Number of days of partial closure = 0 days

Following the scour-bridge methodology presented in Exhibit 4.2.6.2:

Step 1: Threat Data Collection

This step is combined into one step in order to calculate failure probability in Step 5: Vulnerability Assessment (Failure Probability Assessment). More information is provided in Step 5.

Step 2: Asset Data Collection

Exhibit 4.2.6.3 describes the data needs and sources to perform the risk assessment with actual site values included in the "Site Overview" section.

Step 3: Owner Consequence

The WRC for a scour-bridge event is calculated as 100% of bridge ARC plus $5,000 in cleanup costs. For this procedure, CDOT has established the unit cost of bridges of $600/sq ft. Following the equation for scour-bridge shown in Exhibit 4.2.6.13 the calculation for owner consequences is completed:

EXHIBIT 4.2.6.13 SUMMARY OF WRC FOR OWNER CONSEQUENCE

		Threat			
		Debris Flow	**Flood**	**Scour**	**Rockfall**
Asset	Bridge Approach	N/A	100% ARC +$5,000 Cleanup	N/A	N/A
	Bridge	N/A	100% ARC +$5,000 Cleanup	100% ARC +$5,000 Cleanup	100% ARC + $200,000 if length < 100 ft, else $2.5 million
	Culvert	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	N/A
	PTCS	N/A	N/A	N/A	25% ARC of 500 ft section + $200,000 Cleanup
	Roadway	100% ARC + $5,000 Cleanup	100% ARC +$5,000 Cleanup	N/A	100% ARC of 100 ft section + $200,000 Cleanup

EXHIBIT 4.2.6.14
UNIT COSTS

Asset	Units	Unit Cost
Bridge Approach**	sq ft	$350
Bridge*	sq ft	$600
Culvert***	cu ft	$55
PTCS**	sq ft	$550
Road Prism (Asphalt)**	sq yds	$150
Road Prism (Concrete)**	sq yds	$350

* Bridge area is defined as deck length multiplied by deck width, derived from NBI Items 49 and 52, respectively.
**Bridge approach, roadway and PTCS width are derived from CDOT OTIS Highways feature class using fields for lane width, lane count, and shoulder width.
***For culvert (CBC), the volume, in cubic feet, is calculated by multiplying the box height by the box width by the length. These values are derived from the culverts feature class maintained by C-PLAN, CDOT's interactive online mapping platform.

$$Owner\ Consequence\ = \left(100\%\ x\ \left((42\ ft\ x\ 83\ ft)\ x\ \frac{\$600}{sq\ ft}\right)\right) + \$5{,}000$$

$$Owner\ Consequence = \$2{,}091{,}600 + \$5{,}000$$

$$\boldsymbol{Owner\ Consequence} = \$\mathbf{2,096,600}$$

Step 4: User Consequence

Calculating user consequence for scour on bridges requires calculating vehicle and truck operating costs (VOC), as well as the value of lost wages and freight revenue (LW), for both full and partial closure (if applicable) as shown in Equations 3.2 through 3.8 and 3.11.

$$Total\ User\ Consequence = User\ Consequence_{FC} +\ User\ Consequence_{PC}$$

$$User\ Consequence_{FC} = VOC_{FC} +\ LW_{FC}$$

$$User\ Consequence_{PC} = VOC_{PC} +\ LW_{PC}$$

User Consequence for Full Closure (FC)

As presented in Equations 3.5 and 3.6, user consequence is based on the calculation of VOC_{FC} and LW_{FC}. OTIS provides total average annual daily traffic (AADT) data for I-

70, half of the AADT has been assigned to each direction of travel for the purposes of this analysis.

Utilizing Equation 3.5, parameters presented in Exhibit 4.2.6.6 and closure days presented in Exhibit 4.2.6.7, the VOC_{FC} for full closure for the roadway during a flood event is calculated:

EQUATION 3.5

$$VOC_{FC} = \left((C2 \ x \ AADT_{Vehicle}) + (C3 \ x \ AADT_{Truck})\right) x \ d_{FC} \ x \ C7$$

Where:

$AADT_{Vehicle}$	=	4,100 average annual daily traffic (non-truck)
$AADT_{Truck}$	=	1,400 average annual daily truck traffic
$C2$	=	\$0.59 vehicle running cost (\$/vehicle-mile)
$C3$	=	\$0.96 freight running cost (\$/truck-mile)
d_{FC}	=	180 days of full closure
$C7$	=	71 miles difference in distance between detour and original route

$$VOC_{FC} = \left(\left(\frac{\$0.59}{vehicle - mile} \ x \ 4{,}100 \frac{vehicle}{day}\right) + \left(\frac{\$0.96}{truck - mile} \ x \ 1{,}400 \frac{truck}{day}\right)\right) x \ 180 \ days \ x \ 71 \ miles$$

$$\boldsymbol{VOC_{FC} = \$48,091,140}$$

Next Equation 3.6 is used to calculate lost wages and truck revenue for full closures:

EQUATION 3.6

$$LW_{FC} = \left((C4 \ x \ O \ x \ AADT_{Vehicle}) + (C5 \ x \ AADT_{Truck})\right) x \ d_{FC} \ x \ \left(\frac{Dt}{60}\right)$$

Where:

$AADT_{Vehicle}$	=	4,100 average annual daily traffic (non-truck)
$AADT_{Truck}$	=	1,400 average annual daily truck traffic
$C4$	=	\$10.62 average value of time (\$/hour-adult)
O	=	1.77 average occupancy (adult/vehicle)
$C5$	=	\$25.31 average value of freight time(\$/hour-truck)
d_{FC}	=	180 days of full closure
Dt	=	96 of extra travel time on detour (minutes)

$$LW_{FC} = \left(\left(\frac{\$10.62}{adult-hour}\ x\ 1.77\frac{adult}{vehicle}\ x\ 4{,}100\frac{vehicle}{day}\right) + \left(\frac{\$25.31}{truck-hour}\ x\ 1{,}400\frac{truck}{day}\right)\right)\ x\ 180\ days\ x\ \frac{96\ min}{60\ \frac{min}{hour}}$$

$$\boldsymbol{LF_{FC}} = \$\mathbf{32,400,962}$$

Finally, sum of vehicle operating costs incurred due to vehicle travel on the detour and the lost wages and truck revenue due to travel on the detour utilizing Equation 3.3:

EQUATION 3.3

$$User\ Consequence_{FC} = VOC_{FC} + LW_{FC}$$

$$User\ Consequence_{FC} = \$48{,}091{,}140 + \$32{,}400{,}962$$

$$\boldsymbol{Total\ User\ Consequence} = \$\mathbf{80,492,102}$$

User Consequence for Partial Closure (PC):

Since partial closure is not anticipated at this site, VOC_{PC} and LW_{PC} for partial closure is estimated to be $0:

$$VOC_{PC} = \$0$$

$$LW_{PC} = \$0$$

$$\boldsymbol{User\ Consequence_{PC}} = \$\mathbf{0}$$

Total User Consequence:

Total user consequences include the sum of user consequence due to full closures and user consequence due to partial closures as shown in Equation 3.2:

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

$$Total\ User\ Consequence = \$80{,}492{,}102 + \$0$$

$$\boldsymbol{Total\ User\ Consequence} = \$\mathbf{80,492,102}$$

Step 5: Vulnerability Assessment (Failure Probability Assessment)

The annual probability of failure (PF) can be obtained based on the following bridge characteristics:

- Functional classification (NBI 26) = 1 (Interstate)
- Substructure condition (NBI 60) = 7 (Good Condition - some minor problems)
- Channel protection (NBI 61) = 8 (Banks are protected or well vegetated. River control devices such as spur dikes and embankment protection are not required or are in a stable condition)
- Water adequacy (NBI 71) = 8 (Equal to present desirable criteria)

Exhibit 4.2.6.15 presented previously estimates the annual overtopping frequency.

EXHIBIT 4.2.6.15 ANNUAL OVERTOPPING FREQUENCY

Functional Classification (NBI 26)	Waterway Adequacy (NBI 71)										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**N**
Principal Arterials-Interstates (01,11)	C	C	O	O	O	O	S	S	S	R	N
Freeways or Expressways (12)	C	C	F	O	O	O	S	S	S	R	N
Other Principal Arterials (02,14)	C	C	F	O	O	O	S	S	S	R	N
Minor Arterials (06,16)	C	C	F	O	O	O	S	S	S	R	N
Major Collectors (07,17)	C	C	F	O	O	O	S	S	S	R	N
Minor Collectors (08)	C	C	F	F*	O	O	O	S	S	R	N
Locals (09,19)	C	C	F	F*	O	O	O	S	S	R	N

(Source: Federal Highway Administration (FHWA) HYRISK Model (Pearson, 2002))

Where:

Overtopping Frequency	Annual Probability	Return Period
C Bridge Closed	N/A	N/A
N None	0	Never
R Remote	0.01	> 100
S Slight	0.02	11 to 100
O Occasional	0.2	3 to 10
F Frequent	0.3*	< 3

(Source: Federal Highway Administration (FHWA) HYRISK Model (Pearson, 2002))

The annual overtopping frequency is estimated to be S = Slight.

Next, obtain the scour vulnerability rating using Exhibit 4.2.6.16

EXHIBIT 4.2.6.16 SCOUR-BRIDGE VULNERABILITY

Channel Protection (NBI 61)	Substructure Condition (NBI 60)										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**N**
0 Failure	0	0	0	0	0	0	0	0	0	0	0
1 Failure	0	1	1	1	1	1	1	1	1	1	N
2 Near Collapse	0	1	2	2	2	2	2	2	2	2	N
3 Channel Migration	0	1	2	2	3	4	4	4	4	4	N
4 Undetermined Bank	0	1	2	3	4	4	5	5	6	6	N
5 Eroded Bank	0	1	2	3	4	5	5	6	7	7	N
6 Bed Movement	0	1	2	3	4	5	6	6	7	7	N
7 Minor Drift	0	1	2	3	4	6	6	7	7	8	N
8 Stable Condition	0	1	2	3	4	6	7	7	8	8	N
9 No Deficiencies	0	1	2	3	4	7	7	8	8	9	N
N Not Over water	0	1	N	N	N	N	N	N	N	N	N

(Source: Federal Highway Administration (FHWA) HYRISK Model (Pearson, 2002)

The estimated scour vulnerability rating for the bridge was 7 which means "good condition".

Utilizing the annual overtopping frequency obtained with Exhibit 4.2.6.15 along with the scour vulnerability rating from Exhibit 4.2.6.16, the annual probability of bridge failure (PF) is estimated using Exhibit 4.2.6.17:

EXHIBIT 4.2.6.17 ANNUAL PROBABILITY OF BRIDGE FAILURE (PF) FROM SCOUR

Scour Vulnerability (From Exhibit 4.2.6.16)	Overtopping Frequency (From Exhibit 4.2.6.15)			
	Remote (0.01)	**Slight (0.02)**	**Occasional (0.20)**	**Frequent (0.50)**
0 Bridge Failure	1.00	1.00	1.00	1.00
1 Bridge Closed	0.01	0.01	0.01	0.01
2 Extreme Vulnerable	0.005	0.006	0.008	0.009
3 Unstable Foundation	0.0011	0.0013	0.0016	0.002
4 Action Required	0.0004	0.0005	0.0006	0.0007
5 Fair Condition	0.0003	0.0004	0.0005	0.0007
6 Satisfactory Condition	0.00018	0.00025	0.0004	0.0005
7 Good Condition	0.00018	0.00025	0.0004	0.0005
8 Very Good Condition	0.000004	0.000005	0.00002	0.00004
9 Excellent Condition	0.0000025	0.000003	0.000004	0.000007

(Source: Revised FHWA HYRISK Model (Georgia Department of Transportation, 2013))

The estimated annual probability of failure (PF) for the bridge is estimated to be 0.00025.

Step 6: Risk Assessment

Annual Owner Risk

The annual owner risk for bridge scour is calculated utilizing Equation 3.10:

The value for K_1 is 1.0 for spans less than 100 feet long and the value for K_2 *is* 1.0 for unknown foundations or spread footings on erodible soil above scour depth with pier footing top visible or 1- to 2 ft below stream bed

$$K = K_1 * K_2$$

$$= 1.0 * 1.0$$

$$= 1.0$$

EQUATION 3.10 (Scour-Bridge)

$$Annual\ Owner\ Risk = Owner\ Consequence\ x\ PF\ x\ K$$

Where $K = K_1 * K_2$
K_1 is a bridge type factor based on NBI data, and K_2 is a foundation type factor based on information.

$$Annual\ Owner\ Risk = \$2{,}096{,}600\ x\ 0.00025\ x\ 1$$

$$\boldsymbol{Annual\ Owner\ Risk} = \$\mathbf{524}$$

Annual User Risk

Next, the annual user risk is calculated utilizing Equation 3.12:

EQUATION 3.12 (Scour-Bridge)

$$Annual\ User\ Risk = User\ Consequence\ x\ PF$$

$$Annual\ User\ Risk = \$80{,}492{,}102\ x\ 0.00025$$

$$\boldsymbol{Annual\ User\ Risk} = \$\mathbf{20,123}$$

Total Annual Risk

Calculate total annual risk by adding total annual owner risk to total annual user risk utilizing Equation 3.13:

EQUATION 3.13

$$Total\ Annual\ Risk\ = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

Where n= number of events

$$Total\ Annual\ Risk = \$524 + \$20{,}123$$

$$\boldsymbol{Total\ Annual\ Risk} = \$\mathbf{20,647}$$

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4.3 Results of Post-Fire Debris Flow Risk and Resilience Assessment

Debris flow is defined as "a moving mass of loose mud, sand, soil, rock, water, and air that travels down a slope under the influence of gravity" (Colorado Geological Survey, 2019). For this procedure, it is considered the resulting kinetic movement of debris as a result of a rainfall event on post-fire burn scars, beginning with exposed debris within a sub-basin and cascading through channels and avulsions until the loss of kinetic energy restricts its non-hydraulic travel. Debris flows are not the debris flood that occurs downstream of impacted hydrologic channels that may impact downstream assets for the purposes of this procedure. Debris floods would be considered a separate threat that an analyst would need to conduct with different input data and models.

Additionally, while debris flow events typically occur after a 1-2-year rainfall event that impacts the hydrologically sensitive soils of a post wildfire ecosystem, amplifying the hydrologic response, they are not the result of a catastrophic 100-500-year rainfall event, the likes of which are not included in this analysis approach. The analysis provided relies upon data from a post-fire Burned Area Emergency Response (BAER) study and the resulting data produced in cooperation with USGS as an "Emergency Assessment of Post-Fire Debris-Flow Hazards". CDOT staff are urged to review the work completed by USGS after fire events that may leave slopes adjacent to highway assets vulnerable to debris flow.

From 2016-2018 there have been 13 wildfires that prompted a BAER study in Colorado and the resulting USGS debris flow assessment; of these, four were chosen for the final analysis based on the anticipated impacts to CDOT highway assets. Cold Springs, Junkins, 416, and Spring Creek fires were included in the analysis presented in this document and in Exhibit 4.3.3. The selection criteria considered distance from a roadway asset (State Route, US Highway, Interstate), obstruction between the fire and the road (rivers, terrain, buildings), time passage since fire event (no fires from before 2016 were considered due to vegetative regrowth), and burn severity (fires with low burn severity could be ignored due to their unlikely ability to generate a debris flow).

Note, the procedure to estimate debris flow risk to highway assets differs from rockfall and flood threats previously discussed in this procedure. In particular, BAER studies are needed to analyze the potential debris flow, that are completed typically by USGS. In addition, GIS is highly recommended to be utilized to determine potential runout areas where debris may deposit. As requested by CDOT, this section provides the results of the debris flow risk assessment to highway assets downstream of four severe fire areas previously described. For future fires, similar BAER studies will need to be utilized to replicate this approach.

Overview of Data

The process of debris flow analysis for this procedure relies on the datasets in Exhibit 4.3.1, not including asset data.

EXHIBIT 4.3.1 DATA NEEDS FOR POST-FIRE DEBRIS FLOW RISK ANALYSIS

Data Set	Data Source
USGS BAER post-fire debris flow assessment	USGS landslide hazards program https://landslides.usgs.gov/hazards/postfire_debrisflow/
Debris flow depositional data	As produced using any numerical debris flow propagation model
Rainfall intensity to recurrence interval conversion	NOAA Atlas 14 point precipitation frequency estimates https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=co
Digital elevation dataset (10 m)	USGS national map https://viewer.nationalmap.gov/advanced-viewer/
Roadway assets	CDOT culverts (April 2019) & OTIS roadways

The typical process post-fire is described here. After a severe fire has burned an area and been extinguished, a BAER team will be dispatched to its location to analyze the soil conditions after the burn and compare it to pre-burn conditions. Upon completion, this data is used by USGS to analyze the watershed basins that exist within the burn scar of the fire for two variables: volume and probability of debris flow occurrence in a given basin for rainfall intensity within a peak 15-minute interval, ranging from 20-40mm/hour. This value is used in conjunction with NOAA's precipitation frequency estimator to determine applicable recurrence intervals for the burn scar area. In the analyses included here, this has shown to be either 1- or 2-year rainfall events can generate a debris flow.

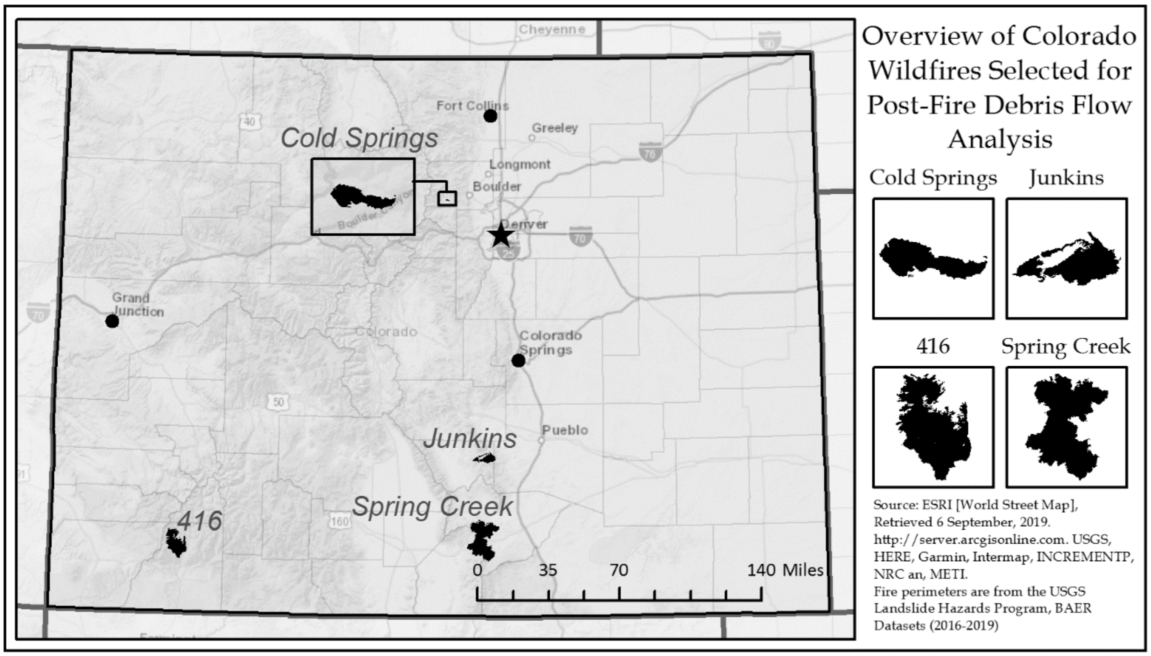
With the basins in mind, a numerical debris flow model is executed to estimate where kinetic flows may deposit. *Flow-R*, a distributed empirical model for regional susceptibility assessments of debris flows, developed by the University of Lausanne, Switzerland was utilized in this document. This model requires multiple digital elevation datasets to execute. The resulting debris flows (an example can be seen in Exhibit 4.3.6: 416 Fire Impact Map 1 of 4) are then spatially joined back to their originating watershed basins and inherit the debris flow data provided by USGS. If a basin contains multiple debris flows, the volume is distributed equally. These debris flows are then spatially linked to intersecting assets in their path, resulting in a calculation of owner and user risk based on asset characteristics through standard risk calculations.

Given the use of *Flow-R* and GIS to spatially join watershed basins to the anticipated debris flow data provided by USGS, the results of the work are shown here without hand calculations as in the assessment of rockfall and flood threats.

Summary of Results

Exhibit 4.3.2 depicts the four selected wildfires that were included in the analysis of debris flow impacts on Colorado DOT assets. All maps are displayed at scale with exception of the Cold Springs fire, which is magnified for readability.

EXHIBIT 4.3.2 MAP DEPICTING THE FOUR SELECTED WILDFIRES IN COLORADO



Summary of Risk

Exhibit 4.3.3 provides an overview of owner, user, and total risk for all assets within a specific fire runout of debris. Again, the 416 fire dominates the other three fires in total risk and owner risk, but this time it is comparable to the Spring Creek fire in terms of the user risk only being $50,000 greater. This is mainly due to the extensive detour route anticipated at the Spring Creek fire location as shown in Exhibit 4.3.4.

EXHIBIT 4.3.3 SUMMARY OF DEBRIS FLOW RISK

Fire	Roadways		Culverts		Total		
	Owner	User	Owner	User	Owner	User	Total
416	$890,110	$512,040	$2,102,310	$1,681,860	$2,992,420	$2,193,900	$5,186,320
Spring Creek	$91,310	$462,200	$25,170	$86,680	$116,480	$548,880	$665,360
Junkins	$8,980	$1,130	$20,440	$4,190	$29,420	$5,320	$34,740
Cold Springs	$20,150	$9,530	$4,850	$3,330	$25,000	$12,860	$37,860
				TOTAL	$3,163,320	$2,760,960	**$5,924,280**

Summary of Impacted Assets

Exhibit 4.3.4 includes the statistics of assets anticipated to be impacted by debris flow across the four fires. The 416 fire is anticipated to impact the most CDOT assets, with 35 road segments totaling more than 3 miles of roadway anticipated to be impacted by projected debris flow. In addition, 23 culverts are at risk for debris flow near the 416 fire.

EXHIBIT 4.3.4 SUMMARY OF IMPACTED ASSETS

Fire	Location	Miles Impacted	# of Road Segments	Culverts Impacted
416	US 550	3.06 mi	35	23
Spring Creek	US 160	0.56 mi	13	6
Junkins	CO-165	0.29 mi	4	3
Cold Springs	CO-119	0.19 mi	4	1

Summary of Detours

For each debris flow that is anticipated to impact a roadway or culvert, a calculation of user risk is estimated. This relies upon determining a detour route to divert traffic around the impacted area, which in some cases (such as the Spring Creek fire) can be significant. Exhibit 4.3.5 includes the estimated detour routes derived based on the shortest possible route that utilize NHS/CDOT highway assets. Spring Creek is situated in the Sangre de Cristo mountain range, and US highway 160 winds its way through an isolated pass including various creeks, connecting the San Luis Valley with the rest of the eastern Plains of Colorado and the City of Pueblo. This detour was selected as to avoid detouring traffic into New Mexico.

EXHIBIT 4.3.5 SUMMARY OF DETOUR ROUTES FOR POST FIRE DEBRIS FLOWS

Fire	Location	Detour Route	Detour Length	Detour Time
416	US 550	US 160 to CO 184 to CO 145 to CO 62	62 miles	~40 min
Spring Creek	US 160	CO 17 to US 285 to US 50 to CO 69 to I-25	196 miles	~3.5 hrs
Junkins	CO-165	CO 165 to I-25 to CO 45 to CO 96	67 miles	~70 min
Cold Springs	CO-119	CO 119 to CO 72 to CO 93 to CO 119	17 miles	~30 min

Overview of Debris Flow Impact: Corridor Maps

Exhibits 4.3.6 through 4.3.9 include debris impact maps of each fire's threat-asset intersections. Each asset impacted is included and labeled with a number that corresponds to information provided in asset data tables presented after each map.

Exhibits 4.3.6 to 4.3.9 are closeup sections of the 416 fire, segmented in a way that allows interpretation of individual impacted assets at a legible scale. The four maps are presented sequentially with regards to milepost designations. Only the 416 fire required multiple maps due to its larger area of impact area. The other fires are presented on one map.

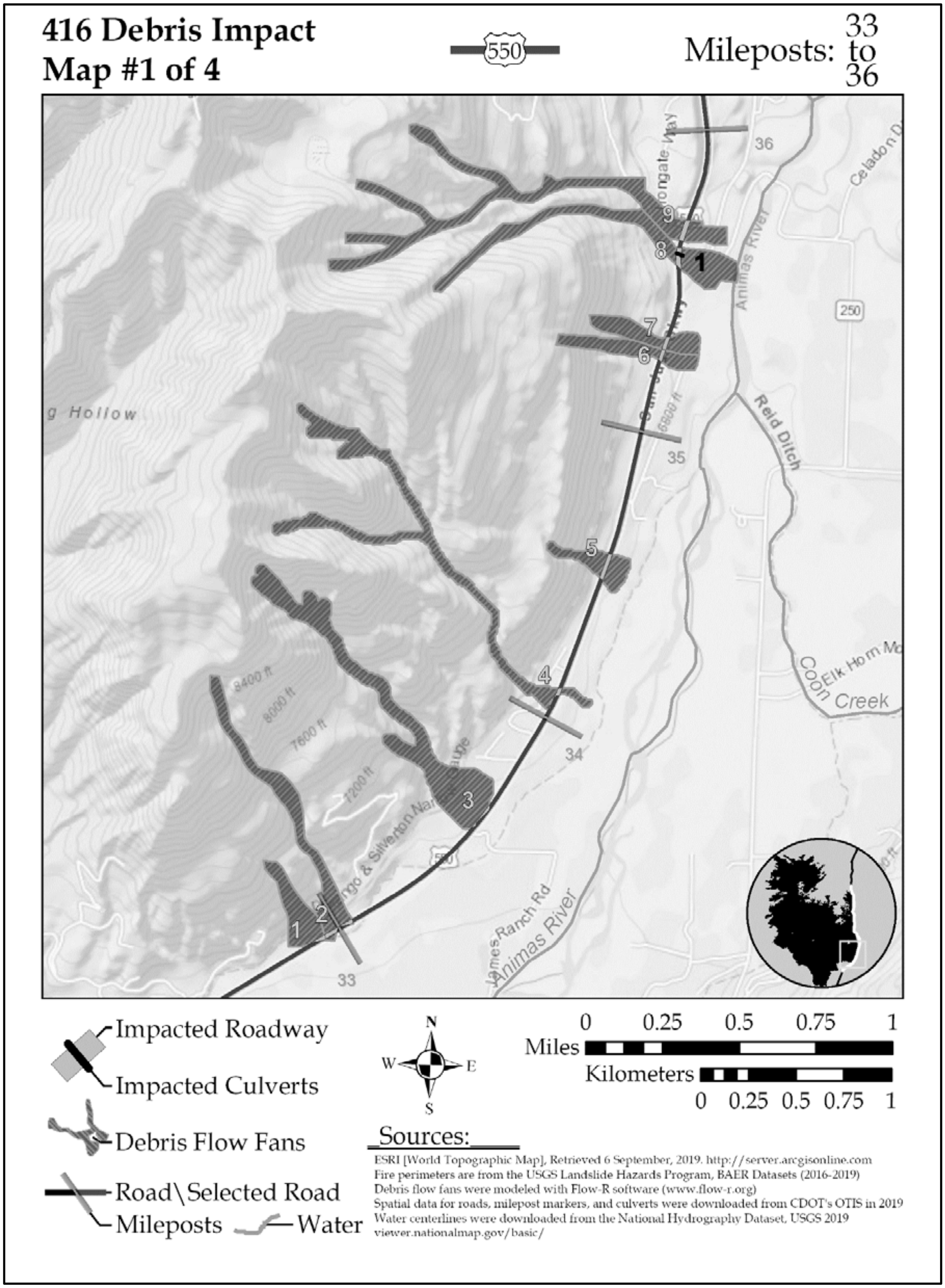
On each map, the debris flow polygons created by the process described in "Overview of Data" are included. Any roadway assets that intersect a polygon are reduced to one polygon to represent the total asset that is at risk from debris flow. On a particularly winding roadway a runout polygon can intersect twice at different mileposts, this can be seen in Exhibit 4.3.15 for the Junkins Fire. When this occurs, both roadways are treated as one, despite the difference in location, and the roadway risk is applied unilaterally. Culverts are a simple intersection between debris flow polygons and the culvert feature. If a culvert intersects a debris flow polygon at any point, it is added to the analysis.

For each asset, a number is provided that corresponds to its position in a following table that outlines the risk estimated to the roadway from the post-fire debris flow. This number acts as a key for the maps to the tables and is in exhibits as shown in the second column heading. A thick line on a table denotes a sequential map and is only present for the 416 Fire table. Within the sections after the culvert table for each fire is a brief overview of the risk hotspots for all assets. In these sections, the number is referenced as R# for roadways and C# for culverts.

For each roadway segment impacted the "From MP" and "To MP" fields indicate which milepost (MP) designation the segment begins and ends. Finally, for culverts, the "FLOC" field refers to Functional Location, a field identifier designation derived from CDOT's culvert database.

EXHIBIT 4.3.6
416 FIRE IMPACT MAP 1 OF 4

416 Fire Impact Map 1 of 4



416 Fire Impact Map 2 of 4

EXHIBIT 4.3.7
416 FIRE IMPACT MAP 2 OF 4

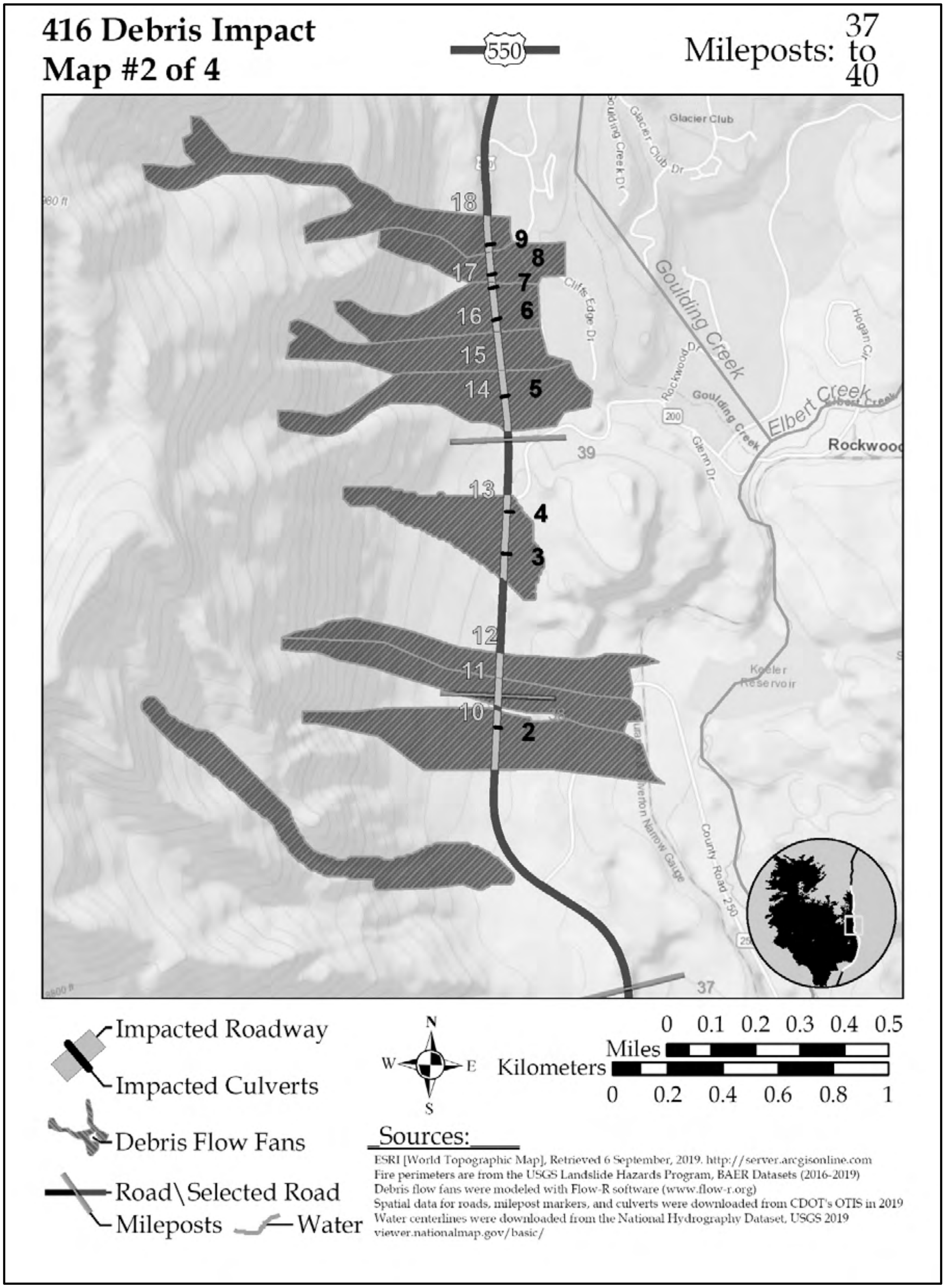


Exhibit 4.3.8
416 Fire Impact Map 3 of 4

416 Fire Impact Map 3 of 4

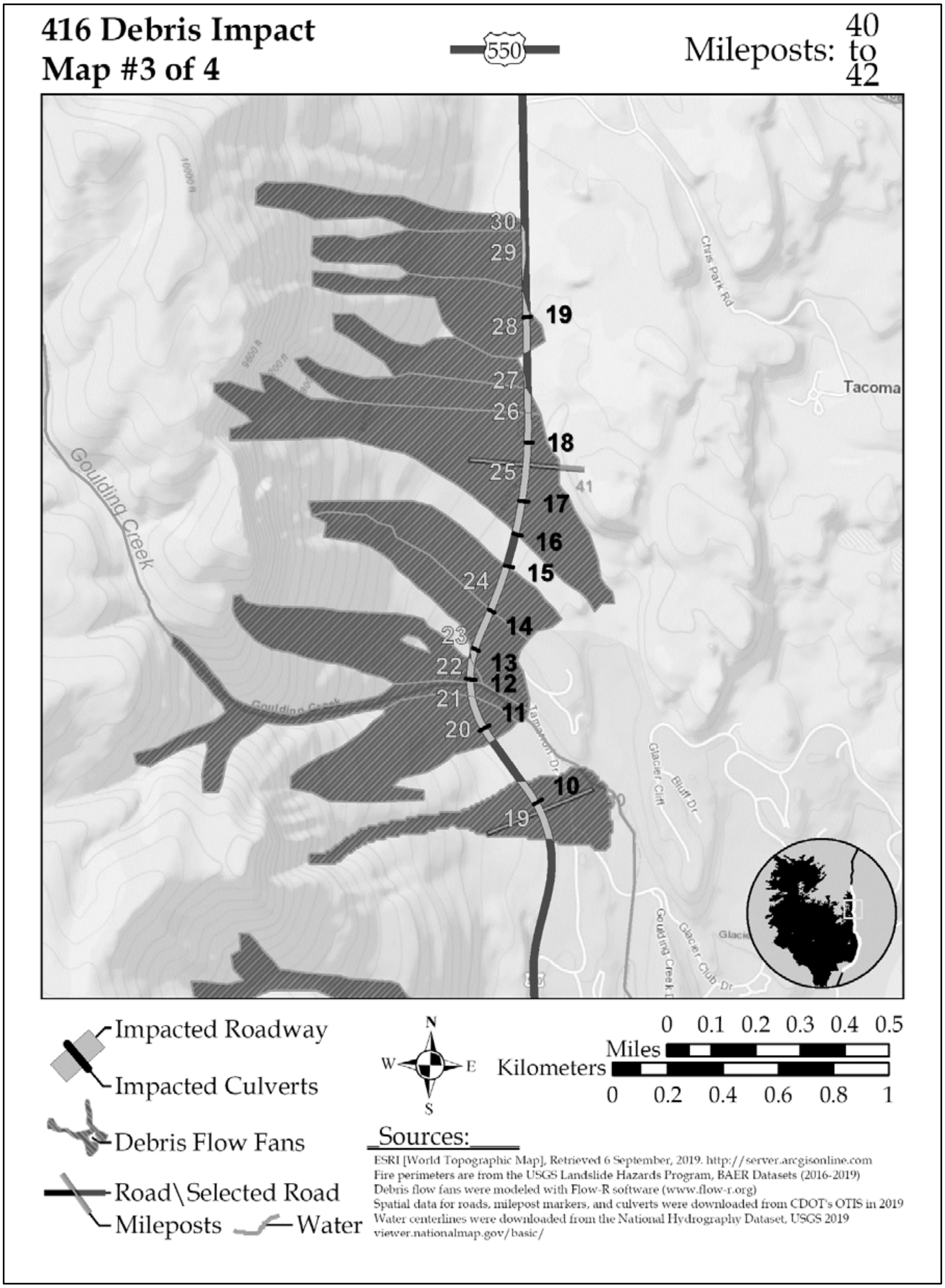


EXHIBIT 4.3.9
416 FIRE IMPACT MAP 4 OF 4

416 Fire Impact Map 4 of 4

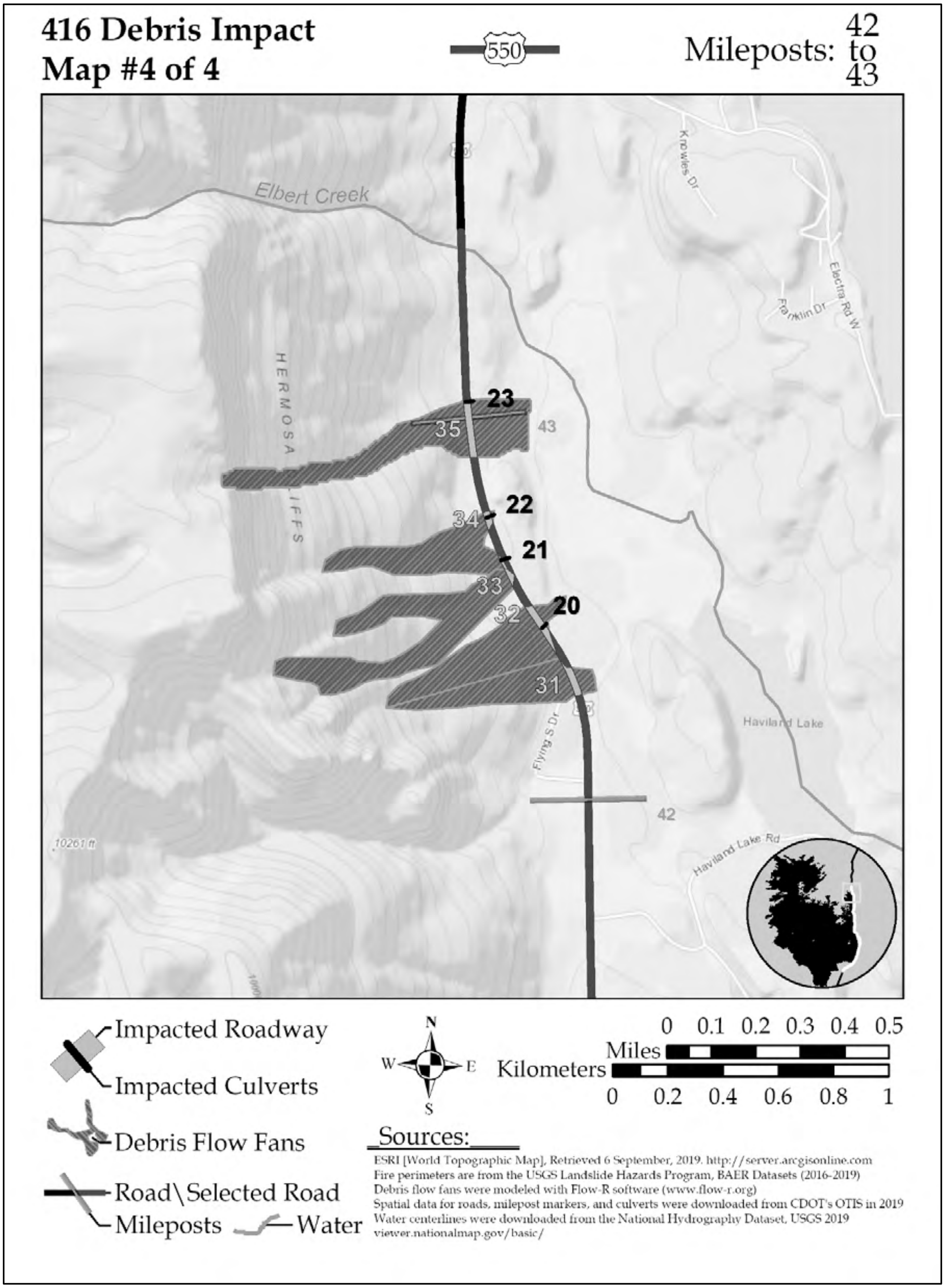


EXHIBIT 4.3.10
416 FIRE
POST-FIRE
DEBRIS FLOW -
ROADWAY PRISM
ANNUAL RISK

Annual Risk for Roadway Prism on US 550

Fire	Key#	Milepost Location		Annual Owner Risk	Annual User Risk	Annual Total Risk
		From	To			
416	1	32.81	32.86	$1,077	$2,215	**$3,292**
	2	32.93	33.03	$6,523	$5,289	**$11,812**
	3	33.54	33.62	$3,340	$5,203	**$8,542**
	4	34.00	34.05	$5,060	$9,348	**$14,408**
	5	34.46	34.54	$36,561	$22,069	**$58,630**
	6	35.20	35.23	$11,078	$17,612	**$28,689**
	7	35.27	35.30	$6,209	$9,309	**$15,517**
	8	35.54	35.61	$31,910	$24,860	**$56,771**
	9	35.61	35.67	$31,669	$21,092	**$52,760**
	10	37.70	37.83	$64,271	$27,012	**$91,283**
	11	37.90	37.96	$32,239	$28,132	**$60,372**
	12	38.00	38.05	$28,397	$28,115	**$56,511**
	13	38.30	38.49	$99,298	$28,032	**$127,330**
	14	39.00	39.13	$72,932	$27,970	**$100,903**
	15	39.13	39.21	$46,456	$27,923	**$74,378**
	16	39.22	39.33	$56,994	$27,631	**$84,625**
	17	39.33	39.39	$37,865	$27,517	**$65,382**
	18	39.40	39.48	$14,073	$8,864	**$22,937**
	19	39.92	40.07	$57,434	$20,288	**$77,723**
	20	40.14	40.24	$21,764	$10,229	**$31,994**
	21	40.30	40.33	$6,885	$9,453	**$16,338**
	22	40.37	40.42	$7,226	$8,011	**$15,237**
	23	40.43	40.56	$60,510	$25,910	**$86,421**
	24	40.56	40.59	$37,049	$18,526	**$55,575**
	25	40.73	41.00	$43,230	$8,635	**$51,865**
	26	41.10	41.15	$2,238	$2,390	**$4,628**
	27	41.17	41.19	$771	$5,809	**$6,580**
	28	41.19	41.30	$24,463	$11,465	**$35,928**
	29	41.37	41.48	$7,972	$7,828	**$15,800**
	30	41.50	41.50	$605	$6,758	**$7,364**
	31	42.20	42.28	$12,718	$9,922	**$22,640**
	32	42.31	42.42	$9,234	$5,436	**$14,670**
	33	42.53	42.55	$2,634	$6,194	**$8,828**
	34	42.60	42.68	$3,739	$4,474	**$8,213**
	35	42.85	42.98	$5,686	$2,520	**$8,206**

EXHIBIT 4.3.11 416 FIRE POST-FIRE DEBRIS FLOW-CULVERT ANNUAL RISK

Annual Risk for Culverts on US 550

Fire	Key#	Milepost	Functional Location	Annual Owner Risk	Annual User Risk	Annual Total Risk
416	1	35.58	CULV36845	$11,346	$8,415	**$19,761**
	2	37.80	CULV40640	$168,784	$192,941	**$361,725**
	3	38.37	CULV36122	$292,866	$200,226	**$493,092**
	4	38.46	CULV36195	$127,344	$94,868	**$222,211**
	5	39.08	CULV40825	$272,784	$199,789	**$472,573**
	6	39.25	CULV36011	$61,987	$52,587	**$114,575**
	7	39.32	CULV40416	$20,332	$16,631	**$36,963**
	8	39.34	CULV38918	$254,765	$196,550	**$451,315**
	9	39.42	CULV36943	$163,706	$124,472	**$288,177**
	10	40.08	CULV41712	$212,274	$144,918	**$357,192**
	11	40.16	CULV42475	$38	$17	**$55**
	12	40.38	CULV38650	$43,319	$30,010	**$73,329**
	13	40.54	CULV38709	$200,631	$185,074	**$385,704**
	14	40.55	CULV41177	$93,141	$87,689	**$180,829**
	15	40.59	CULV37979	$14,442	$11,151	**$25,593**
	16	40.72	CULV41578	$67,661	$51,965	**$119,626**
	17	40.80	CULV41941	$22,837	$16,434	**$39,271**
	18	41.02	CULV38253	$17,622	$16,434	**$34,057**
	19	41.25	CULV41250	$36,508	$28,633	**$65,141**
	20	42.37	CULV39819	$16,912	$20,362	**$37,274**
	21	42.62	CULV38380	$663	$530	**$1,193**
	22	42.66	CULV38300	$199	$168	**$366**
	23	42.98	CULV38858	$2,147	$1,990	**$4,138**

Locations of Note

The 416 fire is, by and large, the biggest current debris flow risk to the State of Colorado as the result of a wildfire as of the time of this document development, however, there is evidence that some of the debris flow has occurred. The statistics presented for risk along US 550 as a result of the 416 fire are substantially higher than that of the other three fires, both in risk dollars and number of assets impacted. A few major areas of focus stand out: MP 37- MP 40, especially for culverts and the highest risk values for roadway, and MP 33-35, an area where despite minimum risks accrued by the roadway (compared to culverts), the detour could still be enacted if one event covers the road.

Spring Creek Fire Impact Map 1 of 1

EXHIBIT 4.3.12 SPRING CREEK FIRE IMPACT MAP 1 OF 1

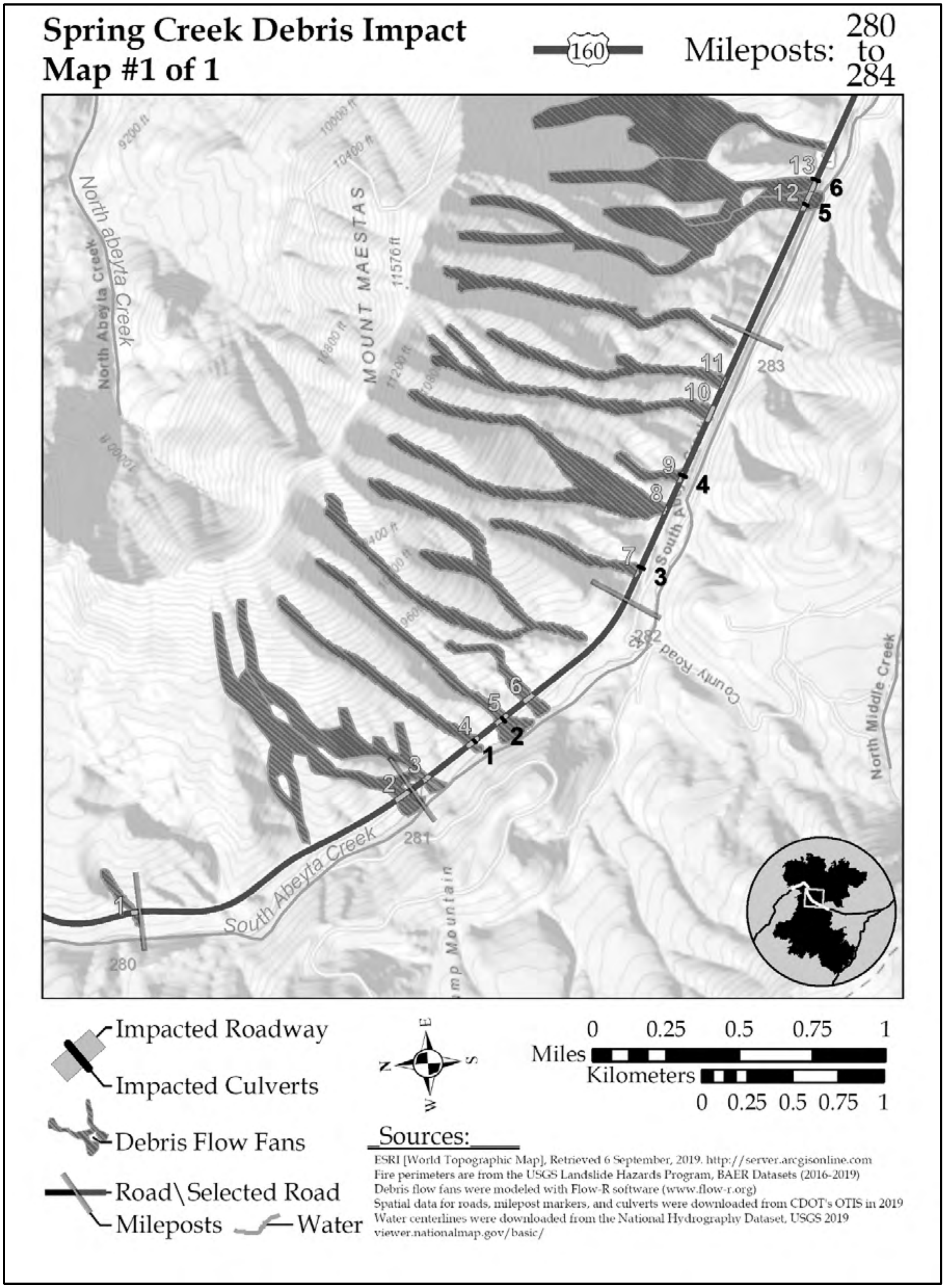


EXHIBIT 4.3.13 SPRING CREEK FIRE POST-FIRE DEBRIS FLOW-ROADWAY PRISM ANNUAL RISK

Annual Risk for Roadway Prism on US 160

Fire	Key #	Milepost Location		Annual Owner Risk	Annual User Risk	Annual Total Risk
		From	To			
Spring Creek	1	279.90	279.92	$3,054	$26,419	**$29,473**
	2	280.86	280.95	$7,425	$23,215	**$30,641**
	3	281.00	281.02	$3,768	$39,938	**$43,707**
	4	281.17	281.21	$15,341	$57,136	**$72,478**
	5	281.30	281.36	$28,180	$106,194	**$134,374**
	6	281.47	281.51	$11,764	$55,833	**$67,597**
	7	282.05	282.07	$3,604	$41,690	**$45,293**
	8	282.30	282.32	$2,241	$28,671	**$30,912**
	9	282.38	282.41	$3,701	$28,671	**$32,372**
	10	282.58	282.63	$5,666	$19,418	**$25,084**
	11	282.78	282.81	$1,495	$15,859	**$17,354**
	12	283.38	283.46	$3,320	$9,794	**$13,114**
	13	283.50	283.54	$1,746	$9,362	**$11,108**

EXHIBIT 4.3.14 POST-FIRE DEBRIS FLOW-CULVERT ANNUAL RISK

Annual Risk for Culverts on US 160

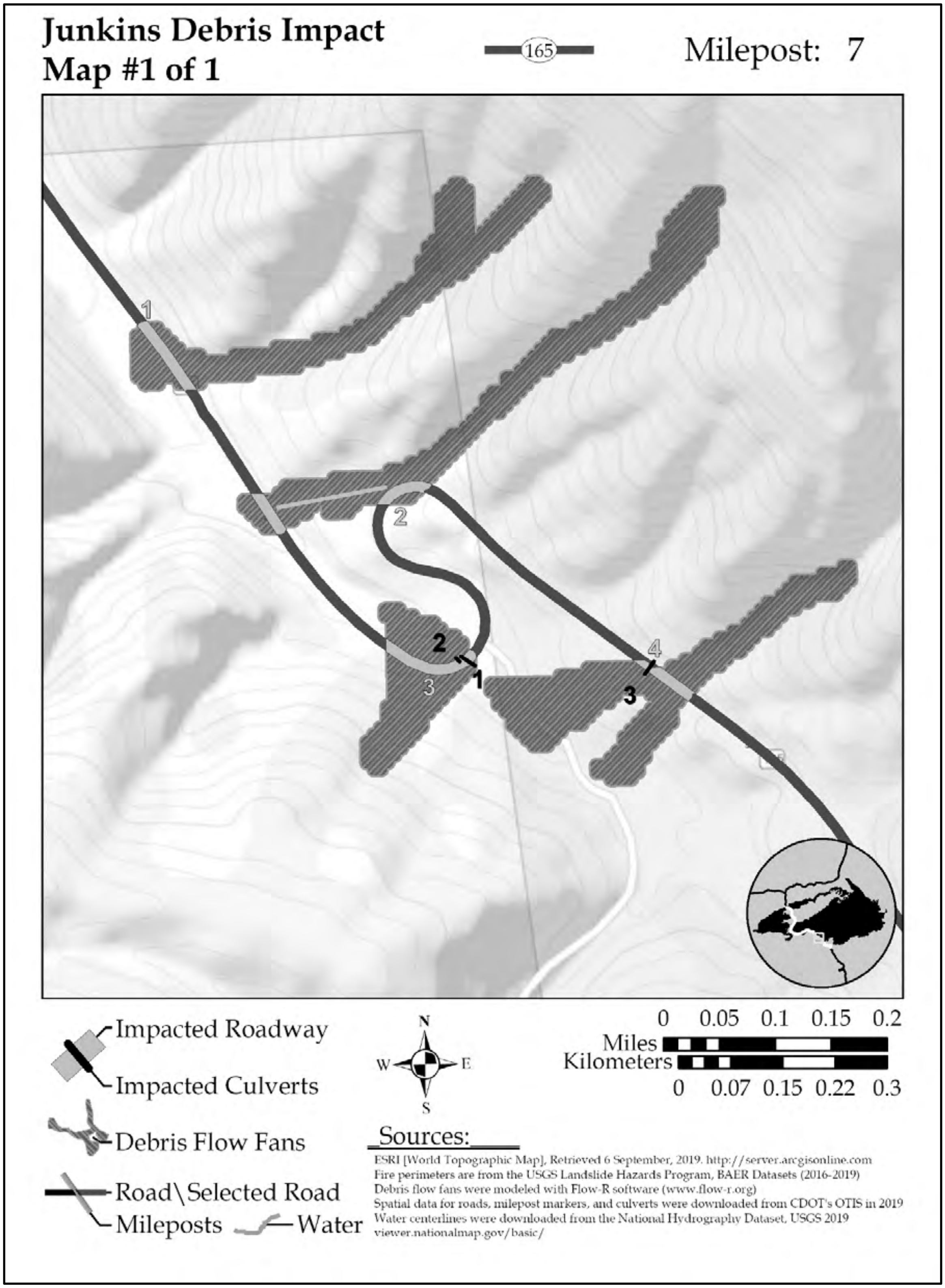
Fire Name	Key #	Milepost	Functional Location	Annual Owner Risk	Annual User Risk	Annual Total Risk
Spring Creek	1	281.20	CULV41975	$11,132	$45,127	**$56,260**
	2	281.32	CULV43558	$11,836	$33,195	**$45,031**
	3	282.03	CULV39711	$32	$104	**$136**
	4	282.37	CULV10307	$185	$494	**$679**
	5	283.39	CULV09687	$1,979	$7,735	**$9,714**
	6	283.48	CULV10329	$9	$23	**$32**

Locations of Note

The Spring Creek fire burn scar is still an issue that threatens La Veta Pass. Some of the highest risk occurs near milepost 281, roadway key #'s 2 through 6 and culvert key # 2, accumulating more than $450,000 of risk in total. The risk to culverts is concentrated at this location with an overall risk to the roadway assets further downstream.

Junkins Fire Impact Map 1 of 1

EXHIBIT 4.3.15 JUNKINS FIRE IMPACT MAP 1 OF 1



Annual Risk for Roadway Risk on CO-165

EXHIBIT 4.3.16 JUNKINS FIRE POST-FIRE DEBRIS FLOW-ROADWAY PRISM ANNUAL RISK

Fire	Key#	Milepost Location		Annual Owner Risk	Annual User Risk	Annual Total Risk
		From	To			
Junkins	1	6.54	6.61	$2,451	$291	**$2,742**
	2	6.72	7.15	$1,754	$177	**$1,931**
	3	6.82	6.90	$2,054	$199	**$2,253**
	4	7.41	7.46	$2,718	$464	**$3,182**

Annual Risk for Culverts on CO-165

EXHIBIT 4.3.17 JUNKINS FIRE POST-FIRE-CULVERT ANNUAL RISK

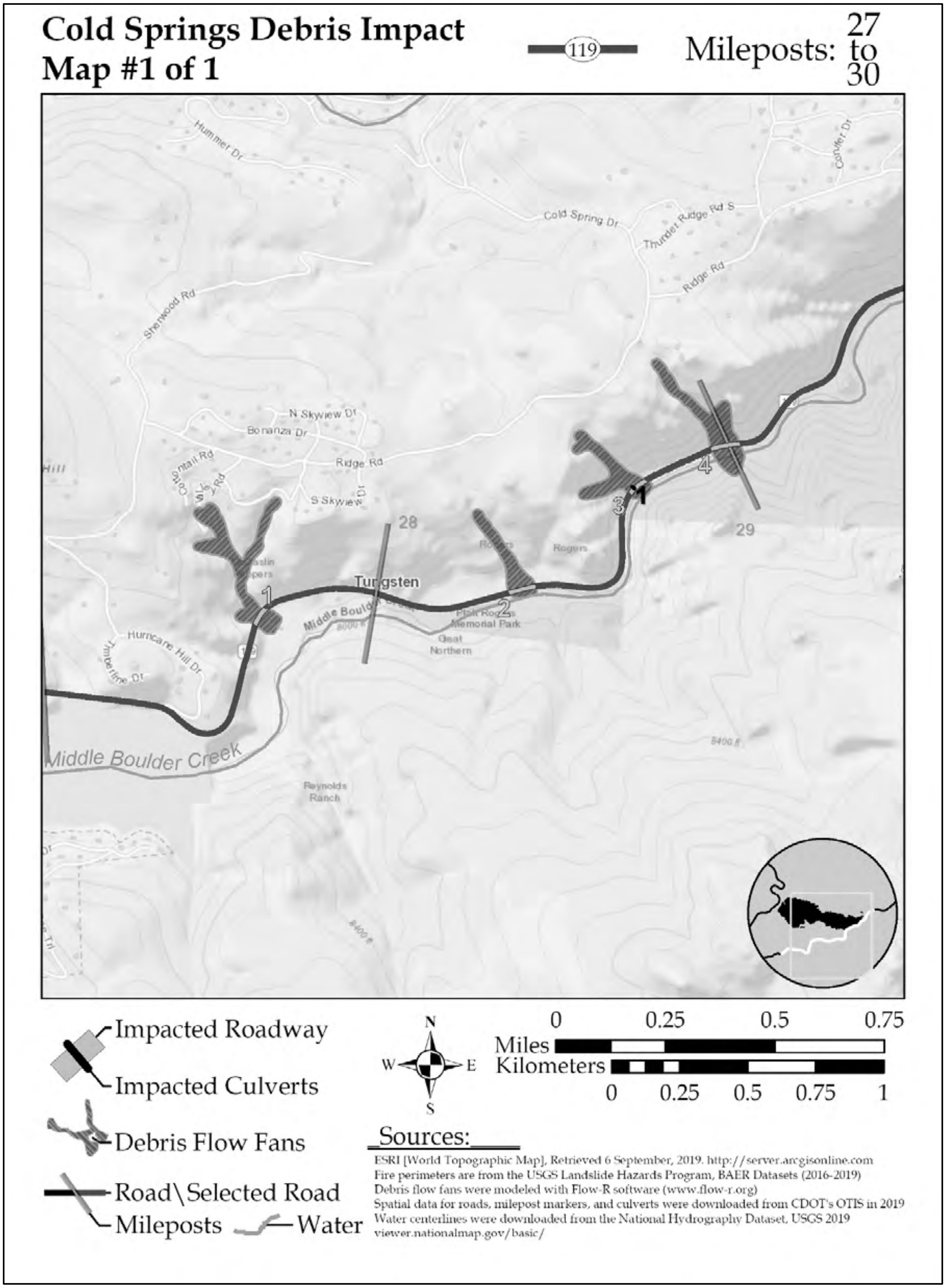
Fire	Key #	MP	Functional Location	Annual Owner Risk	Annual User Risk	Annual Total Risk
Junkins	1	6.94	CULV11055	$13,041	$3,312	**$16,353**
	2	6.96	CULV12593	$29	$0	**$29**
	3	7.46	CULV13133	$7,369	$882	**$8,251**

Locations of Note

The Junkins fire does not pose as high of an annual risk to CDOT assets given the length of time that has passed since its occurrence. The risk at this location is focused on one singular point in the valley of Round Top Mountain, near MP 7. In this location, the debris flow may avulse and impact two areas of the highway.

Cold Springs Fire Impact Map 1 of 1

EXHIBIT 4.3.18 COLD SPRINGS FIRE IMPACT MAP 1 OF 1



Annual Risk for Roadway Prism on CO-119

EXHIBIT 4.3.19 COLD SPRINGS FIRE POST FIRE DEBRIS FLOW-ROADWAY PRISM ANNUAL RISK

Fire	Key#	Milepost Location		Annual Owner Risk	Annual User Risk	Annual Total Risk
		From	To			
Cold Springs	1	27.66	27.70	$982	$556	**$1,538**
	2	28.30	28.36	$2,438	$1,044	**$3,482**
	3	28.67	28.71	$7,625	$4,215	**$11,840**
	4	28.90	28.96	$9,102	$3,720	**$12,822**

Annual Risk for Culverts on CO-165

EXHIBIT 4.3.20 COLD SPRINGS FIRE POST-FIRE DEBRIS FLOW-CULVERT ANNUAL RISK

Fire	Key #	MP	Functional Location	Annual Owner Risk	Annual User Risk	Annual Total Risk
Cold Springs	1	28.68	CULV34098	$4,852	$3,329	**$8,181**

Locations of Note

The Cold Springs fire occurred in 2016 near the town of Nederland. In this location, the most at-risk assets were near MP 28.6 where both a section of highway and a culvert could be impacted resulting in approximately $20,000 of risk.

Conclusion

In conclusion, it is estimated that the annual risk to highway assets from debris flow at these four locations is approximately $5,924. Culvert risk is proportionally higher than roadway risk on the 416 and Junkins fire locations. The 416 fire is the largest source of risk from post-fire debris flow, however, this procedure does not take into account the current loss of debris from rainfall that has occurred since 2018.

Debris flow research is an emerging field and numerous organizations and scientists are working towards a greater understanding of how to best model the threat. The user is encouraged to seek out emerging research and direction provided by lead agencies on debris flow such as USGS for future applications

CHAPTER 5: RISK MANGEMENT

Introduction to Resilience Assessment

Resilience is defined by FHWA as "the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions". The Congressional Research Service documented evolving policy that has moved away from protection and more toward resilience post 9/11 (Moteff, Critical Infrastructure Resilience: The Evolution of Policy and Programs and Issues for Congress, 2012). As noted, "improving resiliency reduces risk primarily by reducing vulnerability to and potential consequences of an attack or natural event."

Risk and resilience terms are often used interchangeably with multiple definitions and metrics from different sectors. The transportation sector defines resilience as "*the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions*." (US Department of Transportation Federal Highway Administration, 2014). However, there is a lack of a standard metric to measure resilience in the highway and transportation sector. From literature, some of the most common principles or components of resilience are robustness, redundancy, resourcefulness and rapidity (Bruneau, et al., 2003).

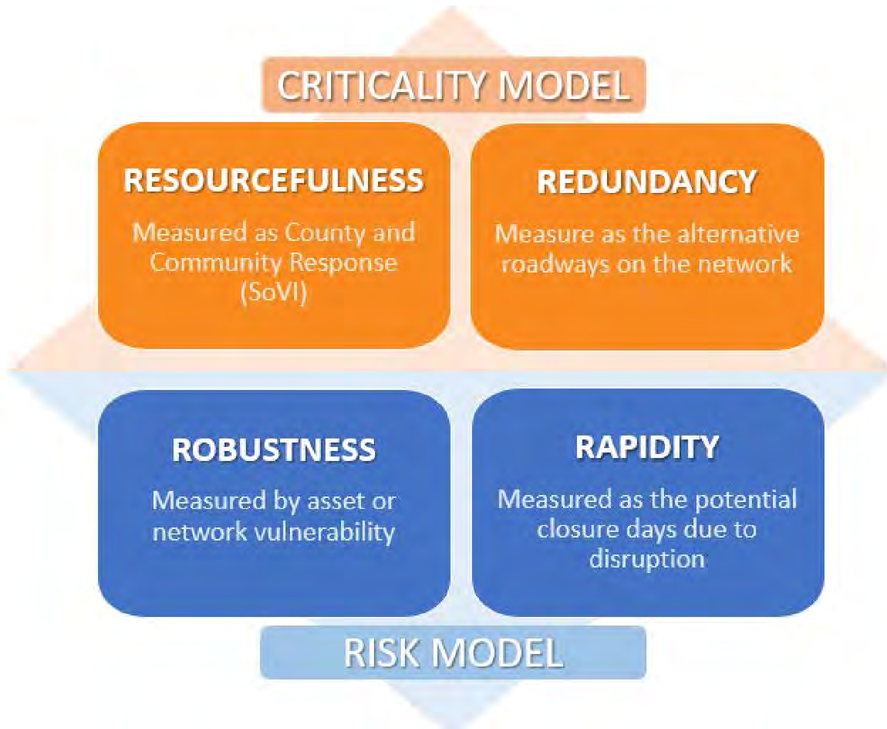
As part of this project, a method to measure the Level of Resilience (LOR) of the transportation system, network or corridor based on the "4-Rs principle" from Bruneau is provided as a potential metric for CDOT. Note: the proposed method has yet to be fully vetted or adopted by CDOT. Exhibit 5.1 presents definitions for the four resilience principles described by Bruneau.

EXHIBIT 5.1 FOUR RESILIENCE PRINCIPLES BY (BRUNEAU, ET AL., 2003)

Robustness	• Inherent strength or resistance in a system to withstand external demands without degradation or loss of functionality
Redundancy	• System properties that allow for alternate options, choices, and substitutions under stress
Resourcefulness	• Capacity to mobilize needed resources and services in emergencies
Rapidity	• Speed with which disruption can be overcome

The proposed Level of Resilience (LOR) Index represents and incorporates the Bruneau's resilience components, merging the annual risk and the criticality for systems resilience level presented in previous chapters of this guide. The Criticality Model for System Resilience presented in Chapter 2 captures the resourcefulness and redundancy of the CDOT System while the proposed risk estimation models presented in Chapter 3 and applied in Chapter 4, capture the robustness and rapidity principles. For example, *Resourcefulness* is represented in the Criticality Model for System Resilience through the factor SoVI® that reflects the ability of counties in Colorado to prepare for, respond to, and recover from hazards. *Redundancy* is captured in the same model in the factor "Redundancy" that represents the number of alternative routes available for travelers on the CDOT system described in Chapter 2. Next, from the Risk Model, *Robustness* is captured in the Vulnerability factor in the quantitative risk calculation. Finally, from the Risk Model, *Rapidity* is captured in the User Risk Model by the number of anticipated days of closure from relevant threats.

EXHIBIT 5.2 LEVEL OF RESILIENCE (LOR) INDEX COMPONENTS



Level of Resilience Index

A potential metric to describe system resilience is portrayed in the Level of Resilience (LOR) Index. The LOR Index is derived using annual risk from applicable threats and a measure of asset criticality as defined in Chapter 2. Risk can be represented as the annual risk in dollars ($) or dollars per lane-mile ($/lane-mi) per 1-mile segment lengths. The annual risk is equally divided in five quantiles where each quantile represents 20 percent of the overall database and ordered from low to high (Quantile 1 through 5). The Criticality Score for Systems Resilience is divided into three categories of low, moderate, and high as previously described in Chapter 2. Next, the Level of Resilience (LOR) Index is developed as shown in Exhibit 5.3 with five categories of resilience. The LOR Index varies from A through E, where LOR A means the system or network has a "Very High" resilience and LOR E means it has a "Very Low" Resilience.

EXHIBIT 5.3 PROPOSED LEVEL OF RESILIENCE (LOR) INDEX TABLE

Annual Risk (Robustness/Rapidity)	Criticality for Systems Operations (Resourcefulness/Redundancy)		
	Low	Moderate	High
0 20% Cumulative Annual Risk	A	B	C
21 40% Cumulative Annual Risk	B	B	C
41 60% Cumulative Annual Risk	C	C	C
61 80% Cumulative Annual Risk	C	C	D
81 100% Cumulative Annual Risk	D	D	E

As shown in Figure 5.3, assets that are categorized as Highly Critical in terms of System Resilience and have annual risk that falls into the highest quantiles of risk will have a LOR of E. By contrast those assets that score with a Low Criticality and have an annual risk that falls into the lowest quantile of risk will have a LOR of A. One potential use of the LOR Index is to see visually across an agency's system the areas that are rated as LOR E or D and begin to investigate potential capital investments or operational strategies to improve system resilience.

Example Level of Resilience (LOR) Index – Utilizing I-70 Pilot Data

To demonstrate the potential development of a Level of Resilience (LOR) Index for Colorado DOT, example data from the 2017 I-70 Risk and Resilience Pilot was utilized. The example LOR index was calculated and presented for the aggregation of total annual risk in dollars per lane-mile ($/lane-mile) for all threats and assets assessed on I-70 for 1-mile roadway segments as shown in Exhibit 5.4. NOTE: it is recommended that additional work be completed to better establish the thresholds of annual risk for each of the five quantiles as the provided thresholds are based solely on data of expected annual risk for I-70 and no other facility type. It is expected that annual risk for 1-mile roadway segments is expected to vary for different facility types (such as two-lane highways or multilane highways) as compared to interstates.

EXHIBIT 5.4 EXAMPLE LEVEL OF RESILIENCE MAP FOR I-70 PILOT DATA

I-70 Corridor Level of Resilience (LOR) Index for 1-Mile Roadway Segments

Level of Resilience (LOR) Index			
Cumulative Annual Risk from Physical Threats	Criticality for Systems Operations		
	Low	Moderate	High
0-20% C.A.R.	A	B	C
21-40% C.A.R.	B	B	C
41-60% C.A.R.	C	C	C
61-80% C.A.R.	C	C	D
81-100% C.A.R.	D	D	E

Level of Resilience (LOR) Index Total Annual Risk		
LOR Index	Number of 1-Mile Segments	% of Total 1-Mile Segments
A	139	30.8%
B	27	6.0%
C	175	38.8%
D	53	11.8%
E	57	12.6%
TOTAL	451	100%

Highways
Counties
I-70
Level of Resilience
A
B
C
D
E

As demonstrated in Exhibit 5.4, when combining the example I-70 pilot data with the criticality map provided in Chapter 2, approximately 12.6% of the 1-mile segments on I-70 fall within the LOR E category signifying high criticality and the highest annual risk quantile for I-70, these would be the 1-mile segments that would warrant review to determine if there are opportunities to reduce annual risk through capital, maintenance, or operational investments or potentially working to reduce the criticality score through improving system redundancy for example. Also, of note is the change in LOR index from the far Western Slope sections of I-70 and the far eastern plains. Contributors to the changes in the LOR include not only the changes in criticality rating but also the reduction in relevant hazards and shorter detour lengths on the eastern end of I-70 as compared to the western portions of I-70.

In the next section, two example problems are provided to demonstrate how potential mitigations to reduce annual risk can be analyzed in terms of their economic viability.

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5.1 - Economic Analysis for Risk Management

Assets identified with poor Level of Resilience (LOR) may warrant consideration of mitigation to reduce anticipated annual risk. To support decision making, an economic analysis approach is provided here to allow the analyst to consider the anticipated return on investment from mitigations under consideration. Note, while the examples presented are focused on capital investments, mitigations can extend to operational or maintenance solutions.

COMPUTATIONAL STEPS

Step 1: Risk Assessment (existing asset)

The total annual risk for the asset and site existing conditions needs to be estimated. This process is explained in detailed in Chapter 4 for all threat-asset pairs that are included in this procedure. The procedure outlined in Chapter 4 can be applied at both the planning level and at the project level as data and information improve. For example, project level data may benefit from a site-specific hydraulic assessment conducted by a hydraulic engineer which may improve the flow estimates and the anticipated assets to accommodate.

Step 2: Mitigation Identification

After estimating the total annual risk of the asset, the agency may identify mitigation alternatives in order to reduce the anticipated annual risk. Example mitigation could include rockfall fencing, elements to increase hydraulic, hydraulic side slope protection, and debris flow catch basins. The data needed for the proposed mitigation alternatives is the same as the data needed to perform a risk assessment including mitigation characteristics such as design, dimensions, and asset replacement cost.

Step 3: Risk Assessment

Conduct risk assessment of proposed mitigation based on methods contained in Chapter 4.

Step 4: Economic Analysis

After estimating the total annual risk of the existing asset and the annual risk of the mitigation, an economic analysis can be performed. Equation 5.1.1 includes an equation to calculate a benefit-cost (B/C) ratio.

EQUATION 5.1.1

$$B/C = \frac{Mitigation\ Benefit}{Annual\ Cost\ of\ Mitigation}$$

Equation 5.1.1 considers the anticipated reduction in benefits between the existing asset and the proposed mitigation as well as the delta in cost between the replacement cost of the exiting asset and the proposed mitigation.

Equation 5.1.2 presents this mitigation benefit calculation.

EQUATION 5.1.2

$$Mitigation\ Benefit = Total\ Annual\ Risk_{BASELINE} - Total\ Annual\ Risk_{MITIGATION}$$

In addition, the annual cost of the mitigation is calculated based on the economic equation to convert a present cost to annual cost as shown in Equation 5.1.3.

EQUATION 5.1.3

$$Mitigation\ Annual\ Cost = Mitigation\ Present\ Cost\ x\ \frac{i\ x\ (1+i)^n}{(1+i)^n - 1}$$

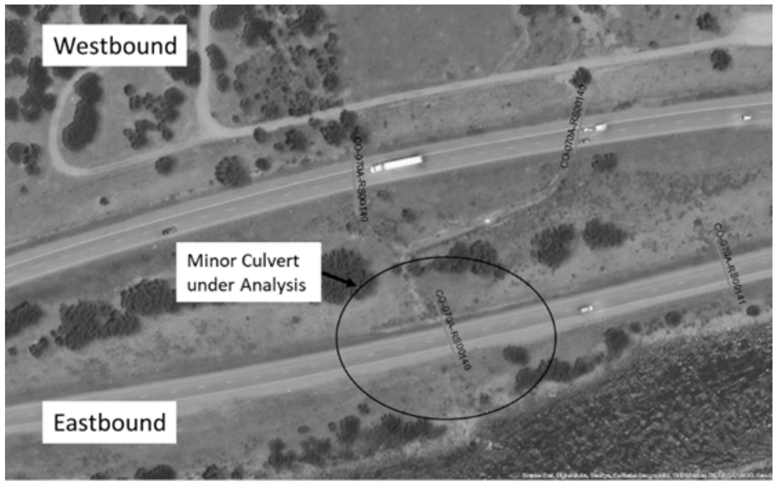
Where:

i = interest rate (3.3% for CDOT)
n = life expectancy of mitigation

Example - Flood-Minor Culvert Risk Management

This example builds upon the example provided for flood-minor culverts. The task is to calculate the benefit-cost ratio of one potential mitigation alternative proposed to reduce risk from flooding to the existing culvert located eastbound I-70 (Identification ID: 070AA112930EL (GIS Link CUL070A395268112)). Exhibit 5.1.1 includes the site with the minor culvert analyzed in Chapter 4.

EXHIBIT 5.1.1 EXAMPLE FLOOD-MINOR CULVERT SITE, I-70, MP 112.9 GARFIELD COUNTY



In this case, CDOT's Regional Hydraulic Engineer performed a hydraulic analysis which altered the anticipated hydrology for relevant events (25-yr, 50-yr, 100-yr). The site conditions were also updated as new data were made available. The economic assessment analysis provided here reflects the latest information provided by CDOT Hydraulic Staff.

Update Site Overview

- Location: I-70, MP 112.9 Garfield County
- Four-lane freeway (two-lanes in each direction)
- Updated culvert characteristics (hydraulic analysis performed):
    - 54 in corrugated metal pipe (CMP), 78 ft long
    - 100 cfs hydraulic capacity (<25-yr event magnitude)
        - Update hydrology from CDOT Regional Hydraulic Engineer
            - 25-yr event – 225 cfs
            - 50-yr event – 300 cfs
            - 100-yr event – 500 cfs

Using the methodology as provided in Chapter 4, each step is executed:

Step 1: Risk Assessment Baseline

The estimated total annual risk, from flood, using the updated culvert information has been calculated to be $260,424. Exhibit 5.1.2 provides the detailed risk assessment results for this culvert based on the procedures outlined in Chapter 4.

EXHIBIT 5.1.2 TOTAL ANNUAL RISK

Rain Event Magnitude	Annual Owner Risk ($)	Annual User Risk ($)	Total Annual Risk ($)
25-yr	$5,439	$132,591	$138,030
50-yr	2,720	$66,295	$69,015
100-yr	$2,104	$51,275	$53,379
TOTAL	**$10,263**	**$250,161**	**$260,424**

Step 2: Mitigation Identification

To reduce the current location from flooding, CDOT provided the following mitigation alternative for analysis. The characteristics of the proposed mitigation alternative are summarized in Exhibit 5.1.4.

EXHIBIT 5.1.3 EXAMPLE OF A PROPOSED MITIGATION ALTERNATIVE

EXHIBIT 5.1.4 CHARACTERISTICS OF PROPOSED MITIGATION ALTERNATIVE

Description of Proposed Alternative	Hydraulic Capacity	Cost of Alternative
Replacement of existing culvert with a 72-inch RCP pipe with headwalls Length = 78 ft Life Expectancy = 100 yrs	50-yr (with roadway overtopping at 100-yr flood events)	$500,000

Step 3: Risk Assessment Mitigation

Threat Data Collection

The threat data needed to analyze for the mitigation alternative was generated and used to establish the baseline risk for the existing conditions. Next, Q_{EVENT}/Q_{DESIGN} ratios are to be calculated for the proposed hydraulic capacity of the mitigation alternative in order to identify the hydraulic events to be considered in the risk assessment. Exhibit 5.2.5 includes the ratios for each applicable rain event.

EXHIBIT 5.1.5 Q_{EVENT}/Q_{DESIGN} RATIO CALCULATIONS FOR PROPOSED MITIGATION

Rain Event Magnitude	Q_{EVENT} (cfs)	Q_{DESIGN} (cfs)	Q_{EVENT}/Q_{DESIGN}
25-yr	225	300	0.75
50-yr	300	300	1.00
100-yr	500	300	1.67

Based on the calculated ratios, the 50-yr and 100-yr events result in a ratio greater or equal to one, therefore, risk assessments for both the 50-yr and 100-yr events need to be completed. Annual treat likelihood for these events are estimated using Exhibit 5.1.6.

EXHIBIT 5.1.6 FLOOD/RAINFALL ANNUAL THREAT LIKELIHOOD

Recurrence Interval (years)	Annual Threat Likelihood
1	1/1
2	1/2
5	1/5
10	1/10
25	1/25
50	1/50
100	1/100
500	1/500

*Flood/Rain recurrence intervals do not necessarily constitute the same flow rate.

Asset Data Collection

The necessary data to calculate the risk assessment for the mitigation alternative was provided on the baseline assessment in Chapter 4, Section 2.4, “Flood-Minor Culvert Risk Assessment”, and the site overview.

Owner Consequence Calculation

A new owner consequence needs to be calculated based on the proposed mitigation. The owner consequence for a 72-inch concrete pipe is calculated using Exhibits 4.2.4.6 and 4.2.4.7. The CDOT provided unit cost for a 72-inch pipe is estimated at $4,235/lin ft. Utilizing the unit cost provided in this procedure for a 72 in pipe with 78 ft in length, the

ARC cost for the culvert is estimated to be $330,330. Based on the provided cost, the owner consequence is calculated as follows:

$$Owner\ Consequence_{Calculated} = \left(100\%\ x\ (\frac{\$4{,}235}{lin\ ft}x\ 78\ lin\ ft)\right) + \$5{,}000$$

$$Owner\ Consequence_{Calculated} = \$330{,}330 + \$5{,}000$$

$$Owner\ Consequence_{Calculated} = \$335{,}330$$

However, the design team provided a total cost for the new pipe to be a $500,000. For this exercise the design team provided cost will be used.

$$Owner\ Consequence_{Provided} = \$500{,}000$$

$$\boldsymbol{Owner\ Consequence = \$500,000}$$

User Consequence

The user consequence for minor culverts is independent of the type or size of pipe used and was previously calculated in chapter 4.2.4. The anticipated user consequence was calculated in Chapter 4.2.4 and can be used to estimate user risk for the new culvert; however, the probability of failure will be reduced given the increased hydraulic capacity.

Total user consequences are calculated using Equation 3.2.

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} +\ User\ Consequence_{PC}$$

$$\boldsymbol{Total\ User\ Consequence = \$5,179,321}$$

Vulnerability Assessment

The vulnerability of the new culvert is estimated using Exhibits 4.2.4.6 and 4.2.4.7. The debris potential of the site is independent of the culvert type, the debris potential calculated for the baseline culvert condition is still applicable and was estimated to be "Very High".

Based on a moderate debris potential, assuming "Good" culvert condition, due to new construction and utilizing the Q_{EVENT}/Q_{DESIGN} ratios obtained in Exhibit 5.1.5, the vulnerability of the new culvert is estimated utilizing Exhibit 5.1.7:

EXHIBIT 5.1.7 FLOOD-MINOR CULVERT VULNERABILITY

Q_{EVENT}/Q_{DESIGN}	Culvert Condition	Debris Potential				
		Very Low	Low	Moderate	High	Very High
1 - 2	Good	0.05	0.06	0.08	0.13	0.30
	Fair	0.07	0.08	0.12	0.18	0.42
	Poor	0.25	0.30	0.42	0.64	0.99
2.1 - 3	Good	0.08	0.09	0.13	0.20	0.47
	Fair	0.10	0.13	0.18	0.27	0.64
	Poor	0.38	0.47	0.64	0.99	0.99
3.1 - 4	Good	0.18	0.22	0.30	0.47	0.99
	Fair	0.25	0.30	0.42	0.64	0.99
	Poor	0.89	0.99	0.99	0.99	0.99
>4	Good	0.64	0.80	0.99	0.99	0.99
	Fair	0.89	0.99	0.99	0.99	0.99
	Poor	0.99	0.99	0.99	0.99	0.99

Using Exhibit 5.1.7 it was determined the vulnerability of the minor culvert for the 50-yr and 100-yr rain events to be the same: $V_{50\text{-}yr} = V_{100\text{-}yr} = 0.30$.

Risk Assessment

Annual Owner Risk Calculation

The annual owner risk is calculated according to Equation 3-9 for 50-yr and 100-yr flood event magnitudes.

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ Risk_i = \boldsymbol{O}wner\ Consequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n= number of events

The annual owner risk is calculated utilizing Equation 3-9 for 50-yr and 100-yr flood event magnitudes. Exhibit 5.1.8 includes the annual owner risk findings for rain events analyzed.

EXHIBIT 5.1.8 ANNUAL OWNER RISK

Rain Event Magnitude	Owner Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual Owner Risk ($)
50-yr	$500,000	0.30	1/50	$3,000
100-yr	$500,000	0.30	1/100	$1,500
			TOTAL	**$4,500**

Annual User Risk Calculation

Next, the annual user risk is calculated utilizing Equation 3.11 for 50-yr and 100-yr flood events:

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ Risk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n= number of events

Exhibit 5.1.9 includes the annual user risk findings for applicable events:

EXHIBIT 5.1.9 ANNUAL USER RISK

Event Magnitude	User Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual User Risk ($)
50-yr	$5,179,321	0.30	1/50	$31,076
100-yr	$5,179,321	0.30	1/100	$15,538
			TOTAL	**$46,614**

The total annual risk is calculated according to Equation 3.13:

EQUATION 3.13

$$Total\ Annual\ Risk\ = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

Where n= number of events

Exhibit 5.1.10 includes the annual risk findings.

EXHIBIT 5.1.10 ANNUAL TOTAL RISK

Event Magnitude	Annual Owner Risk ($)	Annual User Risk ($)	Total Annual Risk ($)
50-yr	$3,000	31,076	$34,076
100-yr	$1,500	$15,538	$17,038
TOTAL	**$4,500**	**$46,614**	**$51,114**

Step 4: Economic Analysis

Estimate Reduction in Risk (Benefit)

The benefit of choosing this culvert as a mitigation is calculated as the reduction in risk from the replacing the existing culvert (baseline). The mitigation benefit can be estimated using Equation 5.1.2 as follows:

EQUATION 5.1.2

$$Mitigation\ Benefit = Total\ Annual\ Risk_{BASELINE} - Total\ Annual\ Risk_{MITIGATION}$$

Total annual risk (baseline) = $260,424
Total annual risk (mitigation alternative) = $51,114

$$Mitigation\ Benefit = \$260{,}424 - \$51{,}114$$

$$\boldsymbol{Mitigation\ Benefit = \$209,310}$$

Estimate Annual Cost of the Mitigation Alternative

The total cost of the new 72-inch concrete pipe was provided at $500,000 and shown in Exhibit 5.1.4. Based on the total cost, the life expectancy provided in Exhibit 5.1.4 and the approved CDOT discount rate of 3.3%, the annual cost of the mitigation can be estimated using Equation 5.1.3 as follows:

EQUATION 5.1.3

$$Mitigation\ Annual\ Cost = Mitigation\ Present\ Cost\ x\ \frac{i\ x\ (1+i)^n}{(1+i)^n\ -\ 1}$$

Where:

i = discount rate (3.3% for CDOT)
n = life expectancy of mitigation

$$Mitigation\ Annual\ Cost = \$500{,}000\ \ x\ \frac{3.3\%\ x\ (1+3.3\%)^{100}}{(1+3.3\%)^{100}\ -\ 1}$$

$$\boldsymbol{Mitigation\ Annual\ Cost} = \$\mathbf{17,168}$$

Estimate Benefit-Cost (B/C) Ratio

In order to estimate the benefit-cost ratio for the proposed design alternative compared to the existing, the calculated benefit and the annual cost of the mitigation alternative are used. Using Equation 5.1.1 the benefit-cost ratio is calculated as follows:

EQUATION 5.1.1

$$B/C\ = \frac{Mitigation\ Benefit}{Annual\ Cost\ of\ Mitigation}$$

$$\frac{B}{C} = \frac{\$209{,}310}{\$17{,}168}$$

$$\boldsymbol{\frac{B}{C}} = \mathbf{12.2}$$

Step 5: Mitigation Alternatives Selection

Based on the obtained B/C ratio being greater than 1.0 (B/C=12.2), the proposed design alternative is a viable economic design for risk mitigation at this site.

Example - Rockfall-Roadway Prism Risk Management

This example builds upon the example provided in Chapter 4.1.2 for rockfall-roadway prism. The task is to calculate the benefit-cost ratios of one proposed mitigation alternative to reduce risk to the existing roadway section located on the westbound traffic direction, near MP 118.2 on I-70. Exhibit 5.1.11 shows the I-70 roadway site section to be analyzed and Exhibit 5.1.12 shows a location map for the example site.

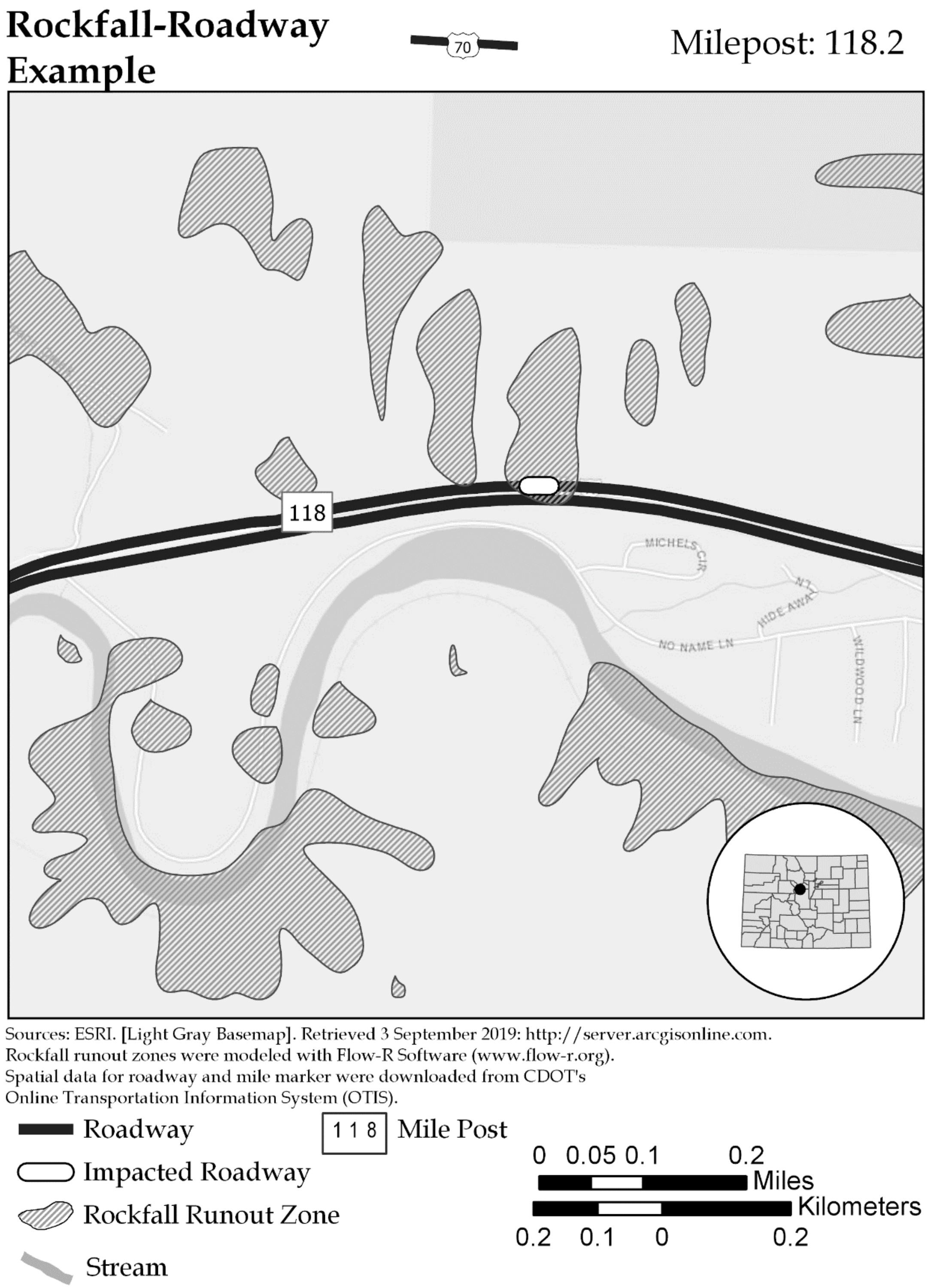
EXHIBIT 5.1.11 EXAMPLE ROCKFALL-ROADWAY, I-70, MP 118.2, GOOGLE EARTH IMAGERY

Site Overview

- Location: I-70, MP 118.2, Glenwood Canyon
- Four-lane freeway (two-lanes in each direction)
- Roadway segment length = 100 ft
- Roadway width = 38 ft
- Unit cost for roadway/asphalt = $150/sq yd
- $AADT_{Vehicle}$ = 13,780 vehicles
- $AADT_{Truck}$ = 2,220 trucks
- Detour length = 140 miles
- Detour time = 167 minutes
- Work zone length = 1 mile
- Normal speed limit = 50 mph
- Work zone speed reduction = 15 mph
- Number of days of full closure = 4 days
- Number of days of partial closure = 14 days
- Rockfall mitigation = None

- Lithology = rock slope
- Slope type = natural

EXHIBIT 5.1.12 EXAMPLE ROCKFALL-ROADWAY, I-70, MP 118.2



Following the methodology presented in Chapter 4, each step is executed:

Step 1: Risk Assessment Baseline

As presented in Chapter 4.1.3 for "Rockfall-Roadway Risk Assessment", the estimated total annual risk, Exhibits 4.1.3.11 and 4.1.3.12, to the roadway section from rockfall with existing site and asset conditions (baseline) was calculated as $1,849,945. Exhibit 5.1.13 includes the risk assessment results for this roadway section.

EXHIBIT 5.1.13 ANNUAL RISK ASSESSMENT

Rockfall Event Magnitude	Annual Owner Risk ($)	Annual User Risk ($)	Total Annual Risk ($)
1-yr	$2,634	$93,301	$95,935
6-yr	$35,113	$1,244,019	$1,279,132
20-yr	$13,036	$461,842	$478,878
TOTAL	**$50,783**	**$1,79,945**	**$1,849,945**

Step 2: Mitigation Identification

To reduce the current site risk from rockfall, CDOT proposed the analysis of a mitigation alternative. Exhibit 5.1.14 shows an image of the proposed rockfall fencing mitigation. The characteristics of the proposed mitigation are summarized in Exhibit 5.1.15

EXHIBIT 5.1.14 PROPOSED MITIGATION ALTERNATIVE

EXHIBIT 5.1.15 CHARACTERISTICS OF PROPOSED MITIGATION ALTERNATIVE

Description	Number	Length	Height	Energy Absorption	Life Expectancy	Cost of Alternative
Fence	1	180 ft	20 ft	5 kj	10 yrs	$290,000

Step 3: Risk Assessment Mitigation

Following the risk assessment methodology for rockfall-roadway presented in Exhibit 4.1.3.1 the total annual risk of the proposed alternative is calculated:

Threat Data Collection

The threat data needed to analyze rockfall risk at this location on I-70 is included in Exhibit 3.6 and repeated here.

EXHIBIT 5.1.16 ROCKFALL ANNUAL THREAT LIKELIHOOD FOR I-70 AT GLENWOOD CANYON

Recurrence Interval (years)	Annual Threat Likelihood
1	1/1
6	1/6
20	1/20

Asset Data Collection

The necessary data to calculate the risk assessment for the mitigation alternative was provided on the baseline assessment in Step 1 and Site Overview, at the beginning of this example.

Owner Consequence

The CDOT approved unit cost for this procedure for roadway prism is $150 per square yard, Exhibit 4.1.3.5. The dimensions of the roadway section are 100 ft by 38 ft. The ARC, therefore, is $63,333. The WRC, Exhibit 4.1.3.4, for a large event where rockfall impacts a roadway section is estimated to be 100% of the ARC of a 100 ft section plus $200,000 in debris cleanup costs, rounded up to the nearest $50. The anticipated owner consequence is:

$$Owner\ Consequence = \left(100\%\ x\ \left((100\ ft\ x\ 38\ ft)\ x\ \frac{\$150}{sq\ ft}\right)\right) + \$200,000$$

$$Owner\ Consequence = \$63{,}333 + \$200{,}000$$

$$Owner\ Consequence = \$263{,}333$$

$$\boldsymbol{Owner\ Consequence \approx \$263{,}350^*}$$

***Final value for owner consequences is rounded to the nearest $50.**

User Consequence

The WRC for user consequences is four days of full closure and 14 days of partial closure as described in Chapter 3. Total user consequences include the sum of user consequence due to full and partial closures as shown in Equation 3.2.

EQUATION 3.2

$$Total\ User\ Consequence = User\ Consequence_{FC} + User\ Consequence_{PC}$$

$$\boldsymbol{Total\ User\ Consequence} = \$\mathbf{9,330,140}$$
Previously calculated in Chapter 4

Vulnerability Assessment

The vulnerability of the roadway section after installing the recommended mitigation is estimated using Exhibit 5.1.17. Based on the assumptions that mitigation has been installed, the slope is a natural, rock slope, and not monitored or actively maintained, the new vulnerabilities are as follows: 0.0 for a small event, 0.25 for a medium event and 0.99 for a large event. The vulnerabilities are highlighted in cells with dark borders in Exhibit 5.1.16.

EXHIBIT 5.1.17 ROCKFALL VULNERABILITY

Magnitude	Factors				Vulnerability		
Return Period (years)	Natural or Cut Slope	Lithology	Ditch	Monitored	No Mitigation	Slope Maintained	Installed Mitigation
1-year (≤ 100 cu yds)	Cut Slope	Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
		Non-Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.00	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.00	0.00
	Natural	Rock Slope	Absent	Yes	0.01	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
		Non-Rock Slope	Absent	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
			Present	Yes	0.00	0.00	0.00
				No	0.01	0.01	0.00
6-year (101 - 499 cu yds)	Cut Slope	Rock Slope	Absent or Width ≤ 10 ft	Yes	0.35	0.30	0.15
				No	0.65	0.50	0.25
			Width > 10 ft	Yes	0.30	0.25	0.15
				No	0.60	0.45	0.25
		Non-Rock Slope	Absent or Width ≤ 10 ft	Yes	0.30	0.25	0.15
				No	0.55	0.45	0.25
			Width > 10 ft	Yes	0.25	0.20	0.10
				No	0.50	0.40	0.20
	Natural	Rock Slope		Yes	0.40	0.30	0.15
				No	0.80	0.50	0.25
		Non-Rock Slope		Yes	0.35	0.30	0.15
				No	0.30	0.25	0.15
20-year (≥ 500 cu yds)	NA				0.99		

Risk Assessment

Annual Owner Risk

The annual owner risk is calculated utilizing Equation 3.9 for 1-yr, 6-yr and 2-yr events.

EQUATION 3.9

$$\sum_{i=1}^{n} Annual\ Owner\ Risk_i = Owner\ Consequence\ x\ Vunerability_i\ x\ Threat\ Likelihood_i$$

Where n= number of events

Exhibit 5.1.18 presents the annual owner risk calculations and results for each rockfall event analyzed:

EXHIBIT 5.1.18 ANNUAL OWNER RISK CALCULATIONS

Rockfall Event Magnitude	Owner Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual Owner Risk ($)
1-yr	$263,350	0.00	1/1	0
6-yr	$263,350	0.25	1/6	$10,973
20-yr	$263,350	0.99	1/20	$13,036
			TOTAL	**$24,009**

Annual User Risk Calculation

The annual user risk is calculated utilizing Equation 3.11 for applicable rockfall events:

EQUATION 3.11

$$\sum_{i=1}^{n} Annual\ User\ Risk_i = \boldsymbol{C}onsequence\ x\ \boldsymbol{V}unerability_i\ x\ \boldsymbol{T}hreat\ Likelihood_i$$

Where n= number of events

Exhibit 5.1.19 presents the annual user findings for applicable events:

EXHIBIT 5.1.19 ANNUAL USER RISK

Rockfall Event Magnitude	User Consequence ($)	Vulnerability (%)	Annual Threat Likelihood	Annual User Risk ($)
1-yr	$9,330,140	0.00	1/1	0
6-yr	$9,330,140	0.25	1/6	$389,756
20-yr	$9,330,140	0.99	1/20	$461,842
			TOTAL	**$850,598**

The total annual risk is calculated utilizing Equation 3.13:

EQUATION 3.13

$$Total\ Annual\ Risk\ = \sum_{i=1}^{n} Annual\ Owner\ Risk_i + \sum_{i=1}^{n} Annual\ User\ Risk_i$$

Where n= number of events

EXHIBIT 5.1.20 ANNUAL TOTAL RISK

Rockfall Event Magnitude	Annual Owner Risk ($)	Annual User Risk ($)	Total Annual Risk ($)
1-yr	0	0	$0
6-yr	$10,973	$389,756	$399,729
20-yr	$13,036	$461,842	$478,878
TOTAL	**$256,406**	**$730,459**	**$874,607**

Step 4: Economic Analysis

Estimate Reduction in Risk (Benefit)

The benefit of choosing this mitigation alternative is calculated as the reduction in risk from the installing the rockfall mitigation. The mitigation benefit can be estimated using Equation 5.1.2:

EQUATION 5.1.2

$$Mitigation\ Benefit = Total\ Annual\ Risk_{BASELINE} - Total\ Annual\ Risk_{MITIGATION}$$

Total annual risk (baseline) = $1,849,945
Total annual risk (mitigation alternative) = $874,607

$$Mitigation\ Benefit = \$1{,}849{,}945 - \$874{,}607$$

$$\boldsymbol{Mitigation\ Benefit = \$975{,}338}$$

Estimate Annual Cost of the Mitigation Alternative

The total cost for installing one 5-kj fence was estimated to be $290,000 and shown in Exhibit 5.1.15. Based on the total cost, the life expectancy provided in Exhibit 5.1.15 and the approved CDOT discount rate of 3.3%, the annual cost of the mitigation can be estimated using Equation 5.1.3 as follows:

EQUATION 5.1.3

$$Mitigation\ Annual\ Cost = Mitigation\ Present\ Cost\ x\ \frac{i\ x\ (1+i)^n}{(1+i)^n - 1}$$

Where:

i = discount rate (3.3% for CDOT)
n = life expectancy of mitigation

$$Mitigation\ Annual\ Cost = \$290{,}000\ x\ \frac{3.3\%\ x\ (1+3.3\%)^{10}}{(1+3.3\%)^{10} - 1}$$

$$\boldsymbol{Mitigation\ Annual\ Cost = \$34{,}519}$$

Estimate Benefit-Cost (B/C) Ratio

In order to estimate the benefit-cost ratio for the proposed design alternative compared to the “Do Nothing” alternative, the calculated benefit and the annual cost of the mitigation alternative are used. Using Equation 5.1.1 the benefit-cost ratio is calculated as follows:

EQUATION 5.1.1

$$B/C = \frac{Mitigation\ Benefit}{Annual\ Cost\ of\ Mitigation}$$

$$\frac{B}{C} = \frac{\$975{,}338}{\$34{,}519}$$

$$\boldsymbol{\frac{B}{C} = 28.3}$$

Step 5: Mitigation Alternatives Selection

Based on the obtained B/C ratio being greater than 1.0, the proposed design alternative is a viable economic design for risk mitigation at this site.