COLORADO
Department of Transportation

Transportation Resilience Metrics

Presentation to National Academy of Sciences
September 14, 2020

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Resiliency:

"The ability to prepare and plan for, absorb, recover from, or more successfully adapt to adverse events."

The 4 Rs: Attributes of Resiliency

- **Robustness** – the strength of an asset or system to withstand relevant threats
- **Redundancy** – the presence of a backup system or plan
- **Resourcefulness** – ability to identify, diagnose and treat problems with available resources
- **Rapidity** – ability to restore functionality in a timely way

Source: The Multidisciplinary Center for Earthquake Engineering Research

Physical and Organizational Resiliency

Resiliency for a DOT can be:

Physical – the ability of the physical assets to perform to an acceptable level when subject to a hazard event;

and/or

Organizational – an organization's capacity to make decisions and take actions to plan and respond to a hazard event to achieve a desired result.

Both are important!

Source: Bruneau – 2003

How Events Disrupt our System

Events disrupt how our system works.

Building resiliency into how we do things minimizes the disruption.

Source: AASHTO CTSSR – Steering Committee

CDOT Lessons Learned

1976 and 2013 floods in Colorado destroyed many of the same facilities

US 34 1976

US 34 2013

What can we do now… to avoid this in the future?

New CDOT Tools and Policies: Measuring Vulnerability and Risk

CDOT Resiliency Program

- Created in 2018, with Policy Directive 1905.0 – the vision for resilience at CDOT
- Works to integrate resilience in CDOT functions
- Coordinates resilience activities at CDOT
- Conducts research to support resilience
- Provides resilience knowledge and resources to CDOT staff

COLORADO DEPARTMENT OF TRANSPORTATION	■ POLICY DIRECTIVE □ PROCEDURAL DIRECTIVE	
Subject **Building Resilience into Transportation Infrastructure and Operations**		Number **1905.0**
Effective **11/15/18**	Supersedes **New**	Originating Office **Division of Transportation Development**

I. PURPOSE

The purpose of this Policy Directive is to implement the principles of resilience into Colorado's transportation system practices. This will enable the Colorado Department of Transportation to proactively manage risks, minimize disruptions and adapt to changing conditions in order to provide continuous transportation service in Colorado. Colorado's transportation infrastructure directly or indirectly affects the lives of all people living in the state, and provides the essential services that underpin the state's economy and the movement of people, goods, and information. Maintaining a secure, functioning, and resilient infrastructure is critical to the state's safety, prosperity, and well-being.

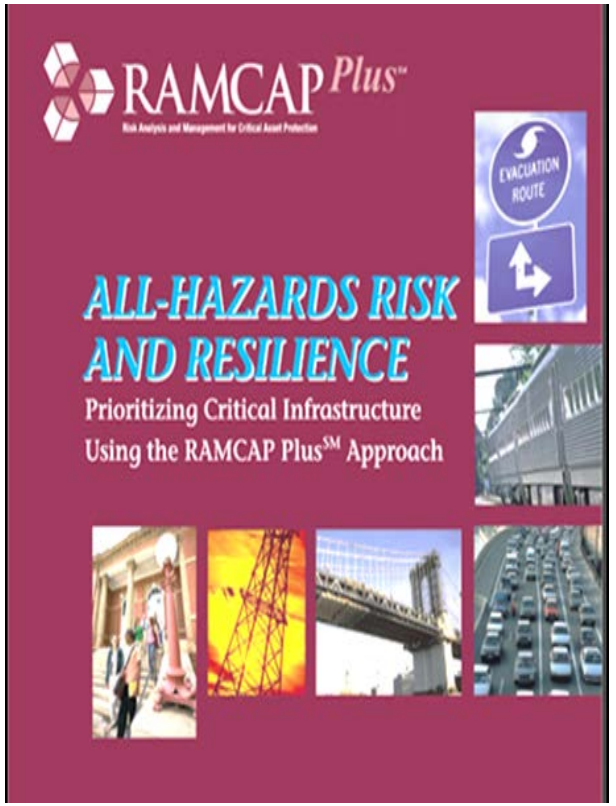
The benefits or resilience are widespread, including fiscal benefits by saving the state money, social and economic benefits, by saving the public time and ensuring timely access to markets for businesses, and safety benefits, by taking action before a disruption becomes disastrous.

Integrating Resiliency at CDOT: Maintenance & Operations

I-70 Corridor Risk & Resilience Pilot

- "Pilot" the data, assumptions, and methodology needed to quantify:
  - What are CDOT's ***assets***?
    - Location, value, condition, criticality
  - What are relevant ***physical threats***?
    - Likelihood and location
  - What ***impact*** would they have on our system?
    - Consequences and vulnerability
  - What are the ***optimal investments*** we can make now to improve resiliency in advance of future events?

BUILDS ON THE 7-step RAMCAP MODEL USED IN FLOOD RECOVERY



Risk (R) = C x V x T

Risk *(R) ($)*	→ *Potential cost of asset losses in a threat-filled environment*
Consequence (C) ($)	→ *Result of asset failure*
Vulnerability (V) (%)	→ *Susceptibility to the threat*
Threat Likelihood (T) (%)	→ *Potential of threat occurrence*

Some Roadways are more Critical than Others

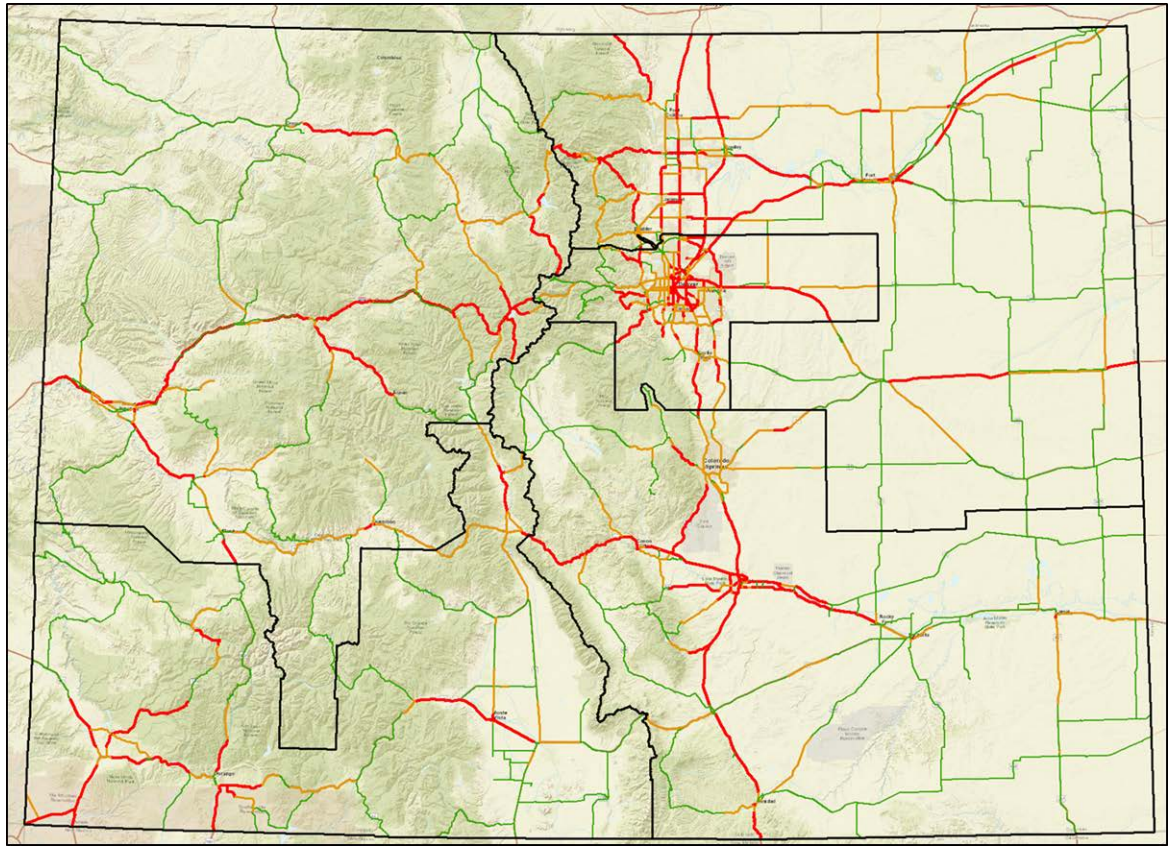
Criticality Map for System Resilience

AADT	16.7%
ASHTO Road Classification	16.7%
Freight $ (County)	16.7%
Tourism $ (County)	16.7%
SoVI	16.7%
Redundancy	16.7%

Equal Weight

- 53.8% Low
- 25.5% Moderate
- 20.7% High

	SOCIAL	ENVIRO	ECON
Usage: AADT + Roadway Classification	✓	✓	✓
Economic Impact: Freight ($) + Tourism ($)			✓
Social Impact: SoVI	✓		
System Impact: System Redundancy	✓	✓	✓



Result – Annualized Risk ($ per threat-asset pair)

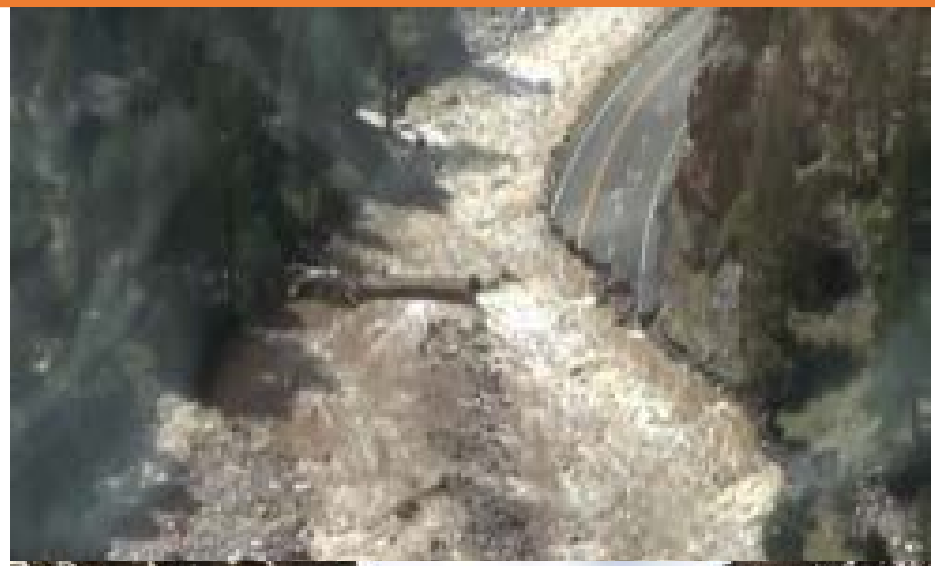
Given the worst reasonable event, what are the consequences? ($)

Owner Cost

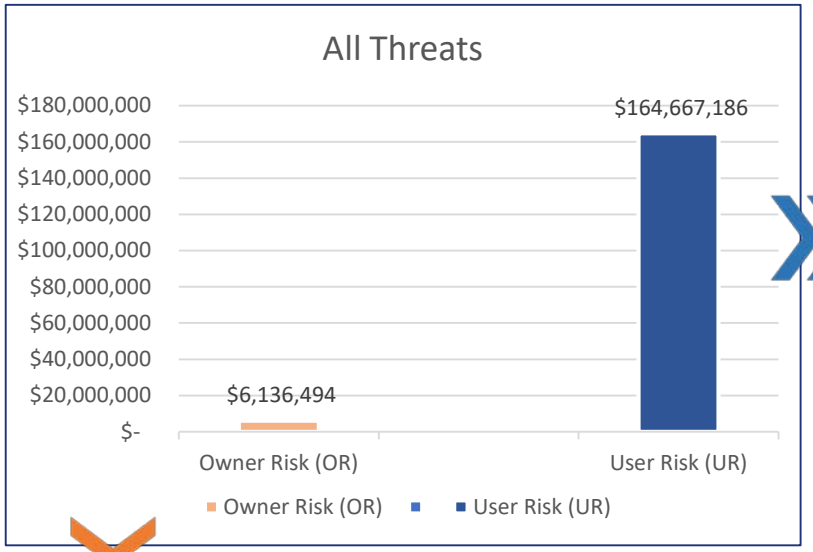
- Asset Replacement Cost

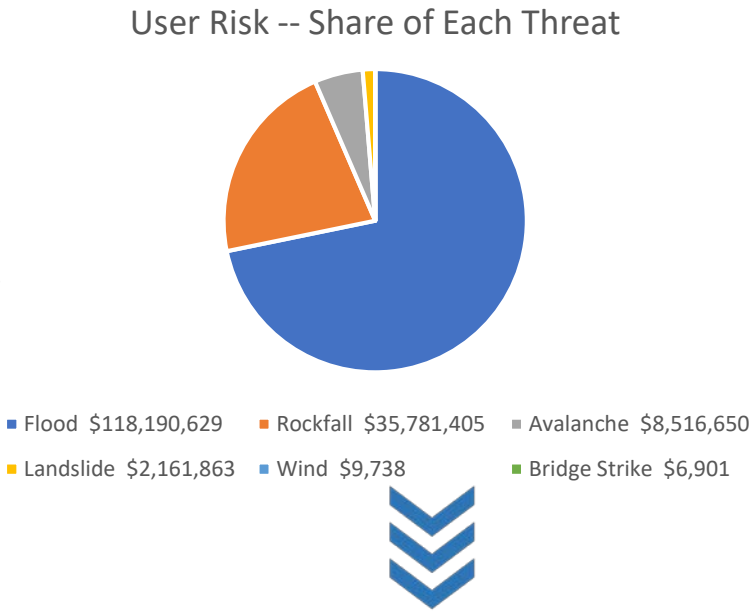
User Cost

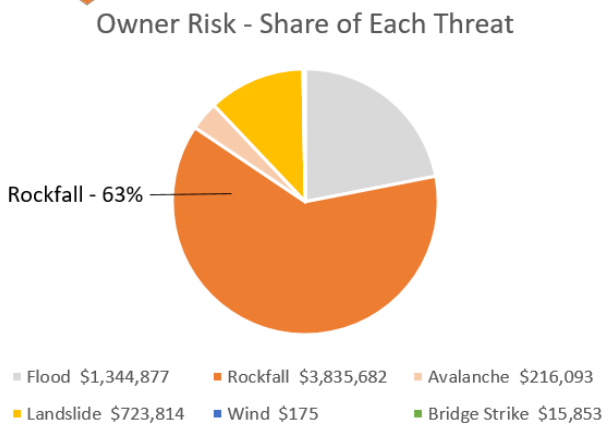
- Value of time (delay/detour)

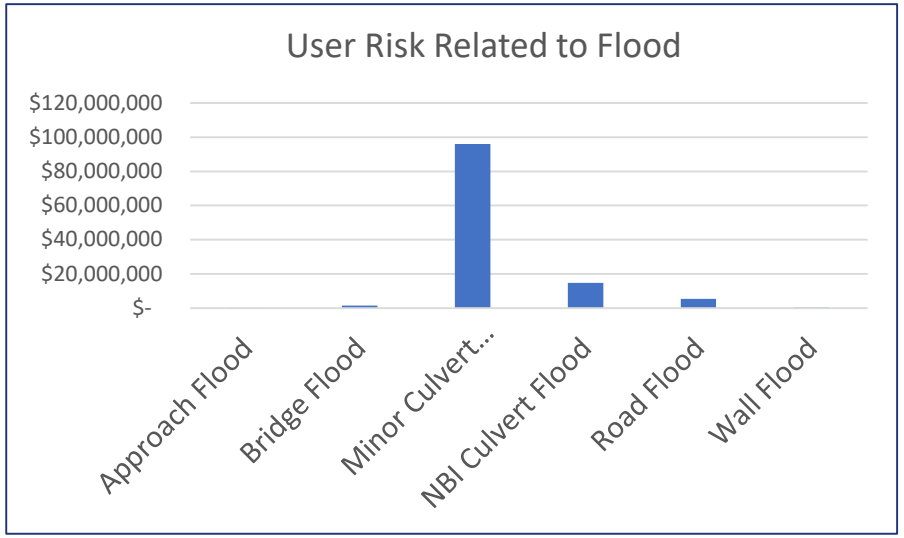


I-70 Pilot Results







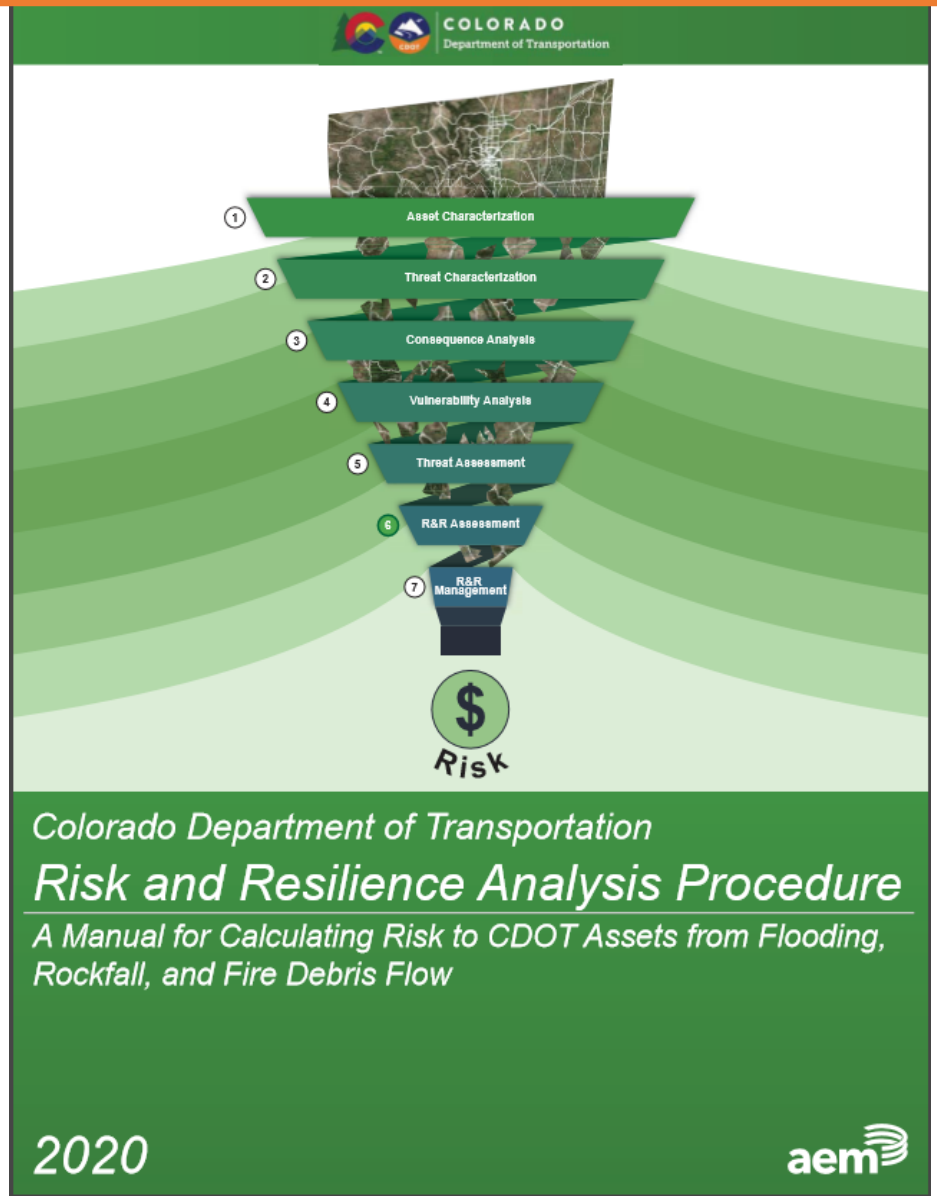


Risk and Resiliency Standard Manual

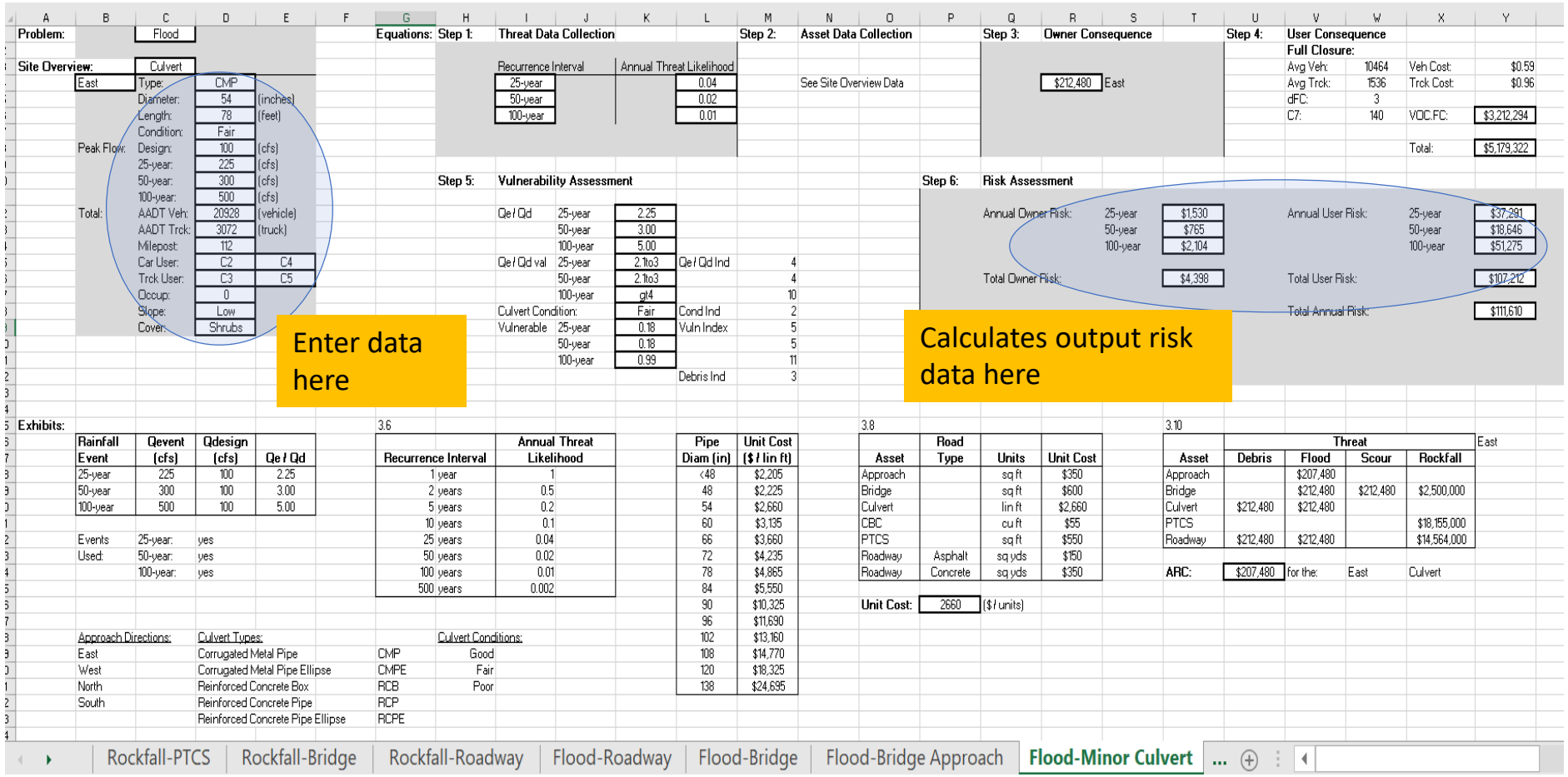
- Published August 2020 -- https://www.codot.gov/programs/planning/cdot-resilience-program

- Refines and Standardizes the data, assumptions, and methodology for conducting risk assessment

- Step by step "Cookbook" on how to calculate risk
  - Flood
  - Rockfall
  - Fire / Debris flow



New Excel Templates
Based on Standard Model and Assumptions



Spreadsheet tabs for each threat asset pair

Calculating Reduced Risk and Benefit Cost

Run the risk model twice

- Once to determine the existing condition and establish baseline risk costs
- A second time to analyze the risk reduction of the mitigation proposed
- Estimate cost of proposed mitigation
- Those values can be used to determine a Benefit to Cost ratio

EQUATION 5.1.3

$$Mitigation\ Annual\ Cost = Mitigation\ Present\ Cost\ x\ \frac{i\ x\ (1+i)^n}{(1+i)^n - 1}$$

Where:

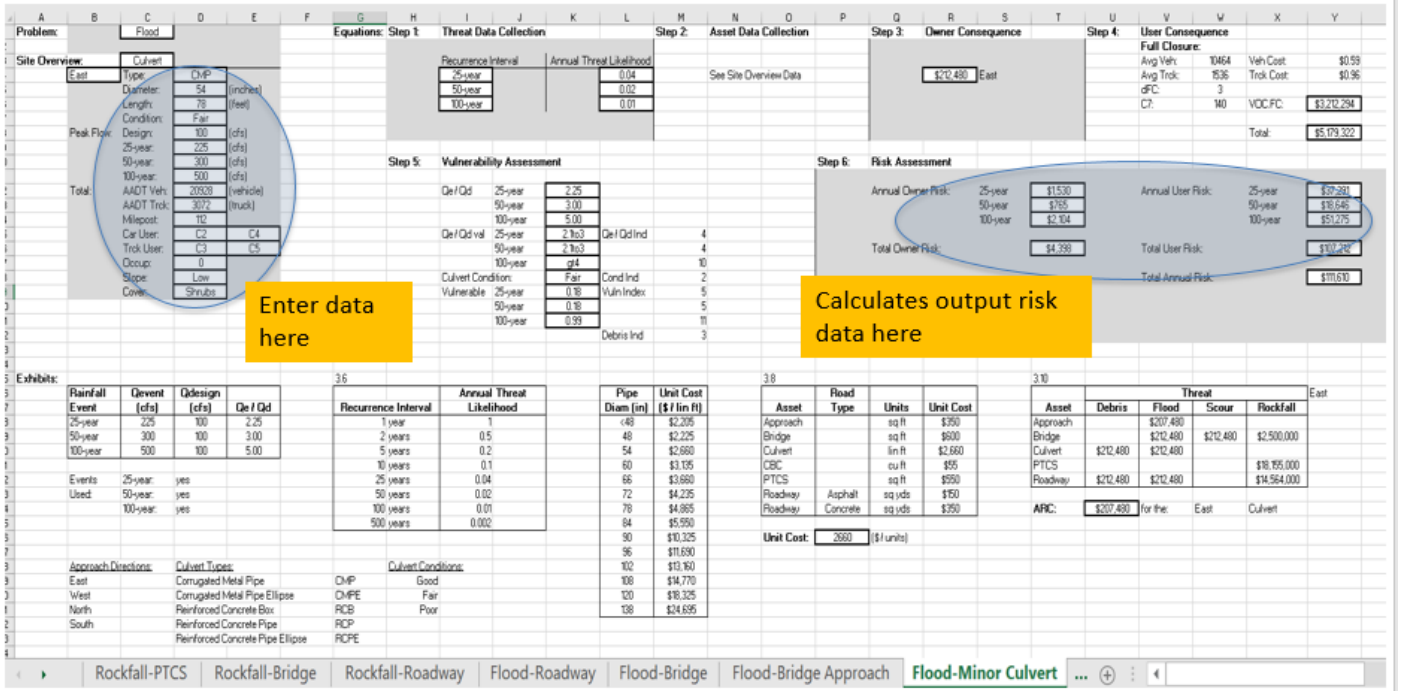
i = discount rate (3.3% for CDOT)
n = life expectancy of mitigation

EQUATION 5.1.1

$$B/C = \frac{Mitigation\ Benefit}{Annual\ Cost\ of\ Mitigation}$$

Excel Templates - Challenges

- Some input data is not readily available
  - Detour routes and times not available statewide
- No easy way to "batch" process many locations at once in an automated way.
  - E.g Water flow (from Streamstats – need to batch process)

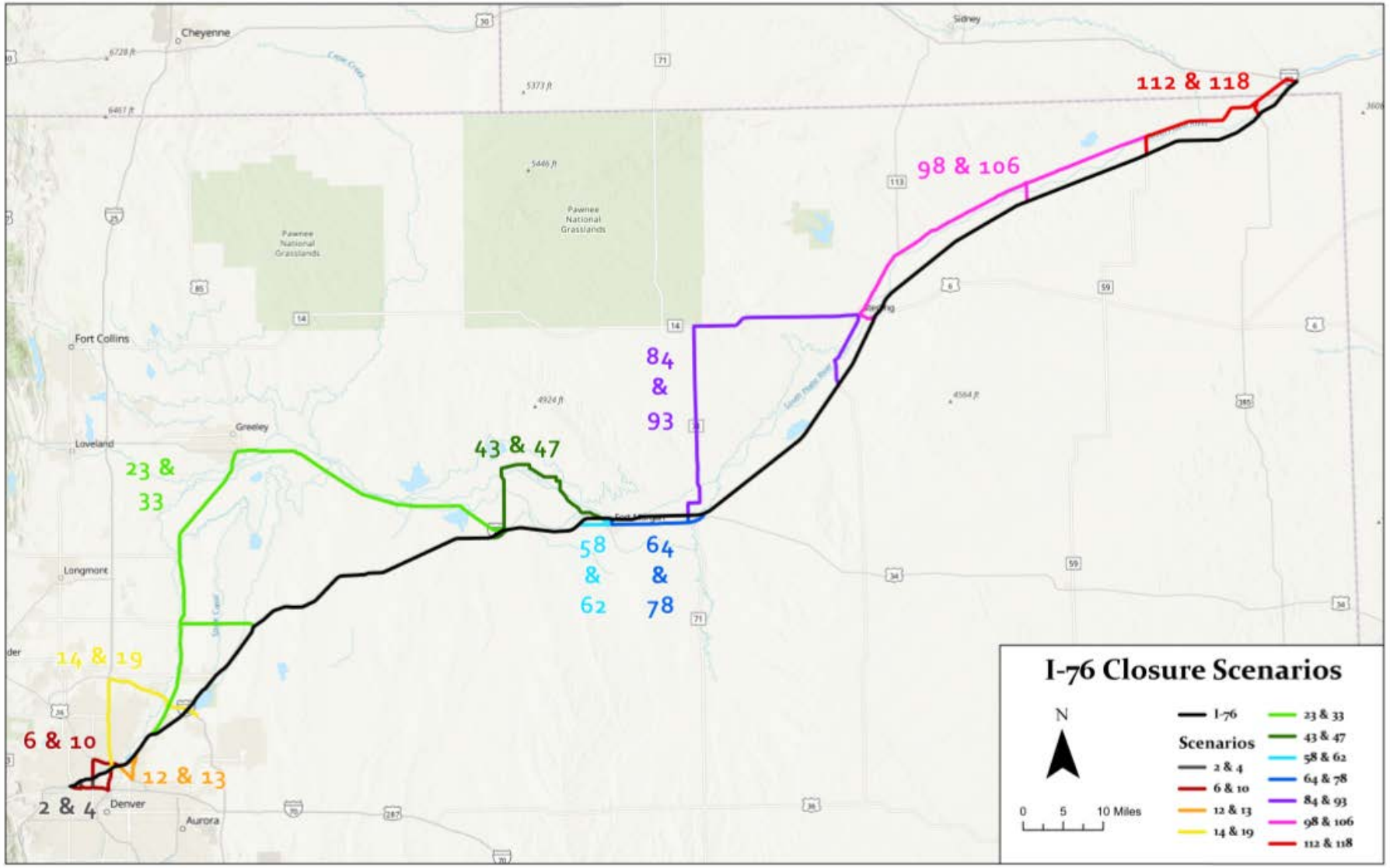


Spreadsheet tabs for each threat asset pair

Detour Times are a Critical Input
Using the State-wide Travel Demand Model for Detours

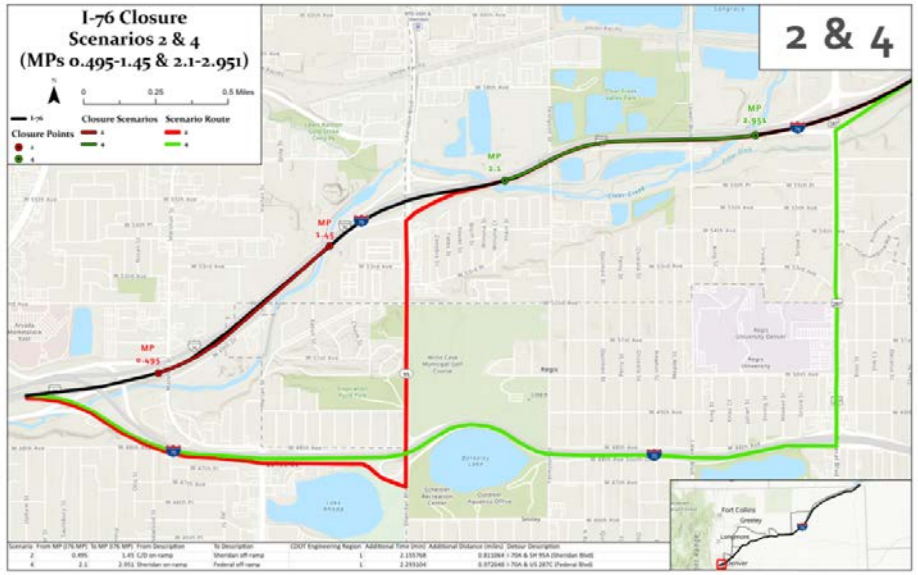
- Minimize travel time (weekday 24-hour average)
- Limit detours to state highways
  - Colorado
  - Neighboring states
- Travel each highway route in each direction
  - One at a time, close each link and find the new minimum-time path

I-76 Test for the Detour Model



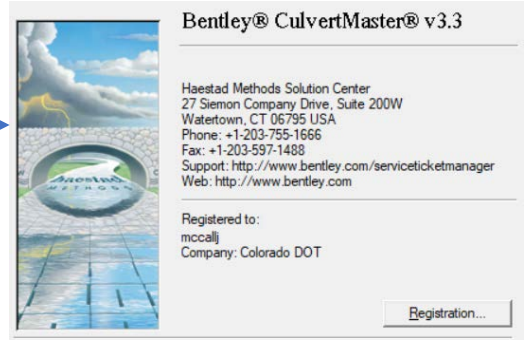
I-76 Test for the Detour Model

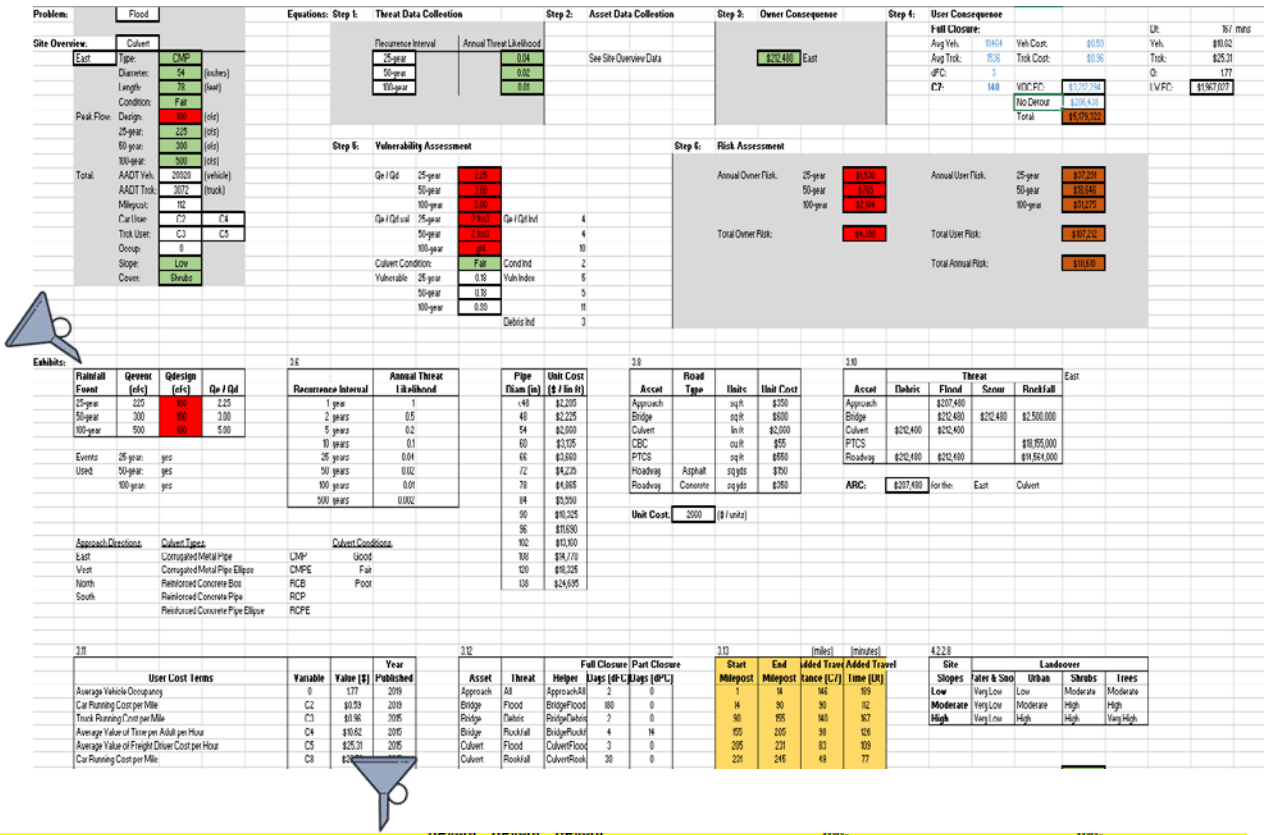
Map Color	Scenario	From MP (I76 MP)	To MP (I76 MP)	From Description	To Description	CDOT Engineering Region	Additional Time (min)	Additional Distance (miles)	Detour Description
	2	0.495	1.45	C/D on-ramp	Sheridan off-ramp	1	2.155768	0.811064	I-70A & SH 95A (Sheridan Blvd)
	4	2.1	2.951	Sheridan on-ramp	Federal off-ramp	1	2.293104	0.972048	I-70A & US 287C (Federal Blvd)
	6	3.575	5.362	Federal on-ramp	I-25 off-ramp	1	3.876046	1.966084	I-70A & I-25A (via Mousetrap)
	10	5.99	6.578	I-25 NB on-ramp	I-270 EB off-ramp	1	5.12266	2.066203	US 287C (Federal Blvd) to US 36B/I-270B
	12	7.472	7.963	I-270 EB on-ramp	SH 224 off-ramp	1	7.398007	3.019391	I-270A & US 6H (Vasquez Blvd)
	13	7.963	9.7	SH 224 off-ramp	US 6/US 85 on-ramp	1	2.672002	0.448469	SH 224A (74th Ave) & US 6H (Vazquez Blvd)
	14	9.7	12.427	US 6/US 85 on-ramp	US 85 off-ramp	1	13.377624	12.324632	I-25A and E-470B (ignores tolls) w/ U-turn at 120th Ave
	19	12.427	18.808	US 85 off-ramp	E-470 on-ramp	1	6.818938	4.294081	US 85C and E-470B (ignores tolls) w/ U-turn at 120th Ave
	25	18.808	31.314	E-470 on-ramp	SH 52 off-ramp	1 & 4	12.198299	5.169041	US 85C and SH 52A
	33	31.637	63.762	SH 52 on-ramp	Wiggins off-ramp (Exit 64)	4	37.395312	21.537103	US 85C and US 34A
	43	63.762	65.944	Wiggins off-ramp (Exit 64)	SH 39/SH 52 off-ramp	4	3.176636	0.062834	US 6I (Central Ave)
	47	66.64	75.3	US 34 Wiggins on-ramp	I-76 Bus off-ramp	4	33.799561	11.504929	SH 39A and SH 144A
	58	76.1	79.046	I-76 Bus on-ramp	SH 144 off-ramp	4	4.014036	0.347774	US 34B and SH 52B
	62	79.2	79.983	SH 144 on-ramp	SH 52 off-ramp	4	2.144287	0.580681	SH 144A and SH 52B
	64	80.391	89.488	SH 52 on-ramp	SH 71 off-ramp	4	8.391263	1.436861	SH 52B, US 34B and SH 71E
	78	89.882	91.4	SH 71 on-ramp	US 6/US 34 off-ramp	4	3.724596	1.220518	SH 71E, US 34B and US 34E
	84	91.919	114.988	US 6/US 34 on-ramp	SH 63 off-ramp	4	32.902617	13.324347	SH 71E, SH 14C and US 6J
	93	115.452	124.453	SH 63 on-ramp	US 6 off-ramp	4	8.649645	2.201863	SH 63A and US 6J
	98	125.141	148.711	US 6 on-ramp	SH 55 off-ramp	4	33.779908	7.862795	US 6J, US 138A and SH 55A
	106	149.056	164.697	SH 55 on-ramp	SH 59 off-ramp	4	23.894413	4.687542	SH 55A, US 138A and SH 59B
	112	165.126	179.983	SH 59 on-ramp	US 385 off-ramp	4	17.346188	1.65528	SH 59B, US 138A and I-80 (in Nebraska)
	118	180.45	184.135	US 385 on-ramp	Nebraska State Line	4	3.567291	1.539206	US 385D, US 138A and I-80 (in Nebraska)



Batch Process – Risk and Resiliency Automation

USGS StreamStats





With In-house staff expertise:

- Time consuming manual process previously performed on a culvert-by-culvert basis has been refined to a two input automated tool
- Can be used by anyone with access to an ArcGIS Pro license and takes two shapefiles as input: culverts and detours
- Exports results to a single spreadsheet for all culverts

FLOC	Slope	Landcover	Debris_Potential	qEvent_25Year	qEvent_50Year	qEvent_100Year	Design_Flow	qEvent Design Ratio_25Year	qEvent Design Ratio_50Year	qEvent Design Ratio_100Year	Drainage_Area	25-Year Owner Risk	50-Year Owner Risk	100-Year Owner Risk	Total Owner Risk	25-Year User Risk	50-Year User Risk	100-Year User Risk	Total User Risk	Total Annual Risk
CULV23867	High	Trees	Very High	27.673113	34.444055	40.509949	4.0355594	6.8573178	8.5351375	10.038249	1.9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CULV20287	High	Trees	Very High	22.231149	27.446462	31.310586	115.10821	0.1931326	0.2384405	0.2720099	0.000541	8414.208	4207.104	2103.552	14724.864	1620.3932	1620.3932	1620.3932	4861.1795	19586.043
CULV29716	High	Urban	High	1247.2092	1872.4136	2723.4611	350.09095	3.5625292	5.3483633	7.779296		8414.208	4207.104	2103.552	14724.864	10362.793	10362.793	10362.793	31088.38	45813.244
CULV38508	Low	Urban	Low	194.76188	285.00082	393.41065	201.08576	0.9685513	1.4173098	1.9564322		5439.488	2719.744	1359.872	9519.104	0	0	0	0	9519.104

Using the Data and Tools to Make Decisions: Prioritizing Which Risks to Mitigate

Resiliency Integration Project

- Kicked Off - February 2020
- Goal – Demonstrate how to drive the ideas of resilience into CDOT day-to-day activities
- 5 case studies – proof of concept
  - ❑ Asset Management – Twice Damaged Assets UNDER WAY
  - ❑ M & O – Flood Mitigation Plans for Minor Culverts KICKED OFF LATE JULY
  - ❑ Planning and Project Prioritization
  - ❑ Environmental Documents
  - ❑ Project Scoping and Engineering

  Coming Soon
- Project Completion – 18 months – late 2021

Twice Damaged Assets Case Study

Twice Damaged Assets Case Study

November 2020 Deadline

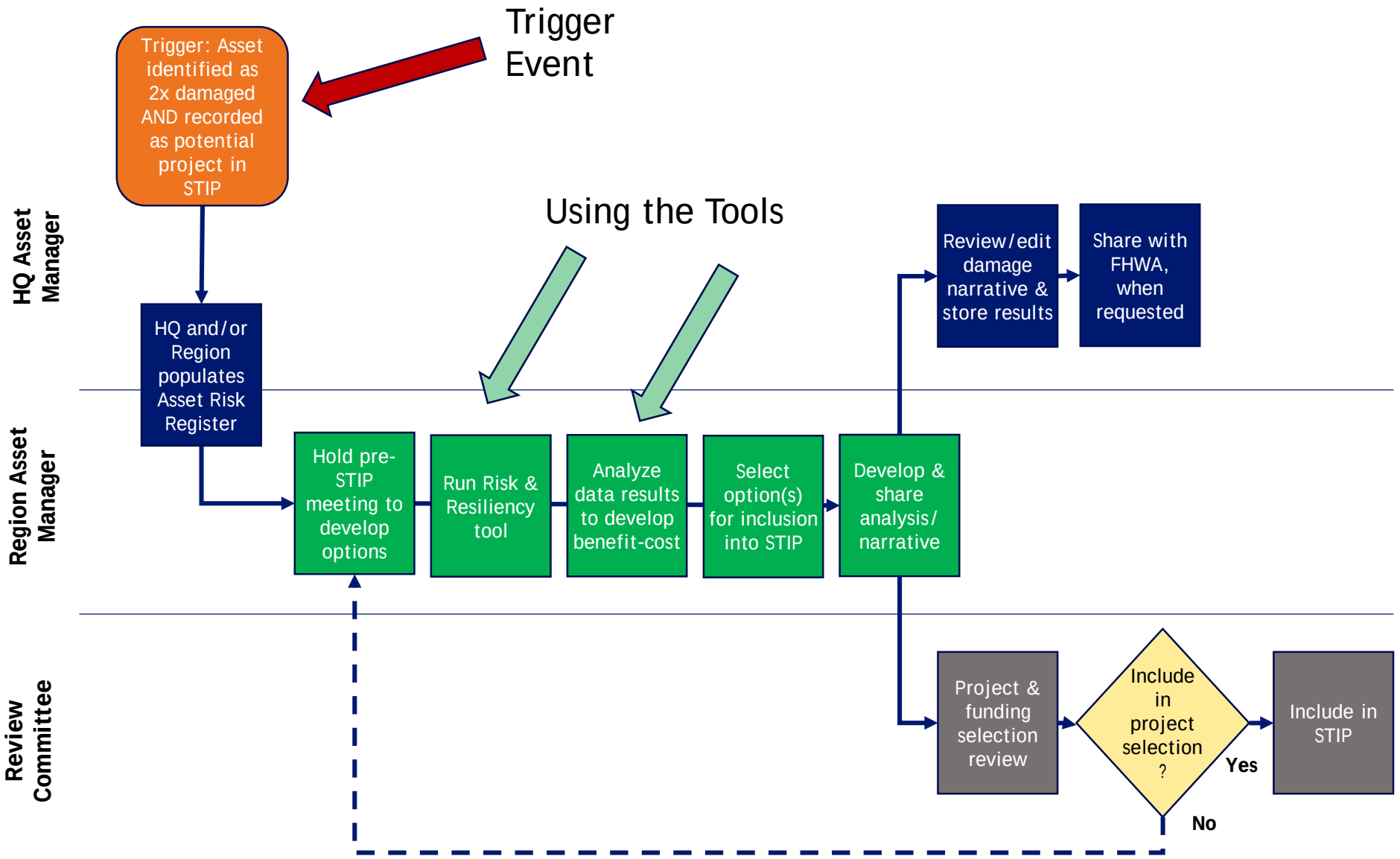
CDOT must prepare evaluations of twice damaged assets before including in the STIP.

Why are we doing this?

23 CFR 667 – Evaluations of Facilities Repeatedly Requiring Repair and Reconstruction from Emergency Events

- Conserves federal resources, protects public safety
- DOTs must conduct periodic evaluations to identify road, highway, and bridge assets with repeated repair and reconstruction stemming from emergency events since 1997
- Must determine if reasonable alternatives exist to mitigate risk, prevents repeated investment in assets facing recurring damage

Draft Process Flow: Twice Damaged Assets



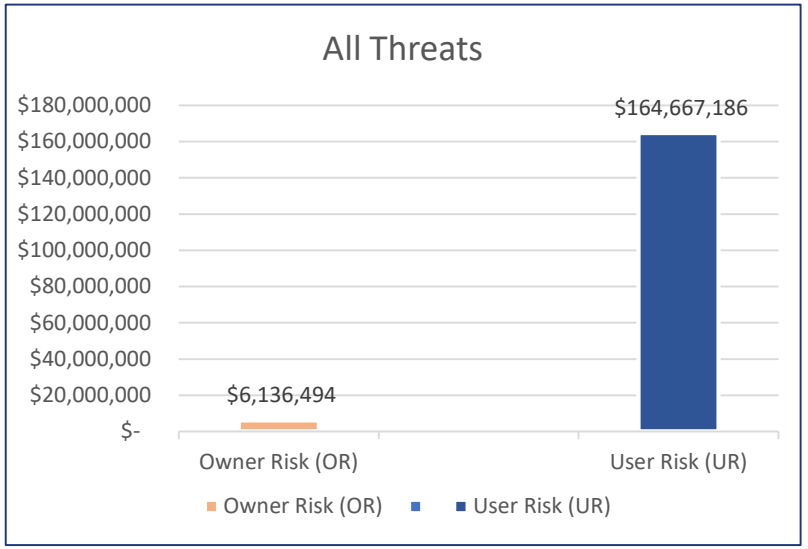
Twice Damaged Assets Case Study

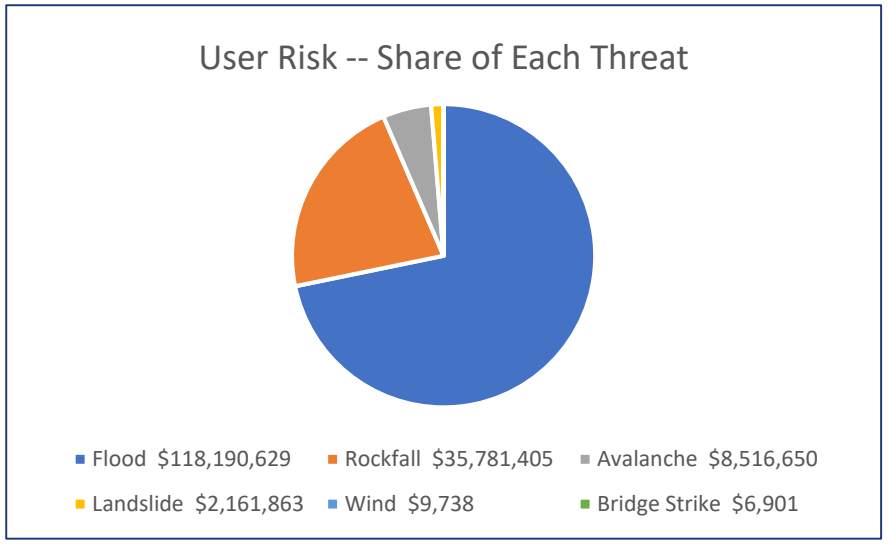
Locations to analyze:

- ❑ US 34 Big Thompson Canyon - Pavement/roadway loss
- ❑ I-25 in El Paso County (MP 144 and 155) - Culverts/bridges
- ❑ Glenwood Canyon – Rockfall resulting in pavement/bridge damage
- ❑ Dowd Canyon Landslide Complex
- ❑ US 24 Waldo Canyon - Debris Flow systems, pavement @ debris flow systems, drainage systems including pavement/roadway loss
- ❑ SH 71 (2013 and 2015 events) – Pavement damage

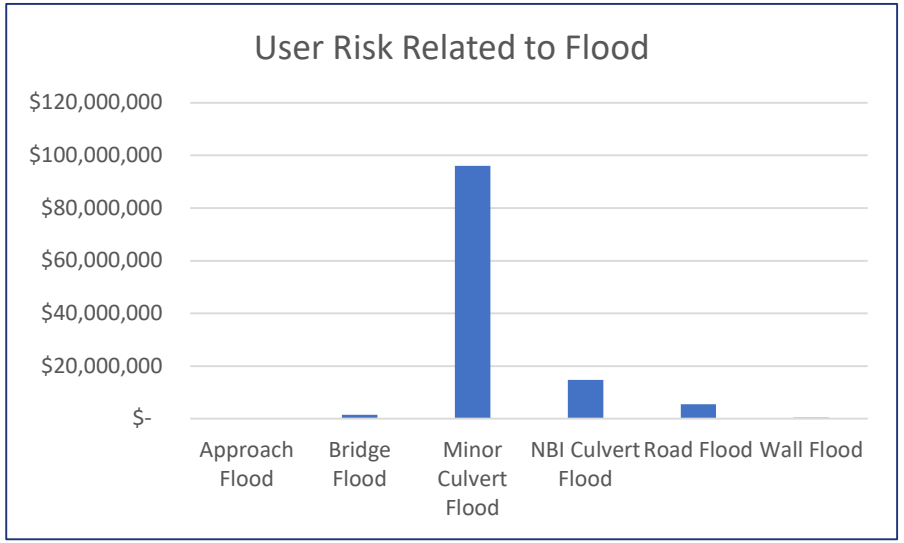
Culvert Mitigation Planning

Small Culvert Risk Mitigation Planning Case Study





Decision – Focus on minor culverts



Small Culvert – Risk Mitigation Planning Project

4 Step Process:

Step 1. Identify a high-risk subset of culverts

Step 2. Culvert Field inspection

Step 3. Develop a prioritized Region treatment plan

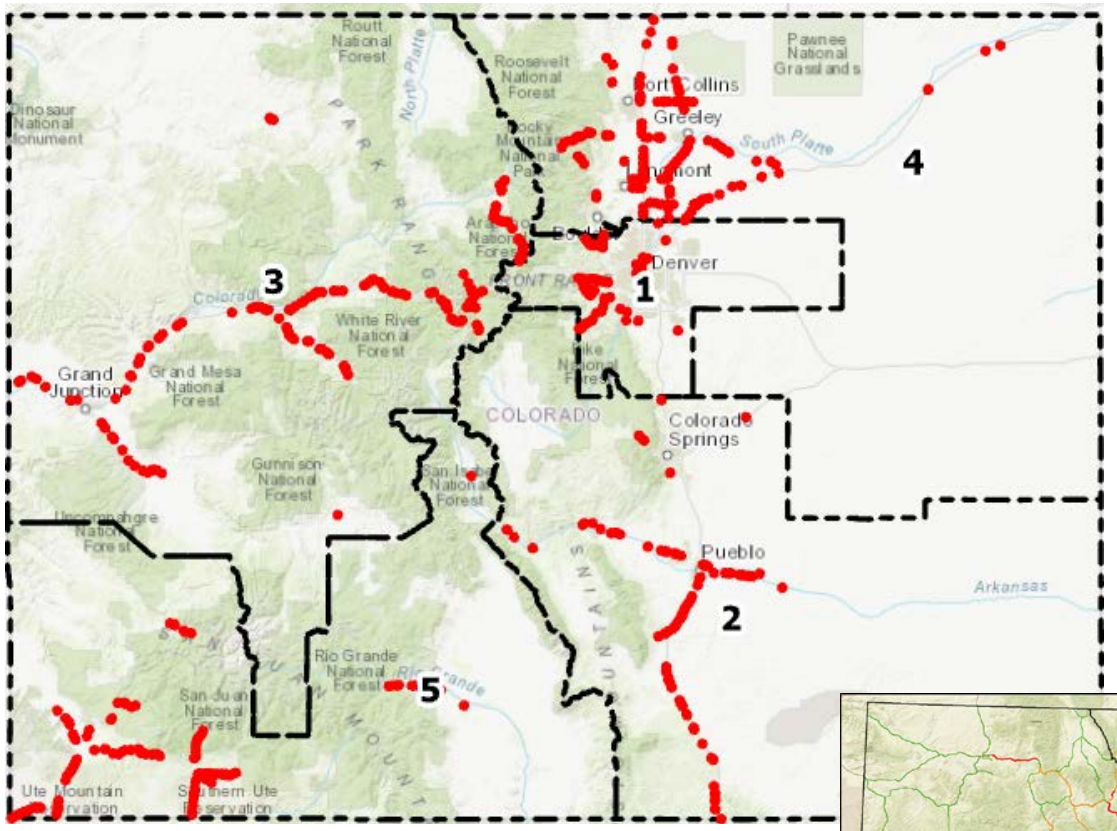
Step 4. Calculate risk and potential risk reduction. Recommend to the EMT a list of risk mitigation projects for culverts that meet the target B/C

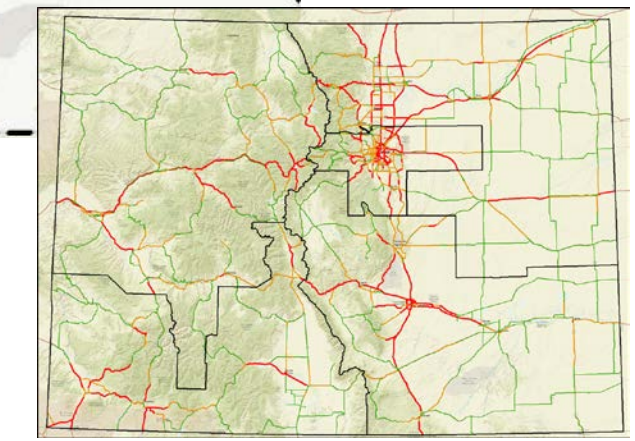
Step 1. Prioritizing At-Risk Culverts

- With just under 65,000 culverts under 4 feet across the state, which subset should we focus on first?

Proposal:

- Focus first on culverts in poor condition that are also on critical routes
- 500 – 1,000 culverts statewide





Criticality

- 53.8% Low
- 25.5% Moderate
- 20.7% High

Step 2. Culvert Inspection

This fall, over 35 identified maintenance staff will inspect the culverts with field visits and standardize condition data using:

- ESRI Collector App – NEW
- Staff Bridge Rating Guide for Small Culverts and Drainage Structures

Step 3. Risk Mitigation Plans

Develop Region Treatment Plan and Prioritize Potential Mitigation Projects

Step 4. Propose Small Culvert Improvements Where they Make Sense

GOAL:

Based on solid, standardized data, recommend a project list and funding for culvert improvements that meet a justifiable benefit cost (B/C) in order to reduce CDOT risk.

Potential Next Steps — 2020-2021 Projects

- ❑ Finish the 5 case studies –
  baking resiliency into day to day CDOT business
- ❑ Revise manuals, etc to memorialize new procedures
- ❑ Develop Performance Measures for Resiliency
- ❑ New Redundancy measure – and statewide detour map
- ❑ Prepare for Federal Resiliency Funding! (if and when it comes)

COLORADO
Department of Transportation

Thank You! For more information:

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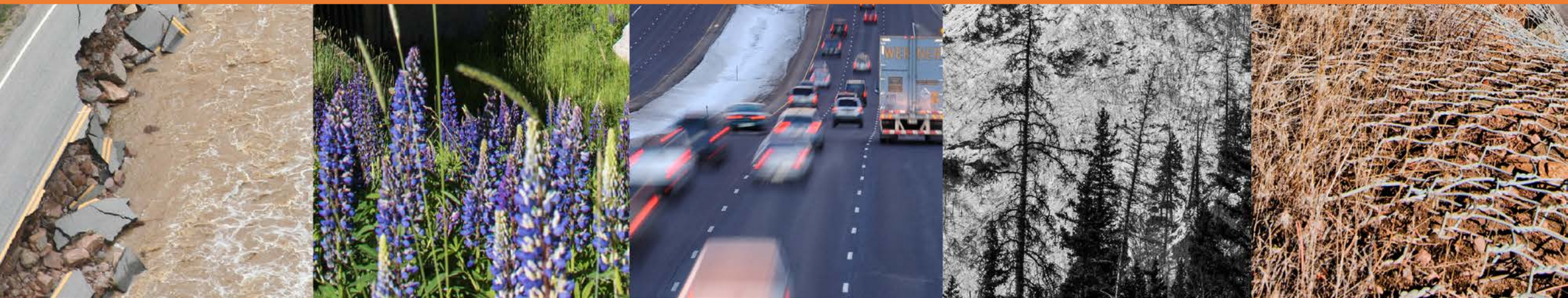


Extra Slides

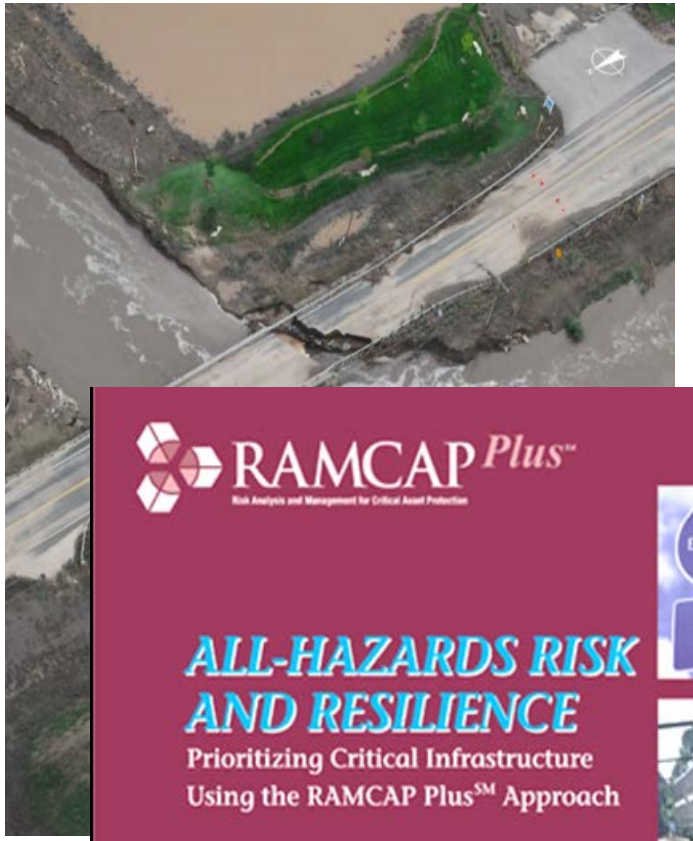
Flood Recovery – FHWA and CDOT:
Partnership to Build Back Better

- Agreement on methodology was key – RAMCAP
- Used flexibility allowed in the Emergency Relief Program
- Quantitative demonstration of how building back better made sense from a $$ B/C standpoint.

Of note: flexibility in ER program has not been the case in many other parts of the country

CDOT/FHWA Risk Review Process: Agreement to Use the 7-Step RAMCAP Model

- How likely is it that future events will happen?
- Which routes are most “critical” for us?
- How vulnerable are our facilities?
- How much will it cost? consequences ($)
- Will “betterments” reduce future risk?
- What’s the cost of betterments compared to reduced risk? B/C?
- Demonstrate to FHWA that building back better makes good long-term financial sense (Benefit – Cost analysis)

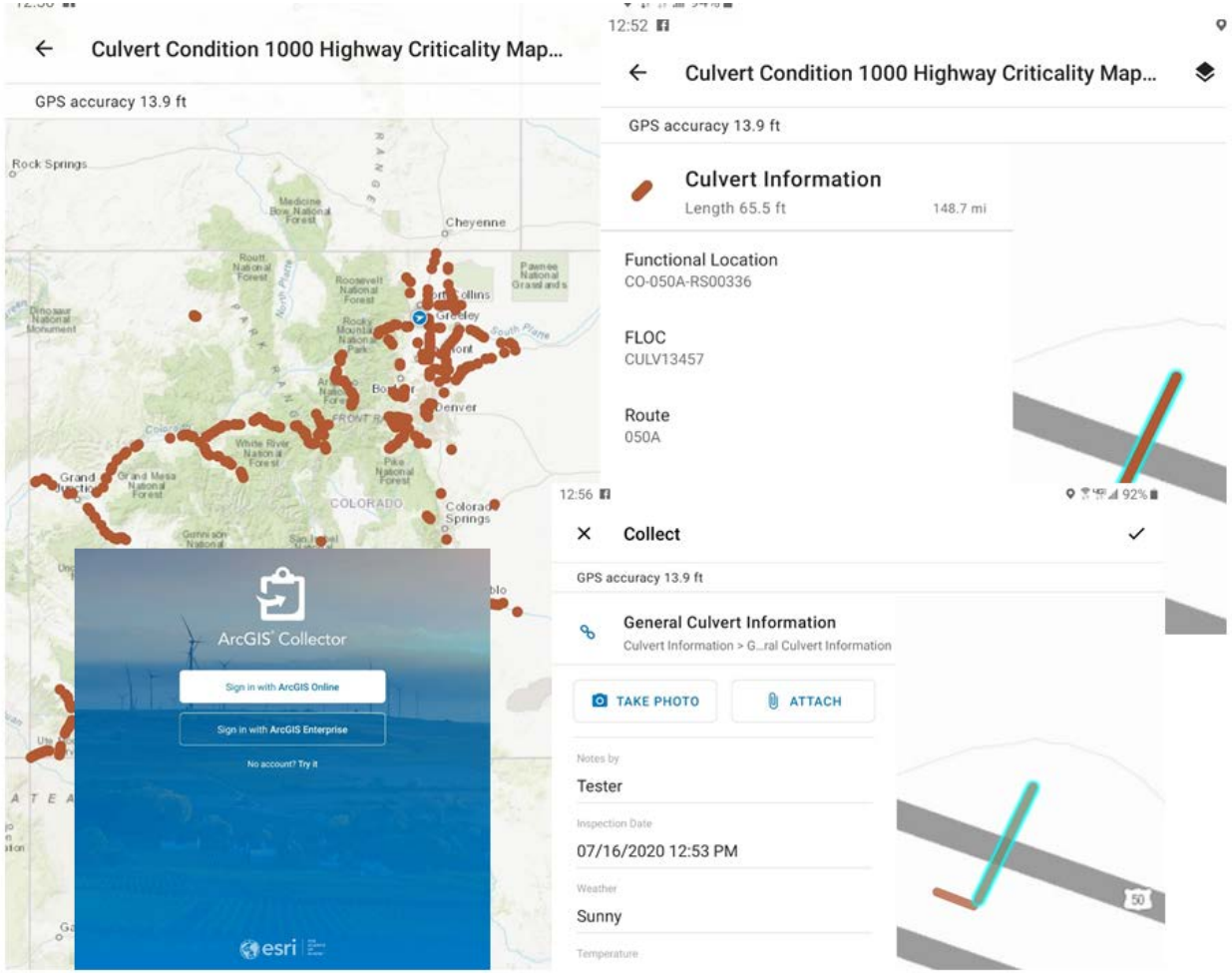


Step 2. ESRI Field Collector App

Culvert Condition App

It uses ESRI Collector for ArcGIS to collect culvert condition data.

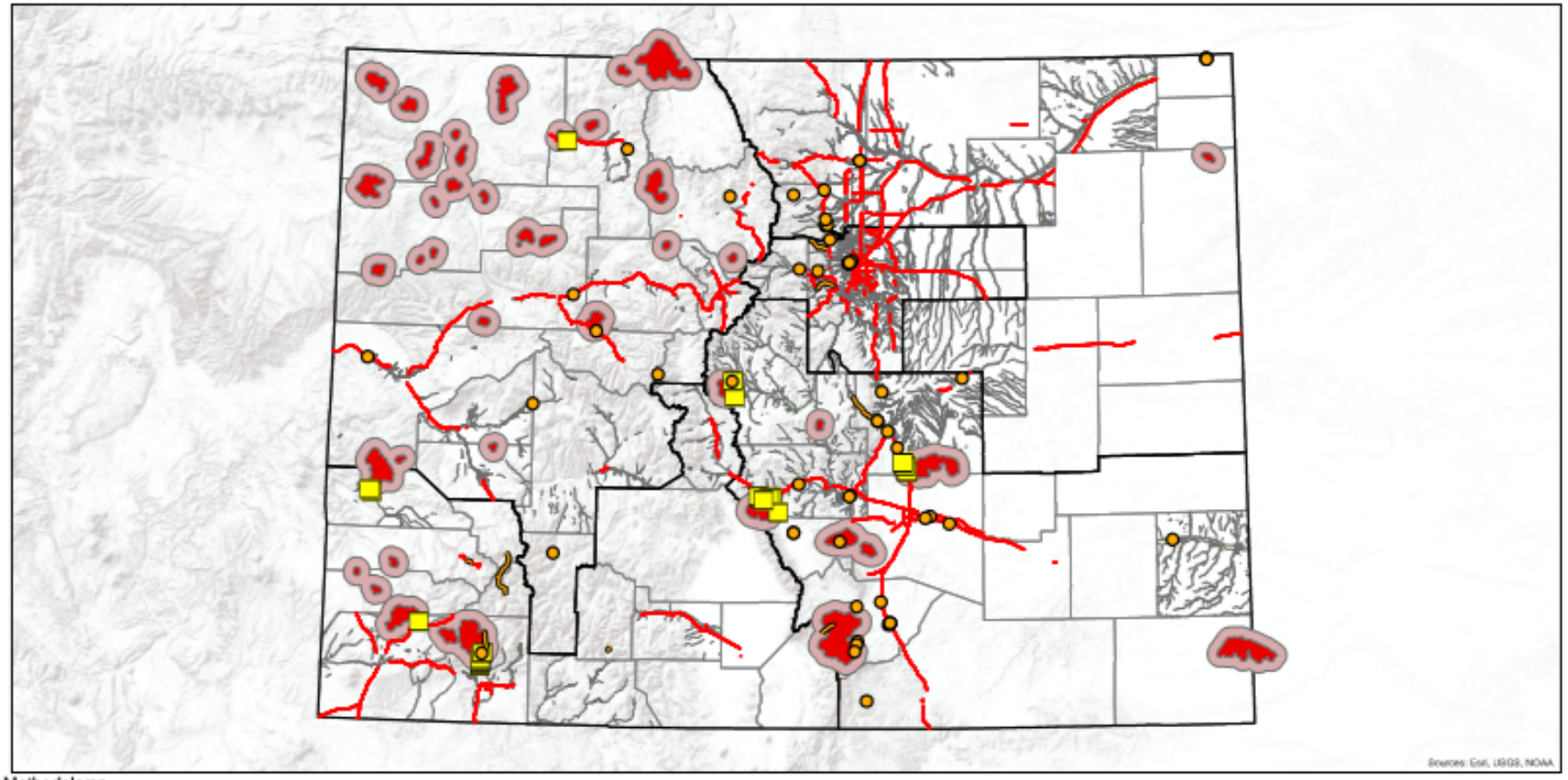
- User selects/clicks on a culvert of interest.
- Show culvert information.
- A set of forms allow users to fill out general and inlet/outlet culvert conditions information.
- Submit data during collection time or later.



Hot Topic: Post-Fire/Flood and Debris-Flow Mitigation

CDOT 2019 Fire/Flood & Debris-Flow Mitigation Planning

Flood Vulnerability Analysis



Methodology:

Data Preparation: After gathering the necessary datasets, a few simple processes were run in order to prepare the data for analysis. Burn scars were given multi-ring buffers to include areas within 1 and 5 miles of the original burn scar. Bridges and Culverts were given a simplified scour rating of 1-4 with 4 being those assets with the worst scour rating. Criticality was symbolized using the standard values of 1-3 with 3 being the most critical roadways. Finally, 100- and 500-year flood plains were selected from the National Flood Hazard Layer (NFHL).

Analysis for Highest Flood Danger Assets: Analysis involved using the select by location tool to identify those road sections and assets that overlayed both the flood plains and areas in and around the burn scars

Regional Priority Assets

Regional Priority Assets

Analysis Results Assets

High Criticality Road Sections

100 Year Flood Plains

2016-2018 Burn Scars with Buffers

1 mi

5 mi

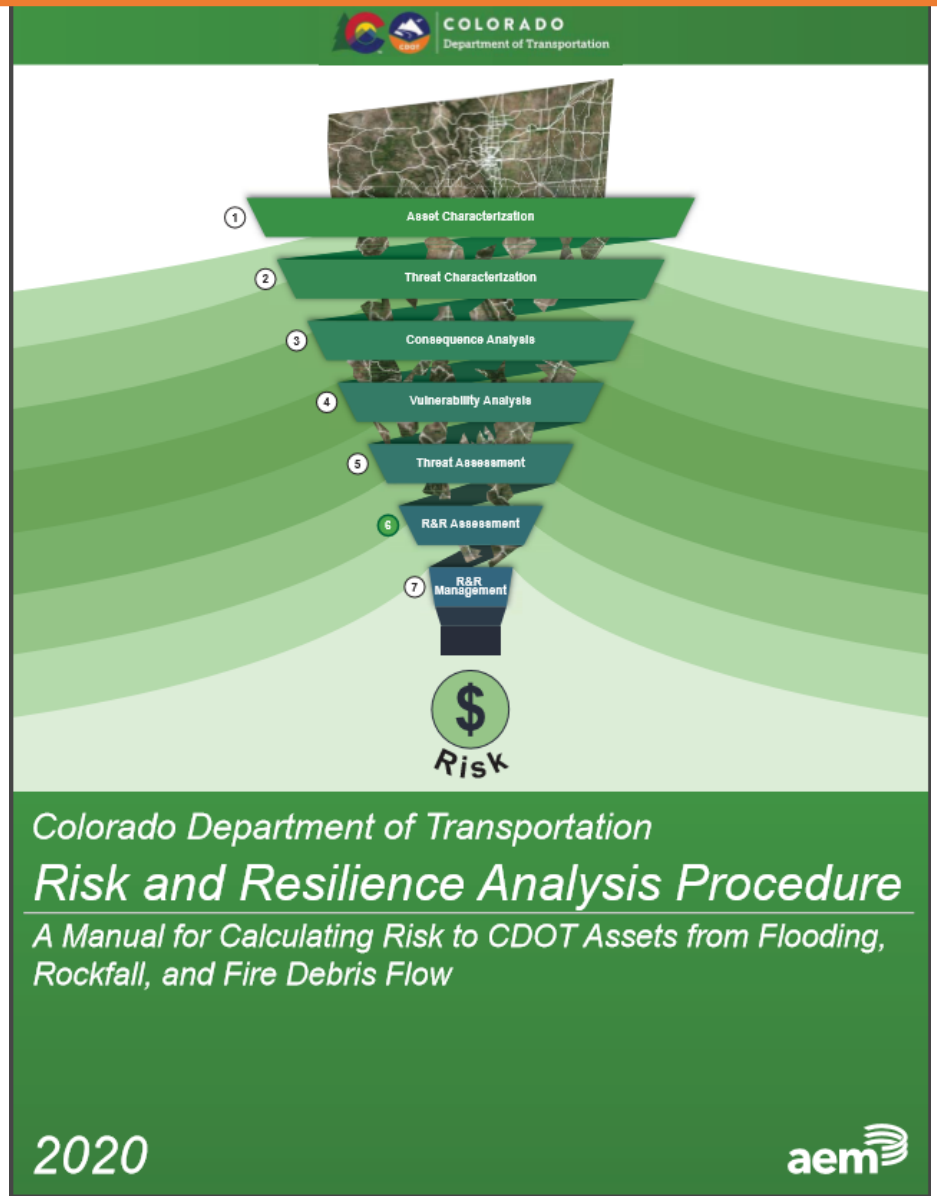
500 Year Flood Plains

Sources: FEMA, USGS, CDOT

Risk and Resiliency Standard Manual

- Published last week – available on the CDOT Resiliency Program Website!
  https://www.codot.gov/programs/planning/cdot-resilience-program

- Includes Post-fire / Flooding and Debris-flow as one of the standardized risk calculations.



Resiliency Standard/Manual

416 Fire Impact Map 2 of 4

EXHIBIT 4.3.7
416 FIRE IMPACT
MAP 2 OF 4

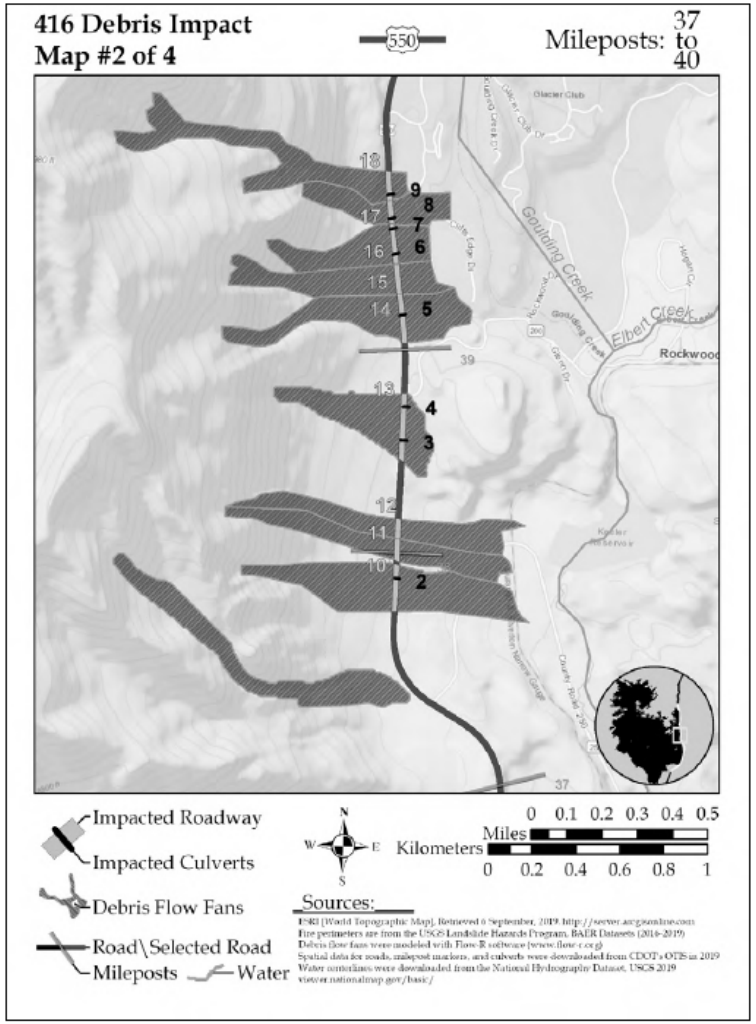


EXHIBIT 4.3.3
SUMMARY OF
DEBRIS FLOW
RISK

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