## CASFM 2018 Annual Conference

### **Technical Modeling Sessions:**

Session1: Regulating 2d Models & Tools for Planning

Isaac Allen (AECOM)

Session2: How to be Less Wrong – Errors & Uncertainty in Hydraulic Modeling

Ryan Carroll & Andrew Friend (Michael Baker International)

**Tools to Stay Ahead of the Storm** 

Dana McGlone (Dewberry Consultants), Kevin Stewart (UDFCD), Kevin Houck (CWCB)

Bendway Weirs and 2D Modeling: An Innovative Stream Design

Aaron Sutherlin & Drake Ludwig (Matrix Design Group)

Quantifying Climate Change Impacts on Flood Hydrology using Global Climate Models to Adjust NOAA Atlas 14 Precipitation Depths

Derek Rapp & Jim Wulliman (Muller Engineering), Brian K. Varrella (CDOT)

Evolution of the 2-D Base Level Engineering Across FEMA Reion VIII and a Case Study from Garfield County, Colorado

Eli Gruber, Garrett Sprouse, & David Sutley (CDM Smith)

# Regulating 2D Models & Tools for Planning

*Isaac Allen CASFM 2018* 





## Purpose of this Presentation

1 Lessons Learned

Share some lessons learned and discussion points raised from CHAMP program on the use of 2D models for regulatory purposes



Highlight important items communities should consider when working with 2D models



# Current FEMA Regulations

- FEMA regulations allow for use of 2D models, but regulations were created with 1D analyses in mind
- Difficult to conform 2D results to 1D based formats, also some regulations require additional clarification for 2D analyses

**SID** 78

The water-surface profiles of different flood frequencies must not cross one another

• Some regulations not conducive for beneficial information that can be generated from 2D models

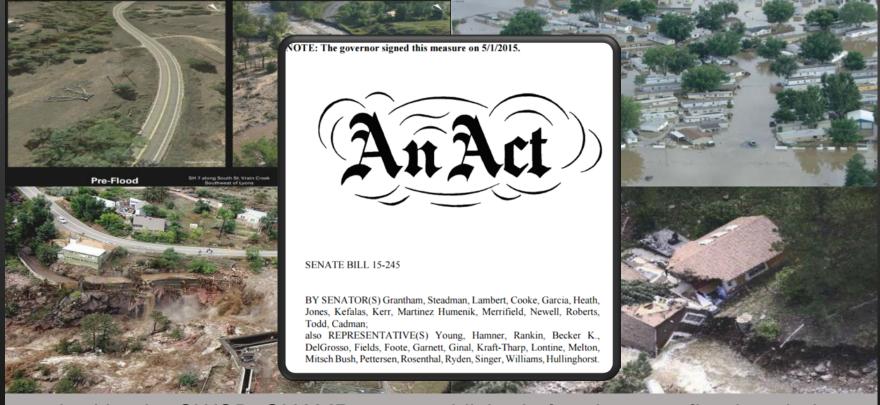
SID 70

Floodway surcharge values must be between zero and 1.0 ft.





## **CHAMP Overview**



Led by the CWCB, CHAMP was established after the 2013 floods to help communities become more resilient through comprehensive mapping of floodplains and other natural hazards.



# Regulating 2D Models & Tools for Planning



1D/2D and 2D Regulatory Products

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1D/2D and 2D Floodways



LOMCs and Other Regulatory Processes



**Next Steps** 



Questions







Regulating 2D Models & Tools for Planning



### 1D/2D and 2D Regulatory Products

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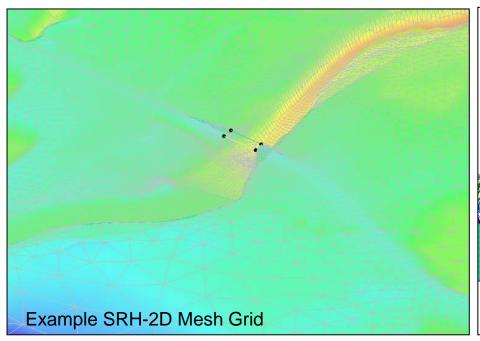


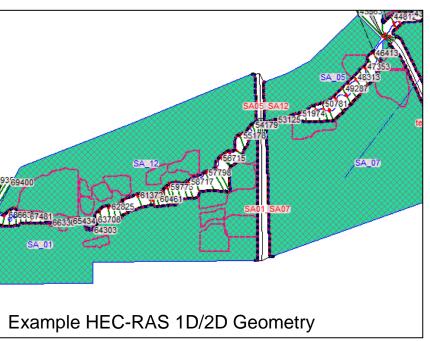




## CHAMP 2D

- Recent Colorado CTP work
  - (2) 1D/2D combined analyses completed in HEC-RAS Version 5.0.3
  - (2) 2D analyses completed in SRH-2D
- 2D models were used because of:
  - Increase in regulatory flow rates in heavily developed town
  - Request by community to complete a 2D analysis to utilize previous 2D work
  - Handle complex flow scenarios after preliminary 1D evaluation





## 2D Developments

- Through Colorado CTP Program, worked with FEMA to develop approved approach for some regulatory items
- FEMA guidance indicates floodways using unsteady flow need to be coordinated with project officers
- Developed process for evaluating 2D floodways, which included:
  - Creating Floodway Data Tables
  - Creating Flood Profiles
- Information is available on CHAMP website:

http://coloradohazardmapping.com/

#### BUT

Approaches are just a temporary fix to conform 2D results to 1D based standards

#### References

1. http://coloradohazardmapping.com/hazardMapping/floodplainMapping/Documents

#### A=COM

#### Technical Memorandum

To:	Thuy Patton, Colorado Water Conservation Board (CWCB) Floodplain Mapping Coordinator and Corey Elliott, CWCB Hazard Mapping Coordinator		
From:	gel Rucker, Deputy Project Manager and Tom Wright, 2D Hydraulics		
Date:	anuary 25, 2017 - Revised May 1, 2017		
Project Title:	Colorado Hazard Mapping Program (CHAMP)	Project Number:	60436665
Subject:	Calculating 2-Dimensional (2D) Floodways for Use on Regulatory Flood Insurance Rate Maps (FIRMs) and Flood Insurance Studies (FIS)		ate Maps

#### Overview

An approach is needed to develop floodways for new studies using 2D models, unsteady flow models, or mixed 1-Dimensional (1D)/2D models (all generally referred to as unsteady flow models in this document). This document outlines a suggested procedure that can create reproducible results in these situations.

Although 2D model use is not new, its use has only become more frequent recently, especially with the release of HEC-RAS 5.0, which includes 2D capabilities at no cost, which are supported and continuously updated by the Army Corps of Engineers' Hydraulic Engineering Center. HEC-RAS has been the primary software tool used for the nation's floodplain mapping efforts since its release in 1997. Current guidance and procedures related to floodways were created for, and are more applicable to 1D steady state flow modeling. Ideally, the following options should be considered in order to comply with existing guidance, where appropriate:

- Remove floodways from FIRMs where 2D analyses are conducted. Communities would then be required to
  manage development by maintaining models, or requiring developers to do so and verify that a cumulative
  surcharge in the floodolain is not resulting from new development.
- 2. Develop a procedure to generate floodways in 1D, 1D/2D or 2D unsteady flow models.
- Develop and calibrate a steady state 1D model using the results of the 2D model that can then be used to generate a floodway. The 2D model will then become backup information for the regulatory model.

Option 1 can be costly and prohibitive for communities that lack resources. Option 3 requires use and maintenance of multiple models; changes in the floodplain would require reconsidering the effects of future encroachments, which is not efficient, confusing to the end user, and time consuming/costly. Potential disputes through the review and approval cycle as to what constitutes a calibrated 1D model could also arise and this memo does not attempt to address that definition. In addition for Option 3, a floodway would be developed on a separate steady state 1D model that does not include the detail or results that were included in the original 2D model. In other words, the 1D floodway would not necessarily be reflective of what would be calculated for a floodway in a 2D model.

For CHAMP, it has been determined that floodways should be produced on all streams. For this reason and the reasons above, this document will focus on Option 2. It should be noted that the other options should be considered, in order (1 to 3), especially if Option 2 does not produce appropriate results. It is also recommended that additional consideration be given to determining a more cost-effective, efficient way to maintain floodways in real time and/or developing guidance based on new technology. This would likely entail discussion with FEMA about modification of standards, use of an available grid system that can be modified to determine impacts based on development, updated tools from software developers, and/or development of accepted guidance and tools to help make the revised floodway procedure more efficient.

Technical Memorandum - Calculating the 1-Percent-Plus Flood Discharge

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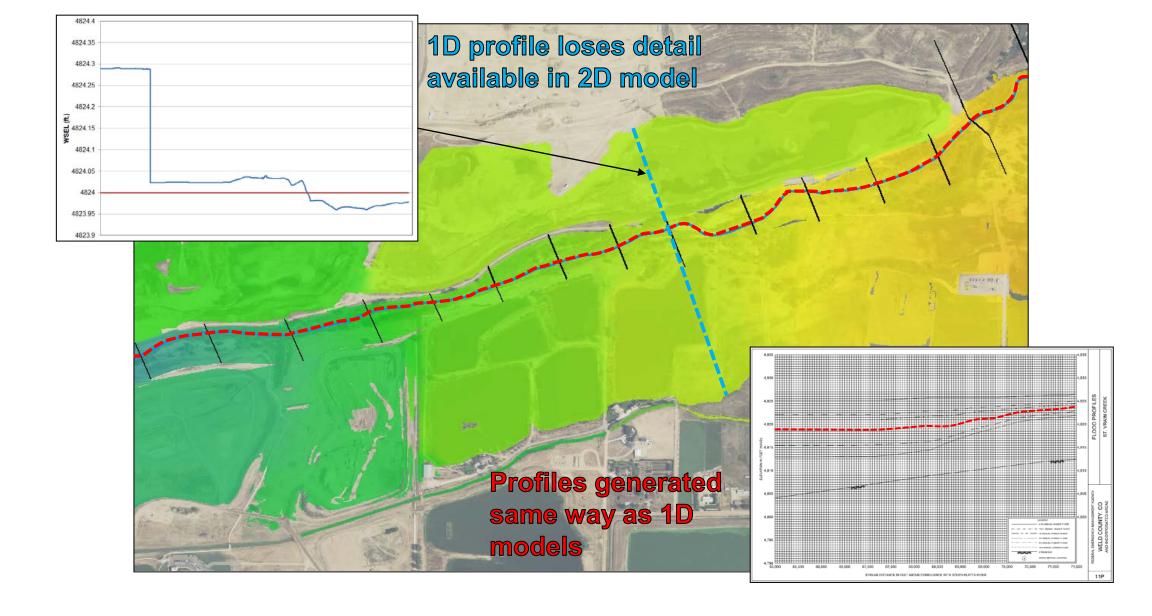
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## **Profiles**

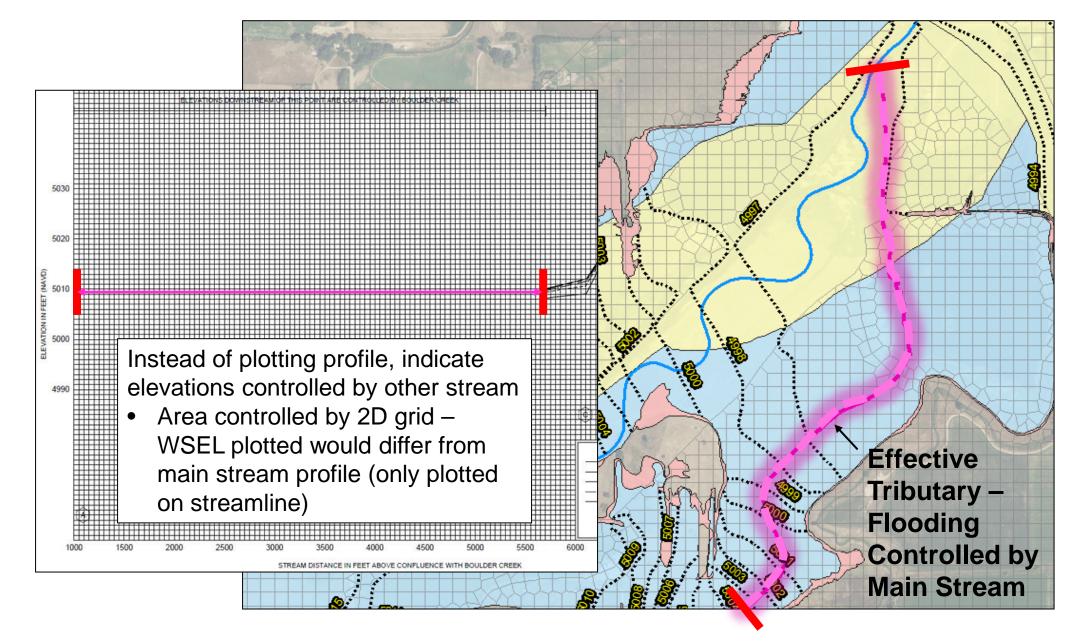








## Profile Tie-ins



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## BFE Lines

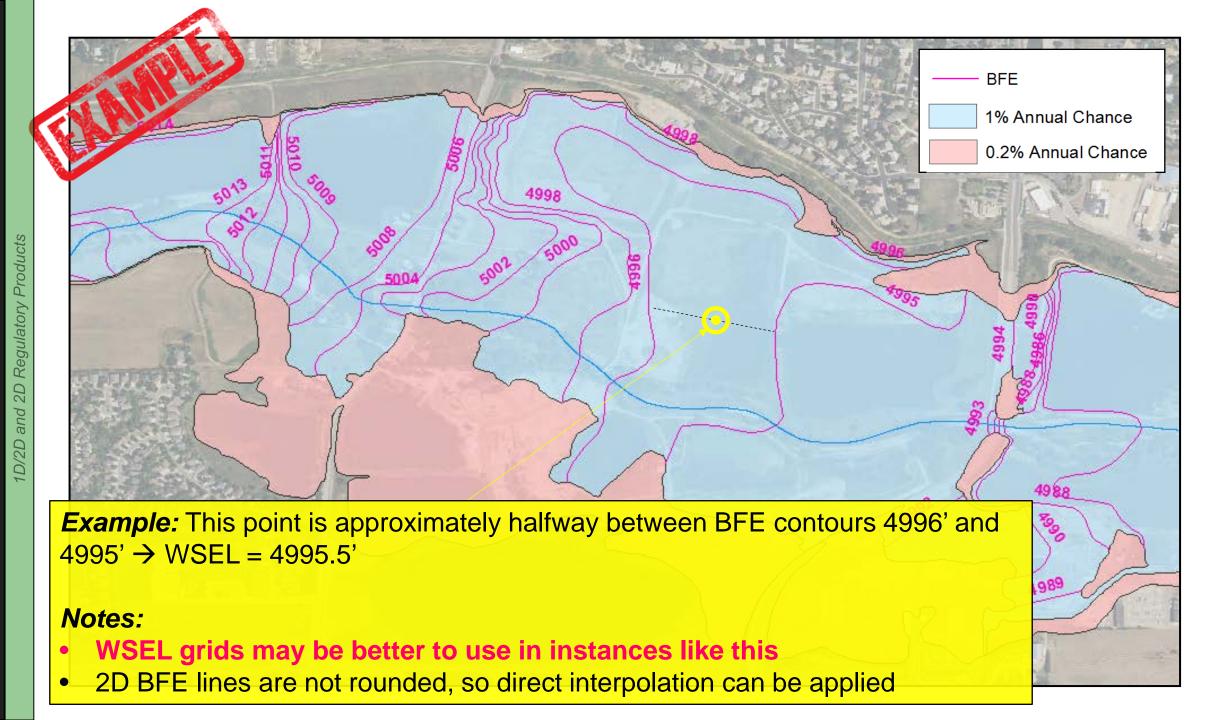
Based on current standards, Base Flood Elevation (BFE) lines for 1D models are used only at confluences and to show backwater elevation. Otherwise, 1D cross sections report WSELs. BFEs for 1D/2D and 2D models are contoured from the WSEL grid.

**1D** 1D/2D **2D** 0.2% Annual Chance **BFE** 1% Annual Chance





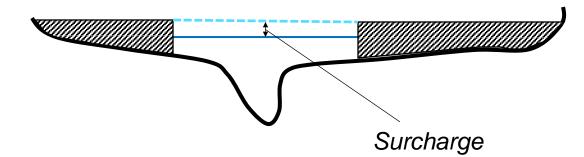




## 1D vs. 2D Floodways

 Major difference between a 1D and 2D floodway is that the surcharge in a 1D model is averaged across the entire cross section, whereas surcharges in 1D/2D and 2D floodways are evaluated at each computational cell

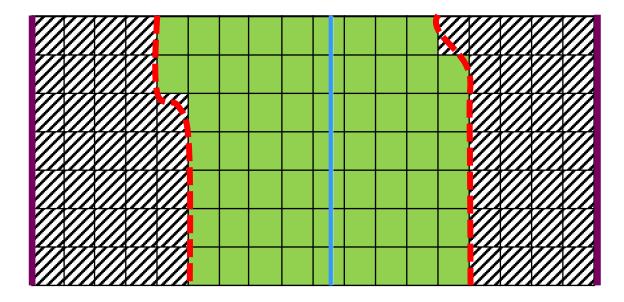




#### So what does that mean?

 1D/2D and 2D floodways tend to be much wider because each cell must fall within the surcharge range. In a 1D/2D or 2D model there are 10,000s of locations that must satisfy the surcharge standard versus in a 1D model where there are 10s or 100s.

#### 2D Floodway



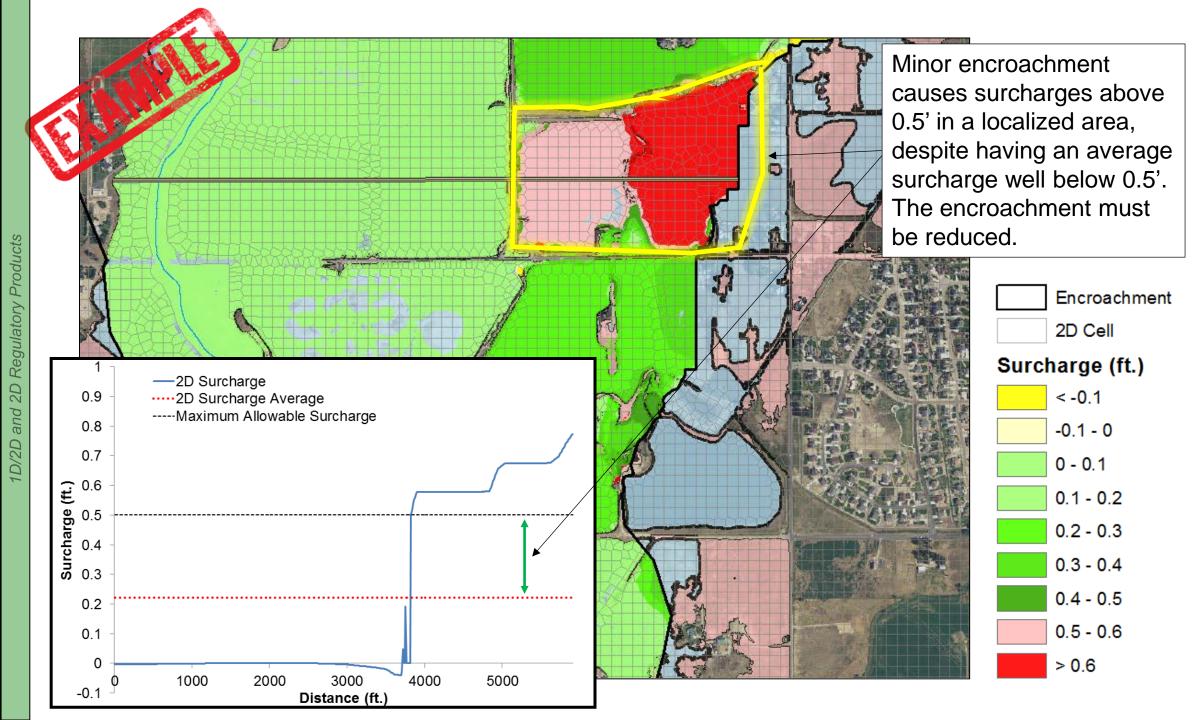
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## Floodway Products

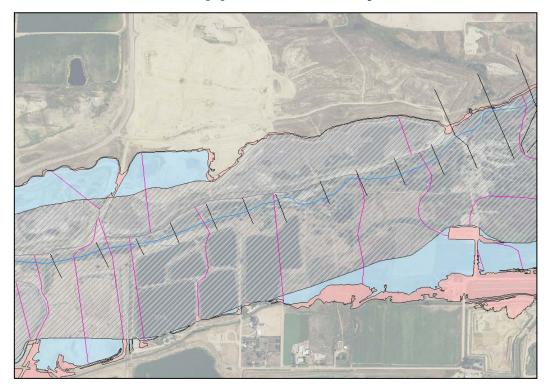
The tools available for managing a 1D/2D or 2D floodway are the same as those available for typical 1D models, including:

### Floodway Data Table



				Table 24: Floo	odway Data			
LOCATION FLOODWAY				1% ANNUAL CHANCE FLOOD WATER SURFACE ELEVATION ( FEET NAVD88)			RFACE	
CROSS SECTION	DISTANCE <sup>1</sup>	WIDTH (FEET)	SECTION AREA (SQ. FEET)	MEAN VELOCITY (FEET/ SEC)	REGULATORY	WITHOUT FLOODWAY	WITH FLOODWAY	INCREASE
*2 *2 *2 *2 *2 *2 *2 *2 *2 *2 *2 *2 *2 *	33,346 35,685 37,219 38,883 39,818 41,865 42,716 44,385 45,454	1,539 2,770 3,197 1,649 1,392 2,161 3,100 2,917 2,143		7.4 6.9 10.3 7.1 6.7 7.3 5.7 7.0 4.6	4,955.0 4,964.0 4,966.0 4,971.0 4,974.0 4,983.0 4,983.0 4,989.0 4,994.0	4,955.0 4,964.0 4,966.0 4,971.0 4,974.0 4,980.0 4,983.0 4,989.0 4,994.0	4,965.2 4,964.0 4,966.1 4,971.0 4,974.0 4,983.1 4,989.1 4,984.0	0.2 0.0 0.1 0.0 0.0 0.0 0.0 0.1 0.1
information includ *Data not availabl	d using a 2D mo ing depth and ve e	odel. Location elocity grids. C	contact the Boul	der County Floo	the FIRMs. Addition dplain Administrate onty Floodplain Adm	or for more inform	ation.	p determine flood
	MERGENCY MA				FI	OODWAY	DATA	
	ID INCORPORA	,			FLOODING SOURCE: BOULDER CREEK			
				59				

#### **Mapped Floodway**



But, the information provided within the tools is slightly different and there is additional information aside from those tools that can help with floodway management.

## **Cross Sections**

AND INCORPORATED AREAS

No cross sections are reported for 1D/2D and 2D floodways. Instead, information is referenced to BFE lines.

CROSS SECTION DISTANCE <sup>1</sup> WIDTH (FEET) SECTION AREA (SQ FEET) (FEET/SEC) REGULATORY WITHOUT FLOODWAY FLOODWAY INCREASE (SQ FEET) (FEET/SEC) REGULATORY REGULATORY WITHOUT FLOODWAY FLOODWAY INCREASE (SQ FEET) (FEET/SEC) REGULATORY REGULATORY WITHOUT FLOODWAY FLOODWAY INCREASE (SQ FEET) (FEET/SEC) REGULATORY REGULATORY WITHOUT FLOODWAY INCREASE (SQ FEET) (FEET/SEC) REGULATORY REGULATORY WITHOUT FLOODWAY INCREASE (SQ FEET) (S		LOCATION		FLOODWAY	,	. ,	AL CHANCE FLO ELEVATION ( F		RFACE
*2 \$1,685 2,770 * 6.9 4,964.0 4,964.0 4,964.0 0.0 0.0 4,965.2 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1	/			AREA	VELOCITY	REGULATORY			INCREASE
		*2 \$5,685 *2 37,219 *2 38,893 *2 39,818 *2 41,855 *2 42,716 *2 44,385 *2 45,454 Station 45,563-	2,770 3,197 1,649 1,392 2,161 3,100 2,917		6.9 10.3 7.1 6.7 7.3 5.7 7.0	4,964.0 4,966.0 4,971.0 4,974.0 4,980.0 4,983.0 4,989.0	4,964.0 4,966.0 4,971.0 4,974.0 4,980.0 4,983.0 4,989.0	4,964.0 4,966.1 4,971.0 4,974.0 4,980.0 4,983.1 4,989.1	0.0 0.1 0.0 0.0 0.0 0.1 0.1

<sup>&</sup>lt;sup>2</sup>Values computed using a 2D model. Locations are represented by BFEs on the FIRMs. Additional information is available to help determine floodway information including depth and velocity grids. Contact the Boulder County Floodplain Administrator for more information

INCREASE

0.1

0.2

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0.3

0.3

0.2

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0.0

FLOODING SOURCE: BOULDER C

Administrative floodway. Model results not available. Contact the Boulder County Floodplain Administrator for more information.

-	FEDERAL EMERGENCY MANAGEMENT AG	FLOODWAY DATA
F E	BOULDER COUNTY, CO	
24	AND INCORPORATED AREAS	FLOODING SOURCE: BOULDER CREEK













#### 1% ANNUAL CHANCE FLOOD WATER SURFACE FLOODWAY ELEVATION (FEET NAVD88) MEAN WITHOUT AREA VELOCITY REGULATORY INCREASE FLOODWAY FLOODWAY (SQ. FEET) (FEET/SEC) 6.074.7 6,074.7 6.074.8 0.1 151.52 49 50 36 80 40 339 14.8 6.105.8 6.105.8 6.106.0 0.2 347 14.5 6.133.9 6,133.9 6.133.9 0.0 328 15.3 6.162.5 0.4 6.162.1 6.162.1 12.5 404 6,187.3 6,187.3 6,187.3 0.0 CN 318 15.8 6.225.0 6,225.0 6.225.0 0.0 CO 43 327 15.4 0.1 6,252.3 6,252.3 6,252.4 CP 97 821 6.1 6,280.4 6,280.4 6,280.5 0.1 CQ 46 344 58,224 14.5 6.318.7 6.318.7 6.318.7 0.0 CR 58 365 13.7 159,109 6,342.8 6,342.8 6,342.8 0.0 CS CT 160,194 44 326 15.4 6,382.1 6,382.1 6,382.4 0.3 160,599 64 662 7.6 6.401.1 6,401.4 0.3 6,401.1 CV 36 304 16.4 6.418.8 6,418.8 6,419.0 0.2 49 363 13.8 6.478.9 6,478.9 6.478.9 0.0 CW CX CY CZ DA 32 34 0.2 0.2 0.0 295 16.9 6,537.3 6,537.3 6.537.5 299 16.8 6,608.6 6,608.6 6,608.8 34 6,679.2 304 16.5 6.679.2 6,679.2 50 6,743.3 6,743.5 340 14.7 6.743.3 410 12.2 6.793.8 6,793.8 6,794.2 DB 168,17 6,843.8 6,843.9 14.4 6,843.8 168,874 14.9 6.876.1 6,876.1 6,876.1

FLOODWAY DATA

FLOODING SOURCE: BOULDER C

Feet above confluence with St. Vrain Cree

FEDERAL EMERGENCY MANAGEMENT AGENCY

BOULDER COUNTY, CO

AND INCORPORATED AREAS

**Data** 

Data (width, mean velocity, etc.) presented in the 2D FWDT is not comprehensive. To get data for any other location in the floodway, the WSEL, velocity, and depth grids should be used.

LOC	NON		FLOODWAY	,	1% ANNU	AL CHANCE FLO ELEVATION ( F	OOD WATER SU EET NAVD88)	RFACE
CROSS SECTION	DISTANCE	WIDTH (FEET)	SECTION AREA (SQ. FEET)	MEAN VELOCITY (FEET/ SEC)	REGULATORY	WITHOUT FLOODWAY	WITH FLOODWAY	INCREASE
*2 *2 *2 *2 *2 *2 *2 *2 *2 *2 *2 *2 *2 *	33,346 35,885 37,219 38,893 39,818 41,455 42,716 44,385 45,454	1,539 2,770 3,197 1,649 1,392 2,161 3,100 2,917 2,143		7.4 6.9 10.3 7.1 6.7 7.3 5.7 7.0 4.6	4,955.0 4,964.0 4,966.0 4,971.0 4,974.0 4,980.0 4,983.0 4,989.0 4,994.0	4,955.0 4,964.0 4,966.0 4,971.0 4,974.0 4,983.0 4,983.0 4,989.0 4,994.0	4,955.2 4,964.0 4,966.1 4,971.0 4,974.0 4,980.0 4,983.1 4,989.1 4,994.0	0.2 0.0 0.1 0.0 0.0 0.0 0.1 0.1 0.0

Feet above confluence with St. Vrain Creek

Administrative floodway. Model results not available. Contact the Boulder County Floodplain Administrator for more information

TAB	FEDERAL EMERGENCY MANAGEMENT AGENCY	FLOODWAY DATA
E	BOULDER COUNTY, CO	
24	AND INCORPORATED AREAS	FLOODING SOURCE: BOULDER CREEK







Values computed using a 2D model. Locations are represented by BFEs on the FIRMs. Additional information is available to help determine floodway information including depth and velocity grids. Contact the Boulder County Floodplain Administrator for more information





## Additional Information for 2D Floodways

• 1D/2D and 2D FWDT only report information at select locations. To find detailed information about specific locations, the surcharge, WSEL, depth, and velocity grids should be used

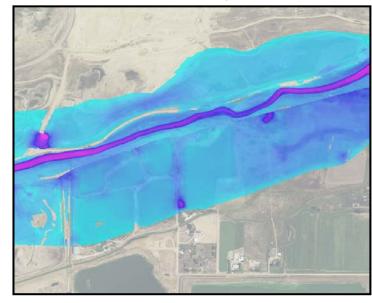
### **Surcharge**



#### Uses

- Shows the WSEL for the encroached floodplain
- Used to evaluate surcharge at individual properties

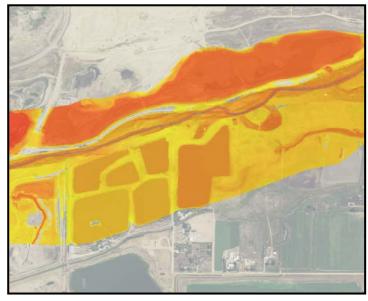
#### **Velocity**



#### Uses

 Supplement for "Mean Velocity" column in FWDT

#### Depth



#### Uses

 Can be used to communicate a depth of floodway at a specific property



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1D/2D and 2D Floodways







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## Purpose of the Floodway

- The floodway represents the "full build" or "ultimate" condition that can occur without creating a surcharge greater than the designated height. The benefit of the floodway is that as development occurs, a new engineering study is not required to determine whether the development will cause a surcharge over the designated height
- Floodways make the job of a Floodplain Manager easier. However, with the introduction of 1D/2D and 2D models there are some additional things to consider:
  - 1) Floodway standards and guidance were established for 1D analyses application to 2D can be:





**Difficult** 

2) Applying 1D floodway principles to 1D/2D and 2D models may result in a more restrictive floodway because of the resolution of the model results.

So with that in mind....







## Floodway Options

Decision on floodway development needs to be made with community input

OPTION	PROS	CONS
Generate 2D Floodway under Current Standards	<ul> <li>Floodway management is very similar to 1D</li> <li>Addtn'l info to help with regulation</li> </ul>	<ul> <li>Time intensive</li> <li>Tend to be wider, limiting potential for development</li> </ul>
Calibrate 1D model to 2D model, Create Floodway from 1D	Keep existing practices	<ul><li>2 models to update</li><li>Lose some detail from 2D model</li></ul>
Manage without a Floodway	<ul> <li>Manage development on case by case basis</li> </ul>	<ul><li>Must track cumulative impacts of development</li><li>Maintain "living" model</li></ul>
Alternate method for 2D Floodway (D x V, Full Conveyance, etc.)	?	?





**Scenario 1**: Floodtown, USA elects to have a 2D floodway delineated on the revised FIRM maps. Scenario 2: Floodtown, USA does not have a floodway on the new FIRMs due to creation of the new regulatory 2D model.

#### Consider three events:

- Event 1: Release of the new Floodtown, USA FIRM Panels and FIS
- **Event 2**: Construction plans for a new shopping center submitted by Development Co.
- **Event 3**: Submittal of a building permit by Resident A to construct a new porch for their house

















# **Scenario 1**: A 2D Floodway is Delineated on the Revised FIRM Maps





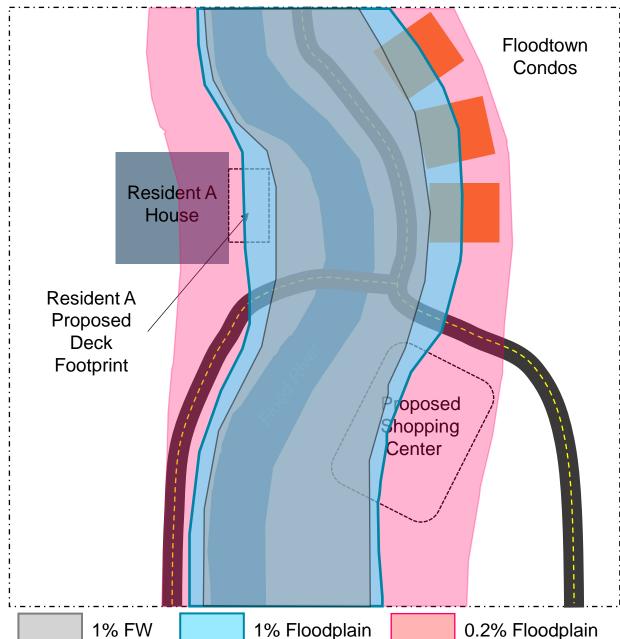
**Event 1**: Release of the new Floodtown, USA FIRM Panels and FIS

#### **Description**:

new FIRMs.

Floodtown, USA's new floodplains just became effective. Included with the floodplains are WSEL, surcharge, depth, and velocity grids generated from the 2D model, as well as a 2D floodway. Development is managed similar to the way it was prior to release of the

### Floodtown, USA









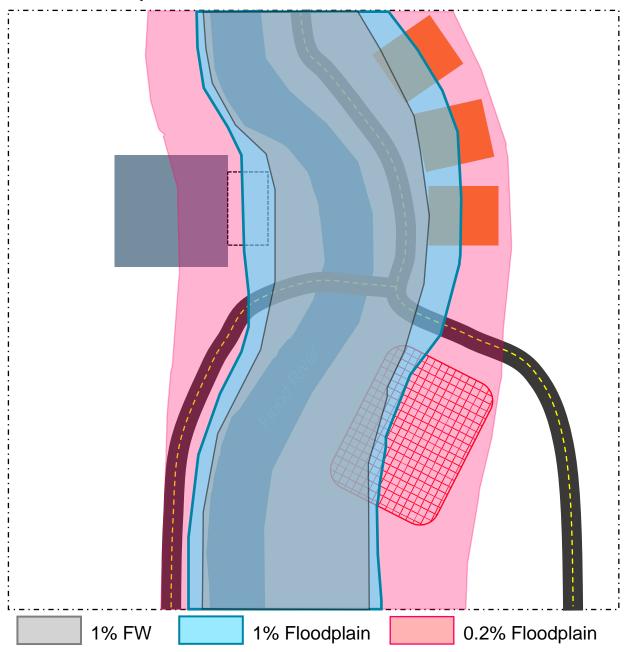
**Event 2**: Construction plans for a new shopping center submitted by Development Co.

#### **Description**:

issued.

Plans are submitted by Development Co. for construction of a shopping center. The Floodtown, USA Floodplain Manager sees that the proposed footprint of the shopping center development is within the delineated floodway so they tell Development Co. they must prove a no-rise or development cannot occur. Development Co. is not able to prove a no-rise so a permit is not















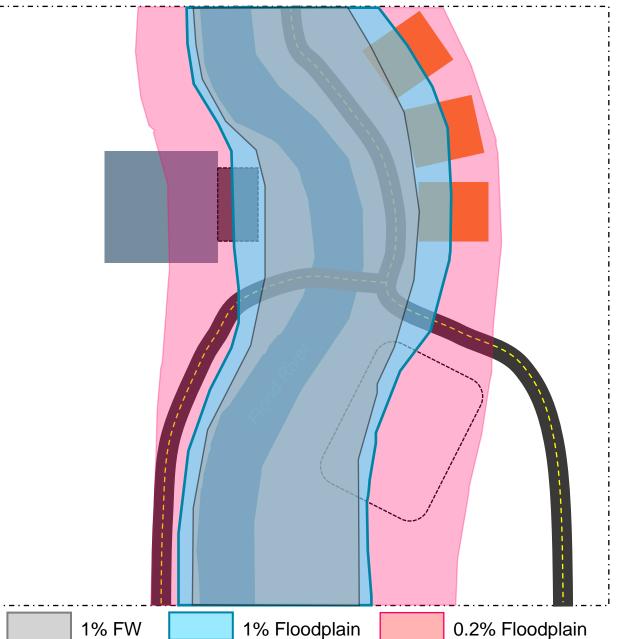


**Event 3**: Submittal of a building permit by Resident A to construct a new porch for their house.

#### **Description**:

Resident A submits an application to construct a porch. The Floodtown, USA Floodplain Manager sees that the proposed footprint of the porch is outside of the floodway. As a result, a permit is issued and Resident A proceeds with construction of their porch.





















# Scenario 2: A 2D Floodway is not delineated on the Revised FIRM Maps





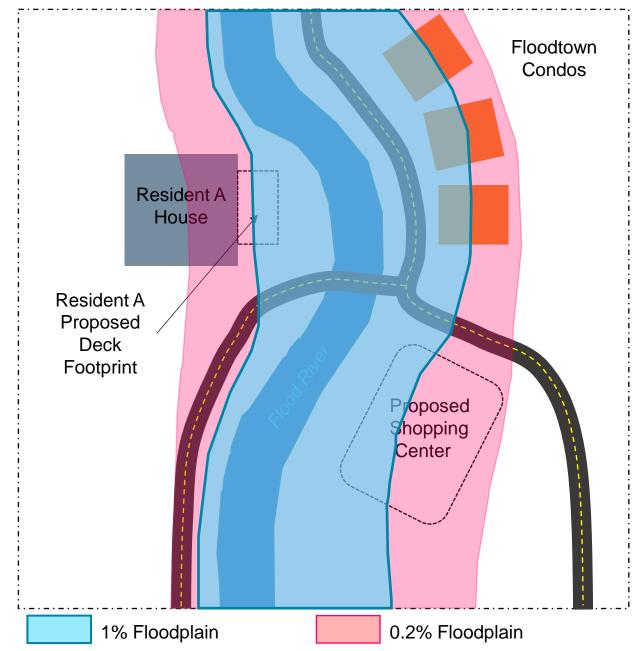


**Event 1**: Release of the new Floodtown, USA FIRM Panels and FIS

#### **Description**:

Floodtown, USA's new floodplains just became effective. Included with the floodplains are WSEL, surcharge, depth, and velocity grids generated from the 2D model. The WSEL grid generated is now the baseline for all future floodplain development in Floodtown, USA.

#### Floodtown, USA













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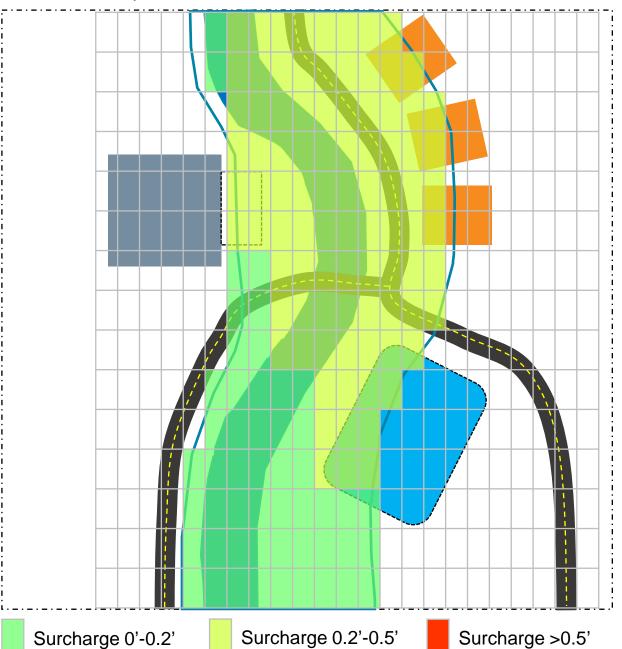


**Event 2**:Construction plans for a new shopping center submitted by Development Co.

#### **Description**:

Floodtown Engineering Co. is contracted to study the impacts of the shopping center construction. They find that when compared to the <u>effective WSEL</u>, the shopping center does not cause an increase in the WSELs above 0.5 foot and does not cause a shift in the floodplain extents. As a result, the shopping center receives an approved floodplain permit and is constructed.

#### Floodtown, USA

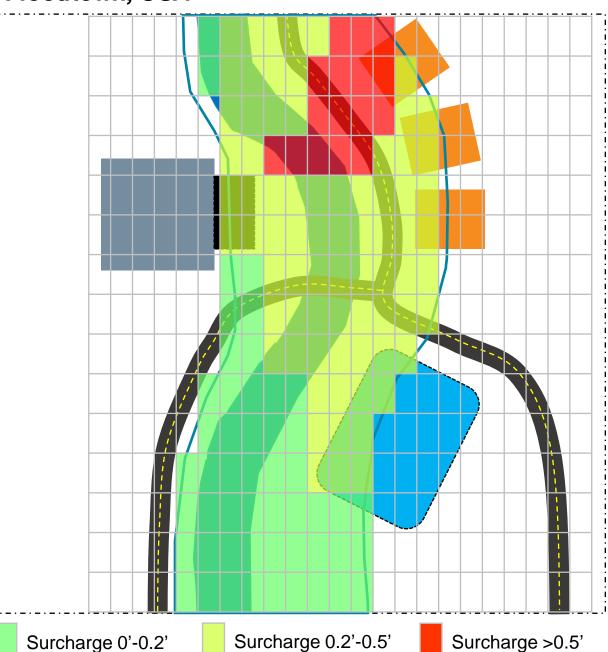




**Event 3**: Submittal of a building permit by Resident A to construct a new porch for their house.

#### **Description**:

Floodtown Engineering Co. is hired by Resident A to study the impacts of constructing a porch. The study accounts for the **cumulative development**, that is the proposed porch design plus any change caused by the shopping center construction. They find that compared to the effective WSEL, the deck *does* cause an increase in the WSEL above 0.5 foot from the **effective WSEL grid**. As a result, Resident A's floodplain permit is denied on the basis that it causes an adverse condition downstream.





Regulating 2D Models & Tools for Planning



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LOMCs and Other Regulatory Processes





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## CLOMR/LOMR

- The CLOMR/LOMR process is the same for either a 1D, 1D/2D, or 2D model.
  - Still follow MT-2 procedures
  - Same fees
- CLOMR/LOMR can be completed using various modeling techniques as long as the CLOMR/LOMR ties-in with the effective data (i.e. 1D CLOMR/LOMR completed in area with 2D model); however, communities should strive to maintain a continuous model.
- CLOMRs/LOMRs may be required more often when using 1D/2D or 2D models because the models show more detail.

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BELOW.	ED ALONG WITH THE ADDRODS	
Diazea maka shask ar man	ED, ALONG WITH THE APPROPR	RIATE FEE, TO THE ADDRESS BELOW OR FAXED TO THE FAX NUMBER
Please make check of mon	ey order payable to the Nationa	al Flood Insurance Program.
Type of Request:	MT-1 application MT-2 application	LOMC Clearinghouse 3601 Eisenhower Ave. Suite 500 Alexandria, VA 22304-6426 Attn.: LOMC Manager
	☐ EDR application }	FEMA Project Library 3601 Eisenhower Ave. Suite 500 Alexandria, VA 22304-6426 FAX (703) 960-9125
Request No. (if known):	Check No.	.: Amount:
☐ INITIAL FEE* ☐ FINA	L FEE FEE BALANCE**	MASTER CARD   VISA   CHECK   MONEY ORDER
	and/or Alluvial Fan requests (as nitting a corrected fee for an on	
COMPLETE THIS SECTION O	ONLY IF PAYING BY CREDIT CARE	
	CARD NUMBER	EXP. DATE
1 2 3 4 - 5	6 7 8 9 10 11	
Date		Signature
NAME (AS IT APPEARS ON (please print or type)	CARD):	_
ADDRESS:  (for your  credit card  receipt-please		_ _
print or type)		
DAYTIME PHONE:		

## No-Rise Certifications

- No-Rise conditions are more difficult to prove when referenced to 1D/2D or 2D models.
- Similar to the discussion of 2D floodways, each cell must meet the no-rise criteria, as opposed to 1D models where the no-rise criteria only needs to be satisfied at each cross section. In a typical 1D/2D or 2D model, there are 10,000s of locations that must satisfy the no-rise standard versus a 1D model where there are 10s or 100s.
- Needs engineering judgement





Regulating 2D Models & Tools for Planning



FW



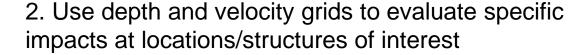


Next Steps

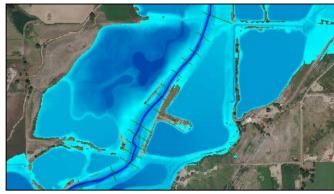


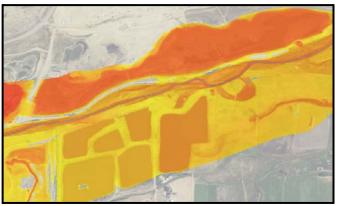
## Revisiting Old Concepts

- Depending on local capabilities:
  - 1. Use water surface elevation grids to determine base flood elevations. More accurate than BFEs and profiles











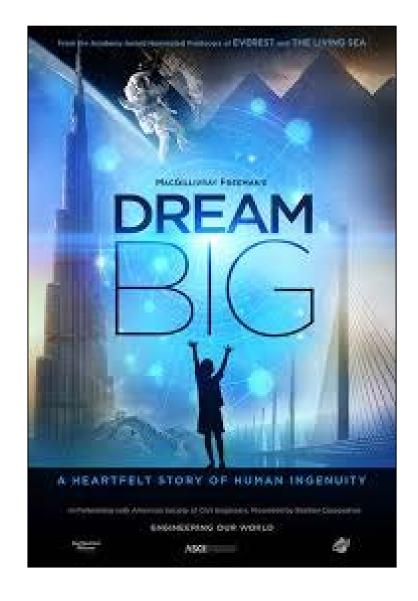


**AECOM** 

### What's Next?

- CWCB looking to test web applications for 2D results
- CWCB looking to add trainings and guides
- Discussion on federal guidance and how it could be revised to incorporate 2D capabilities







Regulating 2D Models & Tools for Planning



FW







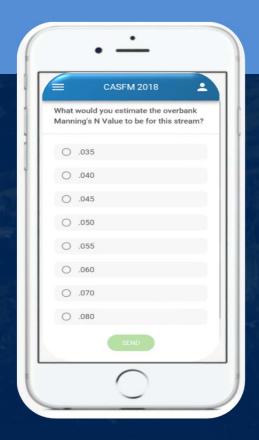
Questions

# Questions?





# On your Smartphone or laptop, go to <u>www.slido.com</u> Enter event code: 4040



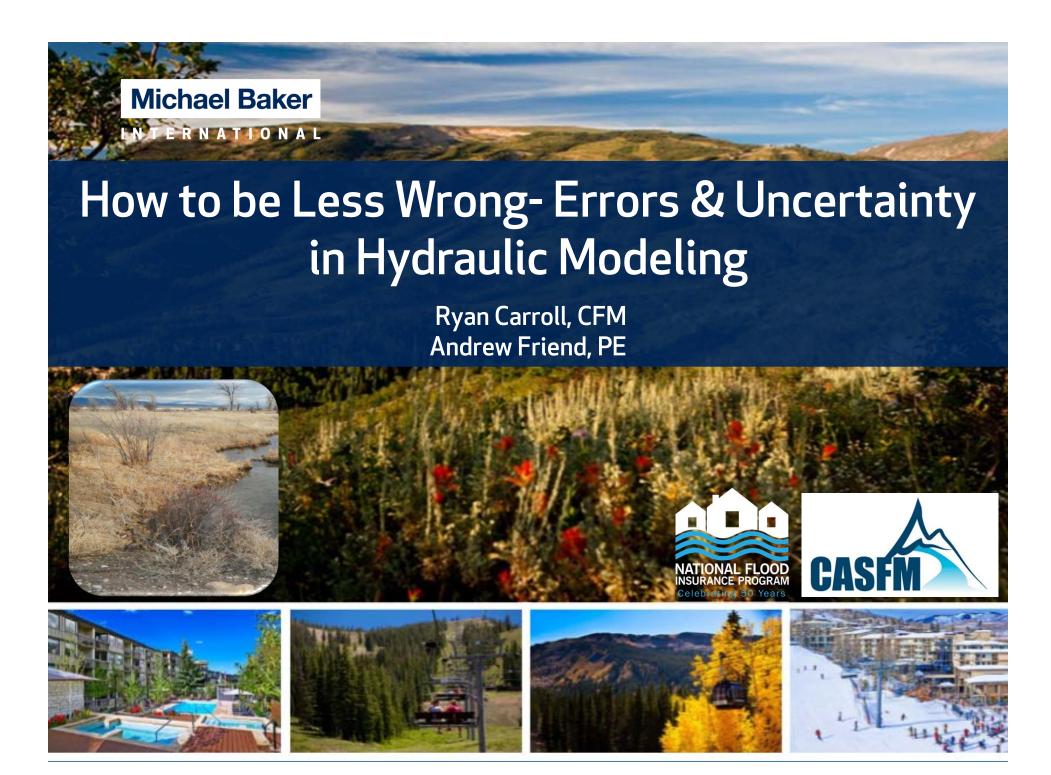


What would YOU estimate as a Manning's N Value for this overbank? Choose your answer (multiple choice)











#### How uncertain are we?



- 'Flaw' of Averages
- Better Data = Better Decisions!
- Do communities understand the uncertainty?
  - Terrain Data & Survey
  - Hydrology
  - Other model inputs

#### https://wall2.sli.do/event/kqnvgwas

















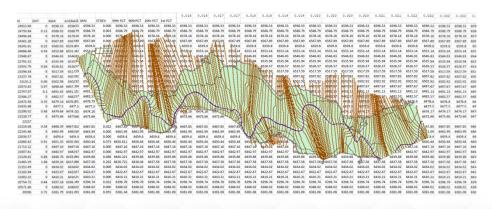
Average standard deviation of their estimates was 25%

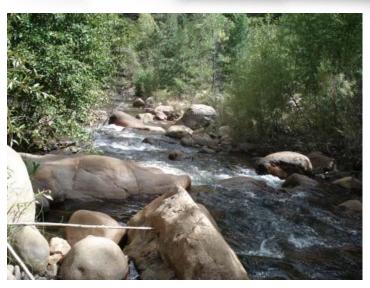
80 USACE Engineers estimating Manning's n values for 10 streams.

#### Our Approach



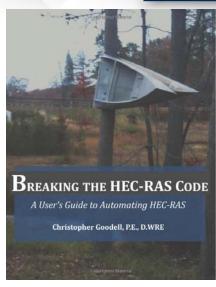
- 3 Variables
  - Manning's N Roughness Values
  - Discharges
  - Cross-section placement/geometries
  - Combined
- 2 Streams- Steep and Flat gradients
- Sensitivity Analysis using HEC-RAS
- 500 model iterations per variable, per stream

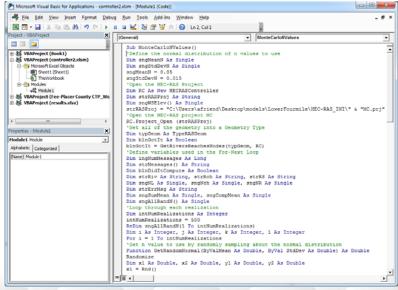






- Iterative modeling performed using HEC-RAS Controller
  - Allows automation and control of HEC-RAS through an API
  - User writes commands in Visual Basic – can be done within Excel
  - Monte Carlo simulations using random values with set parameters





#### Our Approach



#### N Values

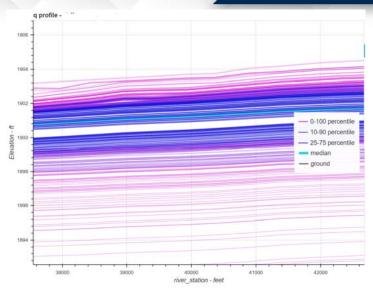
- Estimation of roughness for entire cross-section (Natural Channel & Floodplain)
- Mean N of 0.050 (25% error)
- Values ranged from 0.016 to 0.084

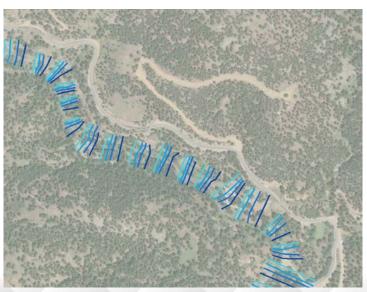
#### Discharges

- Steep Stream- Regression (36% error)
- Flat Stream- Gage Analysis (30% error)

#### Cross-section Placement

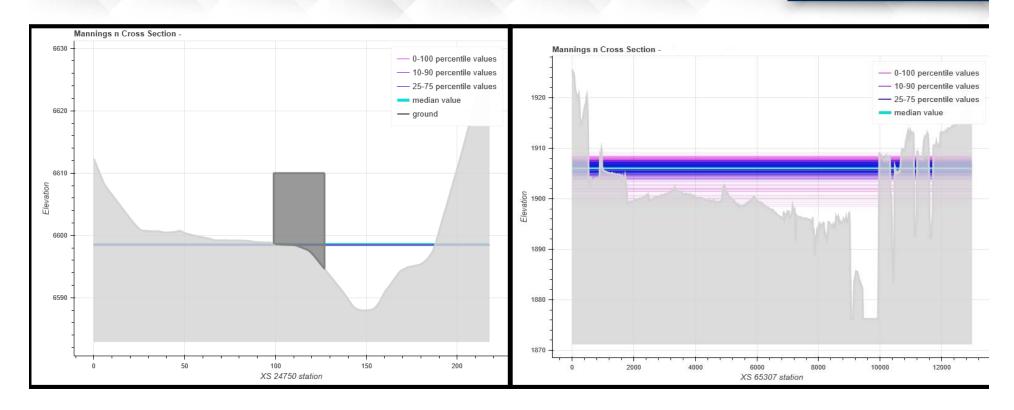
- 5 different layouts
- 40 foot shift for each iteration
- 200 foot XS spacing





#### Results- Manning's n Values



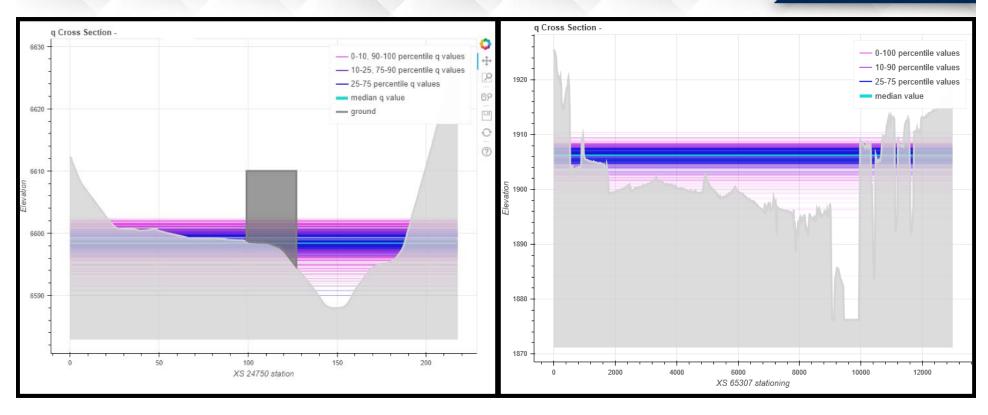


Steep Terrain

Flat Terrain

#### **Results-Discharges**





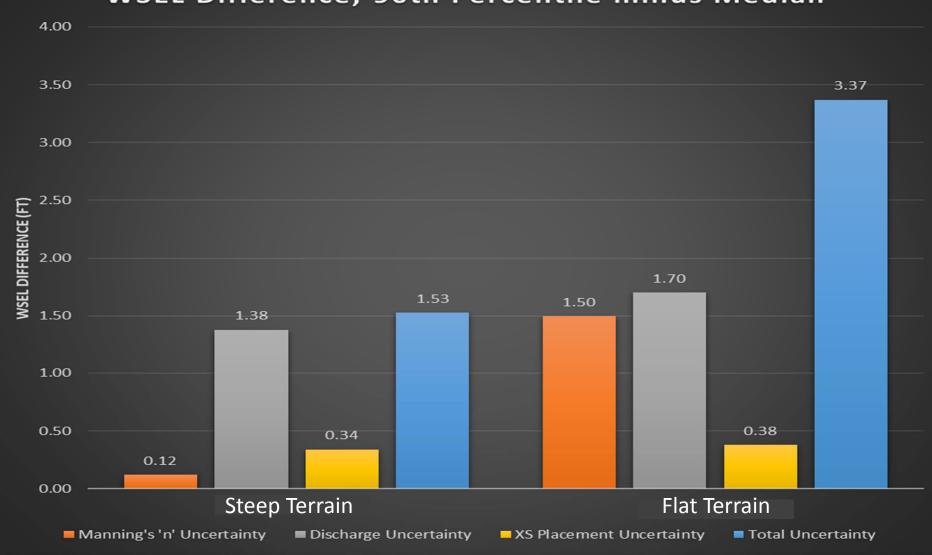
Steep Terrain (Regression)

Flat Terrain (Gage Analysis)

#### Results



#### WSEL Difference, 90th Percentile minus Median



#### **Takeaways**



	WSEL Difference, 90th Percentile minus Median (ft)	
Uncertainty Source	Steep Terrain	Flat Terrain
Manning's 'n' Uncertainty	0.12	1.50
Discharge Uncertainty	1.38	1.70
XS Placement Uncertainty	0.34	0.38
Total Uncertainty	1.53	3.37

#### Mannings n Values

- There's potential for greater uncertainty in flat terrain; less so in steep terrain.
- Spend more time on field data collection and calibration in flat terrain
- Spend less time reviewing n values for models in steep terrain

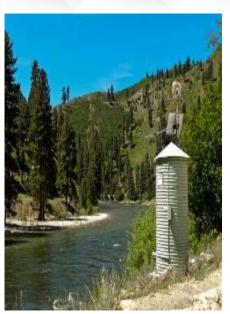
#### Discharges

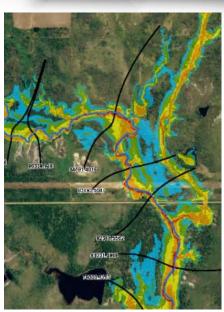
- Uncertainty can be impacted by type of study. Method selection is key .
- Calibrate!
- Investing more heavily in hydrology can increase reliability and validity of flows.

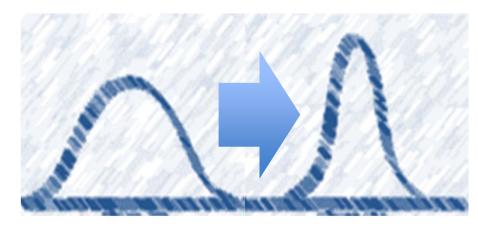
#### Cross Section Placement

- Appropriate spacing helps to reduce uncertainty associated with placement
- Addressing uncertainty in any of these areas will impact your overall model reliability.

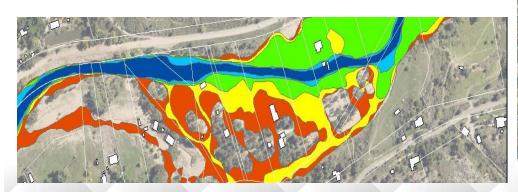
- Other variables at play: time/schedule, cost, weather, study size, years of record, development.
- Stakeholders rely on engineers to develop data they can use, for:
  - Floodplain management
  - Building codes
  - Emergency management, planning, etc.
- Pay attention where it matters.
   Shrink the margin of error.
   Narrow the distribution.
- Better data = better decision making







- Understand the uncertainty that exists and focus efforts to reduce it.
- What types of rivers and streams do you have?
- Hydrologic method can be considered in local regulation- methods/basins with less confidence/higher uncertainty could be regulated differently.
- Consider using FEMA's 1% Plus values in regulation









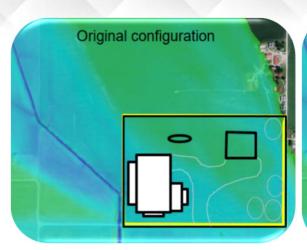


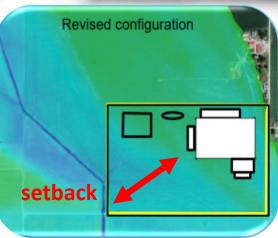


#### **Takeaways- Communities**

Michael Baker

- Enact policies, plans, and code that account for the uncertainty that exists:
  - Buffers & Setbacks
  - Overlay zoning
  - Adoption of a 1% Plus Floodplain
  - Additional regulations in the 500-year floodplain
  - Hazard Mitigation Planning
  - Other planning tools



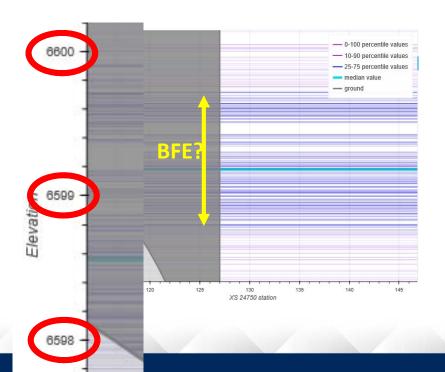


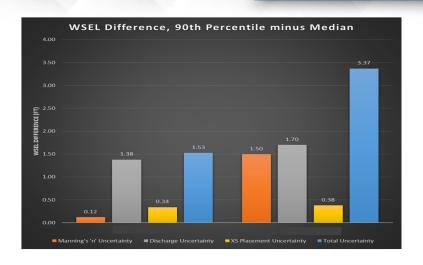


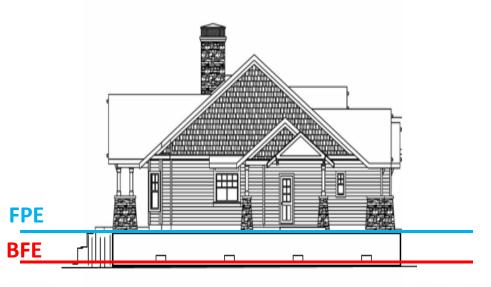
#### **Takeaways-Communities**



- Enact policies and code that account for the uncertainty that exists:
  - Freeboard





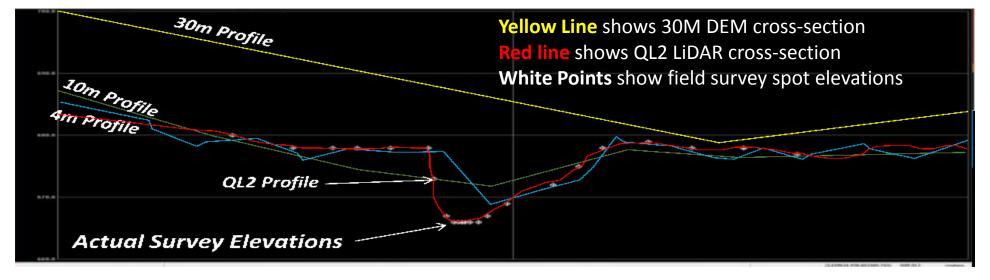


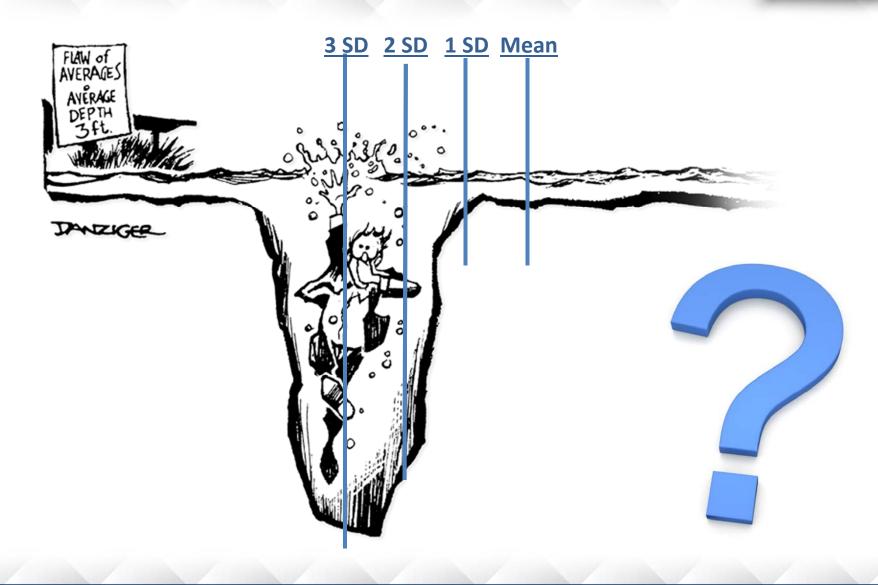
#### **Next Steps**



- A work in progress!
- Refine the assessment
  - Additional stream simulations
    - Are the results repeatable on other streams with similar slopes/characteristics?
    - What about other channel gradients?
  - Additional variables
    - Development
    - Hydraulic structures
    - LIDAR vs. field survey







#### Highway 115 at Pathfinder Park in Florence, CO July 23, 2018









### Tools to Stay Ahead of the Storm

Dana McGlone<sup>1</sup>; Kevin Stewart<sup>2</sup>, PE, Kevin Houck<sup>3</sup>, PE

<sup>1</sup>Dewberry Consultants, <sup>2</sup>UDFCD, <sup>3</sup>CWCB

2018 CASFM Annual Meeting

### Tools to Stay Ahead of the Storm

- Early detection
- Municipalities
  - Mobilizing people and resources
- Project managers
  - Protection of project sites
- Understanding heavy rainfall thresholds
  - Impervious areas, nature of the threat



### What is QPF?

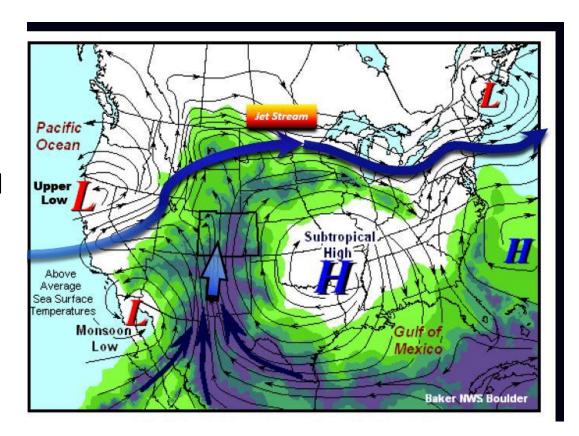
#### **Quantitative Precipitation Forecast:**

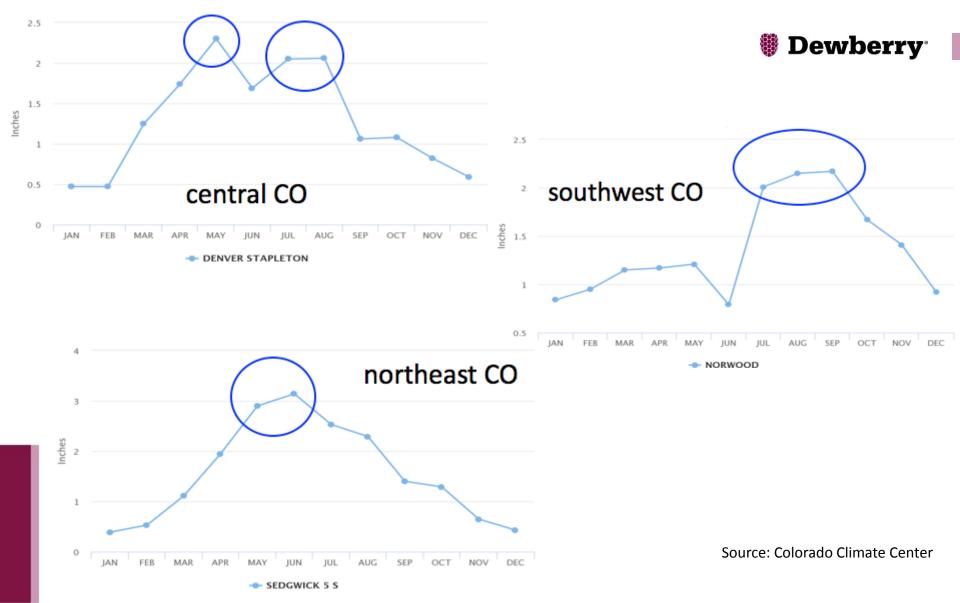
- A deterministic estimate of how much precipitation will accumulate at a given location over a given amount of time
- Typically deduced from atmospheric model
- Extremely difficult to accurately and precisely predict,
   especially for thunderstorm type rainfall
- Key input for many decision making systems
- Key input into many H&H prediction systems



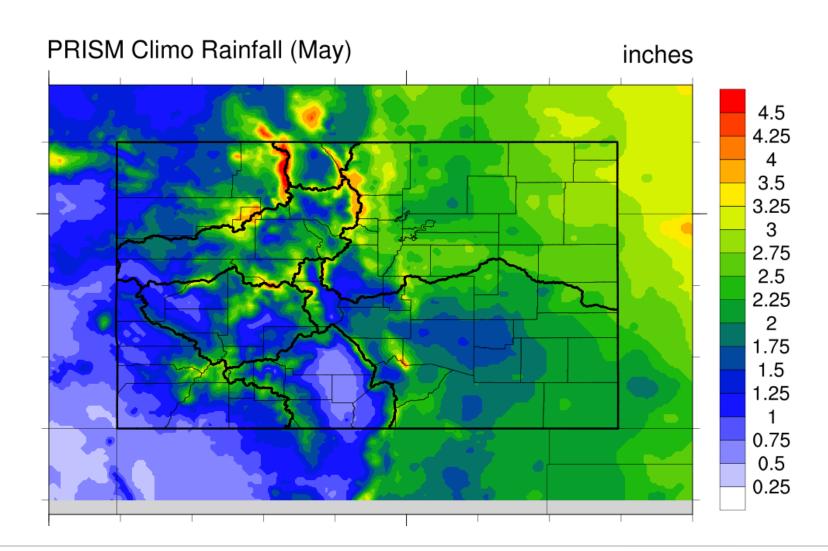
### North American Monsoon (NAM)

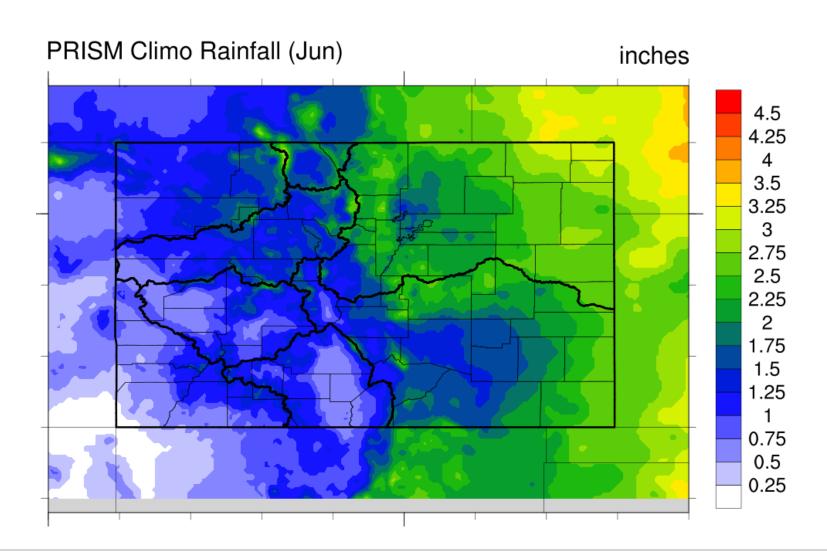
- Monsoon = seasonal shift in the wind pattern
- Gulf of California and Gulf of Mexico combine in "monsoon surge" with this upperatmospheric pattern
- Typically ramps up in July and persists through August

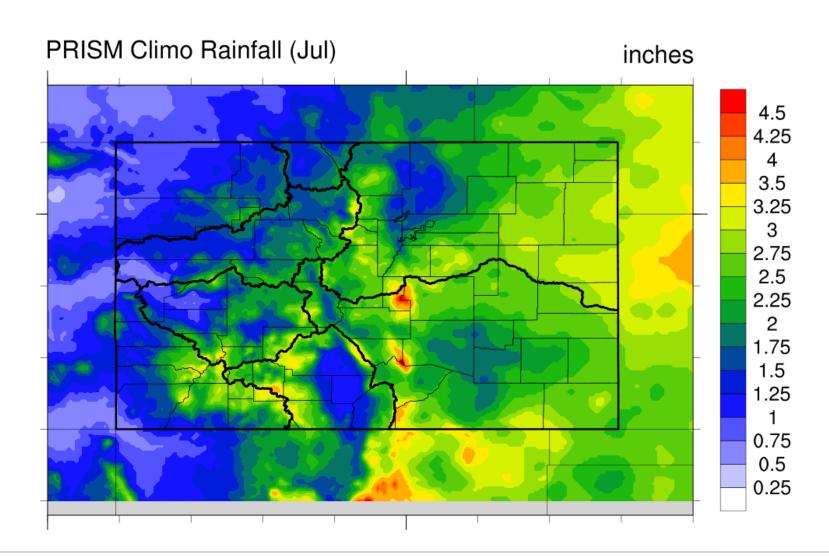


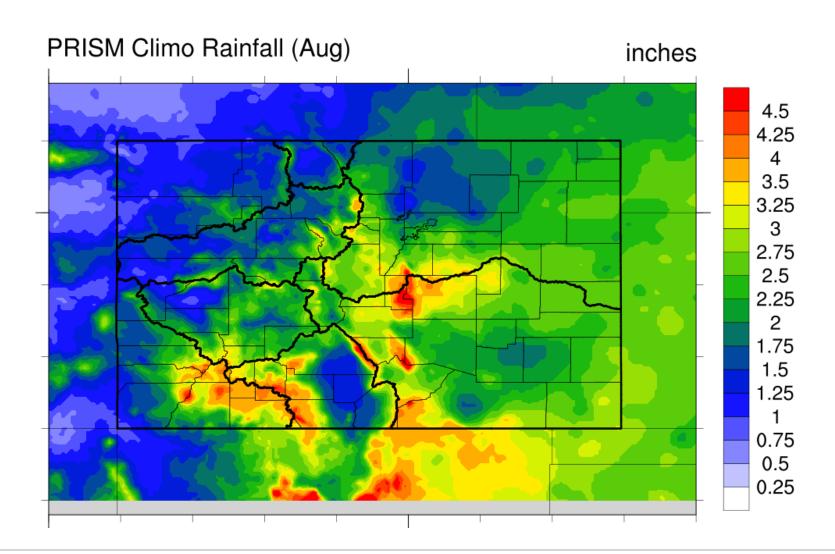


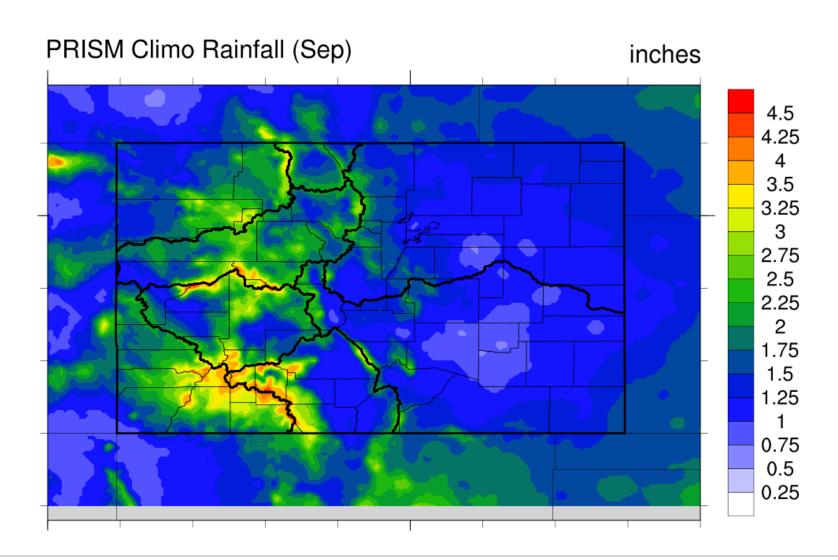
**Proof in the Peak (1981-2010)** 











### Objective versus subjective forecasts

#### **PROS**

- More easily QC'd
- More flexible



Easier to improve



Subjective

Objective



- Labor intensive
- May have constraint on skill

- Not always intuitive
- Maintenance

**CONS** 

### What are we doing to stay ahead?

- Probabilistic approach "ensemble of ensembles"
- Bias correction & post-processing
- Validation!!!

- Urban Drainage and Flood Control District's Heavy Rainfall Guidance Tool: qpf.udfcd.org
- Colorado Water Conservation Board'sColorado Flood Threat Bulletin: coloradofloodthreat.com



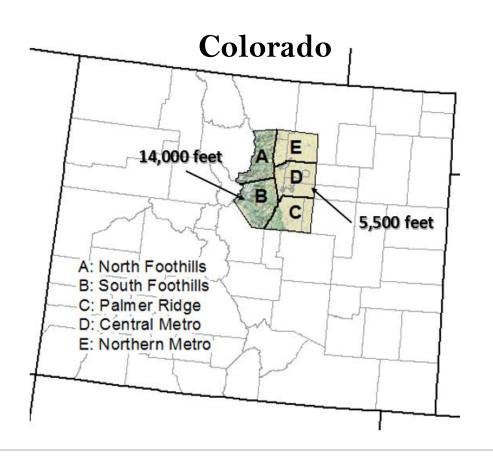
# **Objective Forecast**



### **UDFCD** Heavy Rainfall Guidance Tool

http://qpf.udfcd.org

 Objective: Increase lead time for anticipating heavy rainfall in the Denver metro area

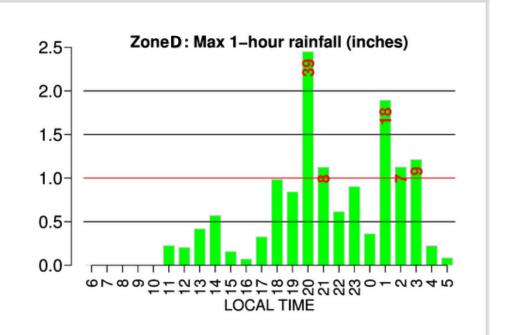


- 5 Forecast Zones covering ~6,000 mi<sup>2</sup>
- Hourly output informs users on heavy rainfall:
  - timing
  - location
  - intensity
  - confidence

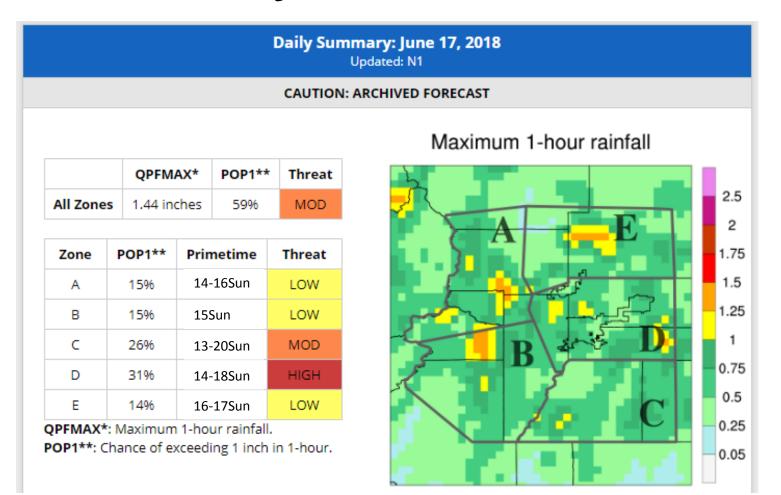
### **UDFCD Heavy Rainfall Guidance Tool**

#### **Zone D: Central Metro**

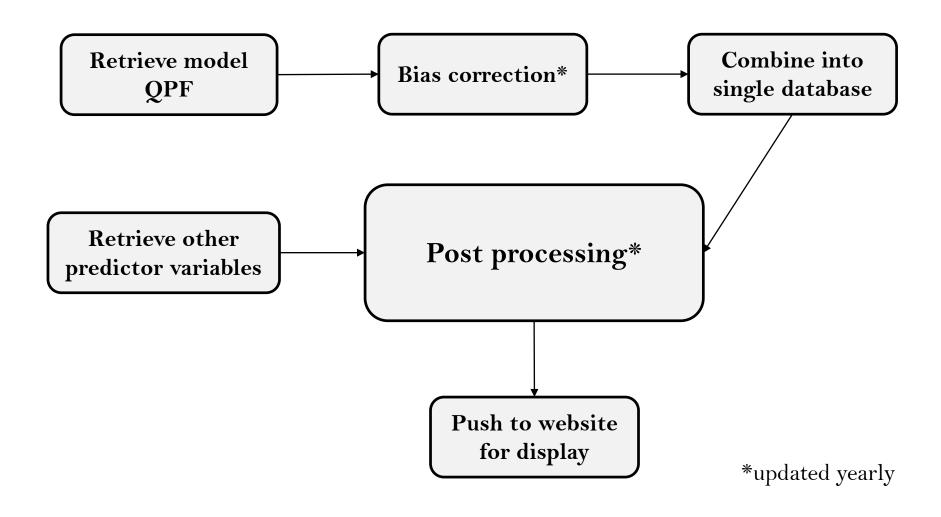
ZONE F: Overall Threat	HIGH
% precipitation	85%
% exceeding 1in. per 1hr	45%
% exceeding 2.25in. per 3hr	7%
% exceeding 3.5in. per 6hr	<5%
% exceeding 4.5in. per 24hr	<5%
Primetime	20-4Wed



### **UDFCD Heavy Rainfall Guidance Tool**



## **Operational Process Flow**



## **QPE/Rain Gage Data**

Objective: Estimate observed daily maximum 1-hour rainfall in each zone. Value over 1 inch triggers "Flood Day" classification.

#### Used the higher of:

- NOAA Stage IV hourly QPE
- UDFCD ALERT Rain Gage Network ~ 200 gages

Used CoCoRaHS (~300 rain gages) and hail reports for additional quality control.



# **Subjective Forecast**

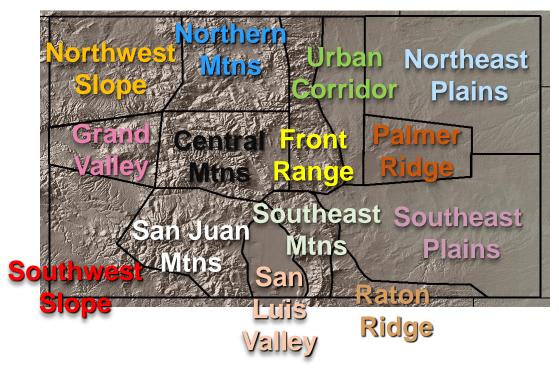


### **Colorado Flood Threat Bulletin**

http://www.coloradofloodthreat.com

 Objective: Increase lead time for anticipating heavy rainfall over Colorado during the warm season

#### Colorado

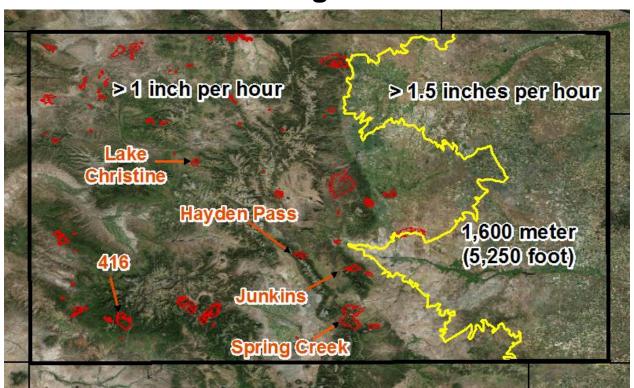


- 14 Forecast Zones with a large range in topography
- Product informs users on heavy rainfall:
  - timing
  - location
  - intensity
  - confidence
  - nature of the threat



#### **Motivation**

- Many heavy rainfall events occur with little to no lead time
- Can we estimate a daily "realistic" worst-case scenario?
- Can we develop a system that is reliable and discriminates between higher and lower threat days?



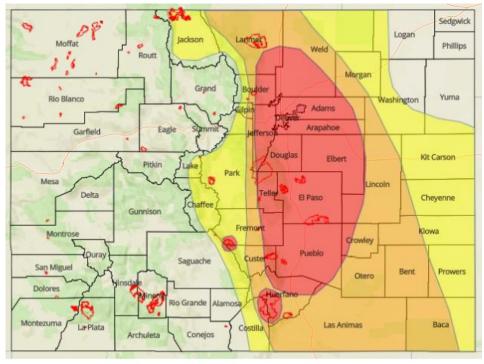
#### **Products**

- Flood Threat Bulletin (FTB)
  - Issued by 11am daily
  - Identifies areas of flood risk for a 24-hr period
  - Possible PM updates
- State Precipitation Map (SPM)
  - Issued by 11am daily
  - Recaps the past 72-hours of hydrometeorolgical conditions
    - ✓ Rainfall totals, flooding, antecedent soil conditions
- Flood Threat Outlook (FTO)
  - Issued Monday and Thursday by 3PM
  - Outlook of threat and precipitation totals over the next 15 days
  - Rapid snowmelt, local heavy rainfall, drought development



# Flood Threat Bulletin (FTB)

THREAT	DESCRIPTION					
NONE	No flood threat is expected.					
Low probability (<50%) that isolated/widely scattered flooding will occur. If flooding occurs, low impact/severity flooding is anticipated.						
MODERATE Moderate probability (50-80%) of flooding occurring.						
HIGH	High probability (>80%) of flooding occurring.					
HIGH IMPACT	High probability (>80%) of high-impact flooding due to a combination of factors including, but not limited to: high population density, antecedent rainfall and/or long-term duration.					



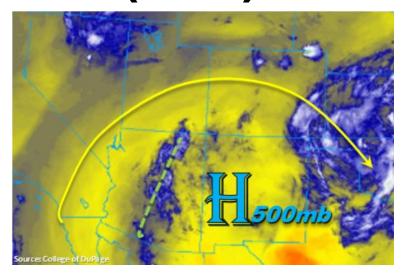
Flood Threat Map July 23, 2018





# Flood Threat Bulletin (FTB)

# Discussion (not shown) with an image:



#### **Zone-Specific Forecasts:**

Front Range, Urban Corridor, Palmer Ridge, Southeast Plains, Northeast Plains, Southeast Mountains, Raton Ridge:

Very moist low-level will support heavy rainfall this afternoon. Showers and thunderstorms should kick off just after noon over the higher terrains. Over the higher terrains max 1-hour rain rates up to 1.25 inches are possible, which could trigger mud flows, debris slides and local stream flooding. Rain rates increase over the adjacent plains with 1-hour rain rates around 1.75 inches/hour. Localized 1-hour rain rates over 2 inches/hour are not out of the question in areas of the highest low-level moisture. A High flood threat has been issued for portions of these regions with the largest threat over the Urban Corridor, Palmer Ridge and Southeast Plains. A High flood threat has also been issued for all recent burn scars over the Southeast Mountains as storms could trigger debris slides and local stream flooding that track over these areas. Thunderstorms and showers will continue to rumble into the night, but the flood threat should decrease after midnight.

Primetime: 12PM to 7AM

Southwest Slope, San Juan Mountains, San Luis Valley, Northern Mountains, Grand Valley, Central Mountains, Northwest Slope:

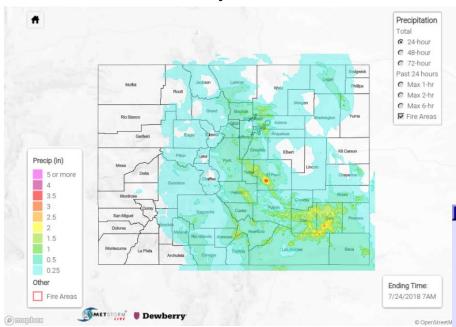
Low-level moisture won't be quite as high over western Colorado. Max 1-hour rain rates up to 0.4 inches/hour are possible over the higher terrain this afternoon. Upslope flow will be the main driver of thunderstorm development today, and with westerly winds, the rainfall should remain over the mountains with the greatest cover near the Continental Divide.

Primetime: 1PM to 8PM



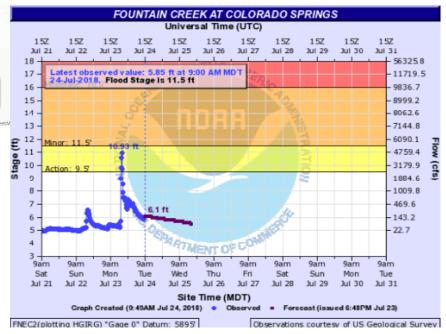
# State Precipitation Map (SPM)

SPM - July 24, 2018



# Discussion (not shown) with relevant image:

- 4.12 inches north of Fountain
- 1.18 inches in 20min NW of CO Springs
- 2.76 inches at Aurora ALERT gage



# Flood Threat Outlook (FTO)

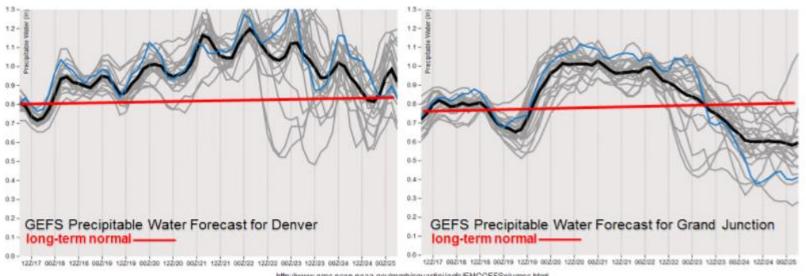
Issue Date: Monday, July 17, 2017

Issue Time: 2:10PM MDT Valid Dates: 7/18 - 8/1

	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue
Next 15 Days	18-Jul	19-Jul	20-Jul	21-Jul	22-Jul	23-Jul	24-Jul	25-Jul	26-Jul	27-Jul	28-Jul	29-Jul	30-Jul	31-Jul	1-Aug
	Ever	nt #1			Event #2										
No Apparent Threat Elevated Threat High Threat															

FLOOD THREAT LEGEND

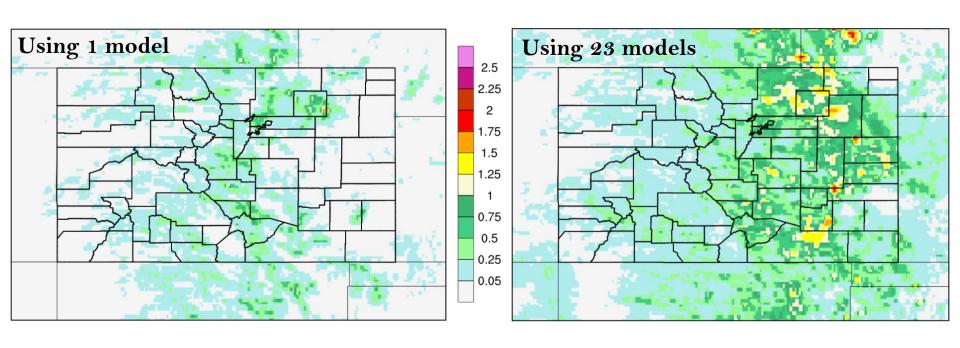
#### Discussion (not shown) with relevant images:



http://www.emc.ncep.noaa.gov/mmb/cguastini/gels/EMCGEFSplumes.html

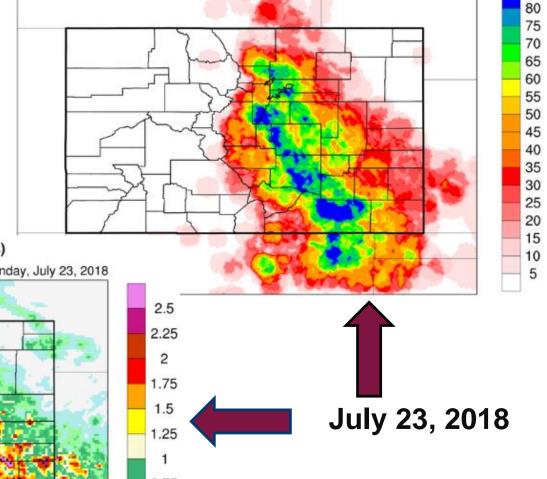
## The benefit of an ensemble

#### Max 1-hour precipitation for 6/7/2017

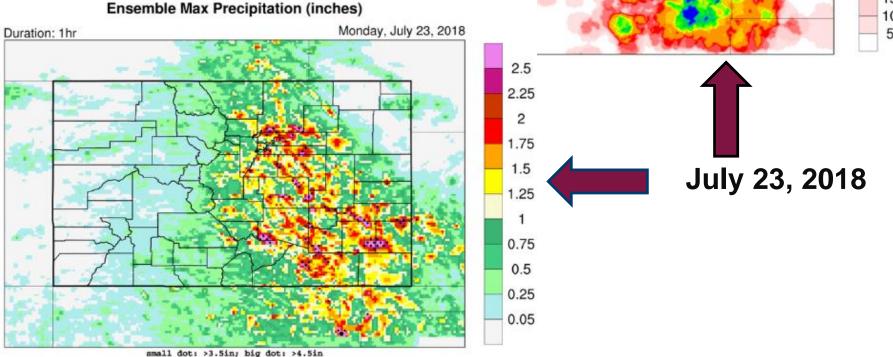




# The benefit of an ensemble



Ensemble Neighborhood Exceedance Probability (%)



Threshold: 1.0in. per 1hr

Monday, July 23, 2018

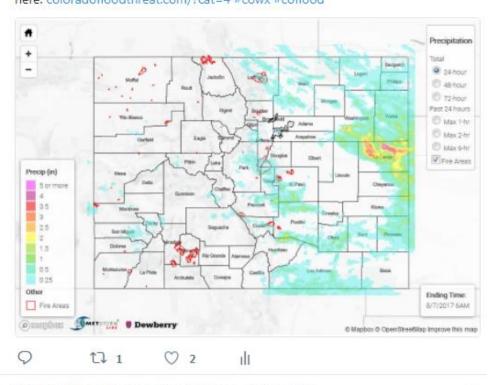
# Twitter: @COFloodUpdates Facebook: Colorado Flood Threat Bulletin



CO Flood Updates @COFloodUpdates · 7 Aug 2017

Replying to @COFloodUpdates

Check out full 24-hour rainfall summary and our new State Precipitation Map here: coloradofloodthreat.com/?cat=4 #cowx #coflood



#COFlood #COwx #COFire



CO Flood Updates @COFloodUpdates · 7 Aug 2017

Heavy rain for Eastern CO yesterday. A CoCoRaHS station in Kit Carson County recorded 6.2 inches, which is a 1 in 200-500 year event! #cowx

Q 1

17 1

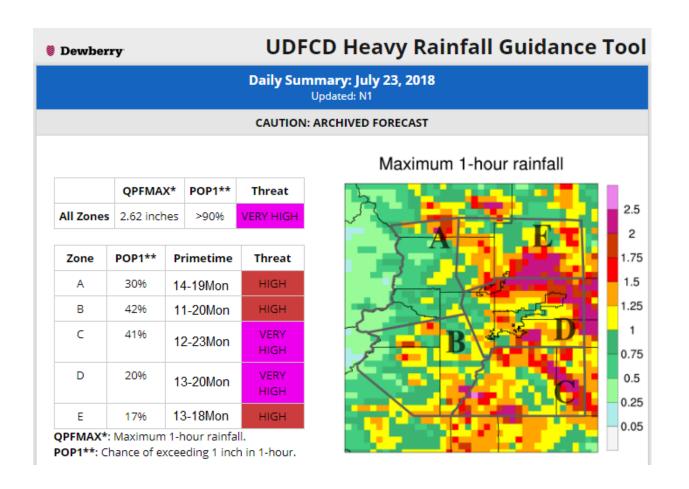
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## **QPF-Max Application**

Kevin Stewart - UDFCD



### **Conclusions**

- QPF reliability
- Climatology of warm season, heavy rainfall events in Colorado
- Objective vs subjective forecasts
- Heavy rainfall tools available to the public
- Applications for early detection of heavy rainfall events

For questions contact:
Dana McGlone
dmcglone@Dewberry.com





**Overview** 

History

Approach

Morphology

**Alternatives** 

Criteria

Modeling

Construction

Post-Construction



OOD CONTROL & GREENWAY DISTRI



Construction





## Fountain Creek: A Perspective

**Overview** 

History

**Approach** 

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Criteria

Modeling

Construction





- Plain bed gravel channel with sandy behaviors
- Over 5' of mobile bed
- 927 sq. mile drainage area
- ≈ 1,350' Drop from Col. Springs to Pueblo (44 miles)

#### **Overview**

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**Post-Construction** 



## Fountain Creek: A Perspective

- June 17, 1965: 53 city blocks were inundated with water up to 8 feet deep, damaging 370 homes and 59 businesses. Damage estimated at \$3.7 million. Peak flow of the flood was estimated at 47,000 cubic feet per second.
- June 11, 1864: Flow of 45,000 cfs. Waters rose 20-30 feet, sweeping away Colorado City.
- May 30, 1894: Flow of 40,000 cfs. Five lives lost and \$2 million in property damage.
- May 30, 1935: Flow of 35,000 cfs. Damages in Colorado Springs were \$1.8 million, and four people died. In Pueblo, damages were \$500,000.
- June 3-4, 1921: Fountain Creek's flows were 34,000 cfs, adding to the
  worst flood in Pueblo history on the Arkansas River, where flows were
  110,000 cfs. After the flood, 78 bodies were recovered. More than 500
  homes and 100 commercial buildings were destroyed. Damage was more
  than \$10 million.
- April 30, 1999: Peak flow of 18,900 cfs. A highway bridge at Pinon was swept away by the waters. Pueblo's Target store was threatened.
   Damages in Pueblo and El Paso County totaled more than \$30 million.
   Extensive damage in North La Junta as well. By comparison, the most recent flood on Fountain Creek peaked at 13,800 cfs in Pueblo on June 16.

#### Overview

History

Approach

Morphology

**Alternatives** 

Criteria

Modeling

Construction

**Post-Construction** 



#### Goals & Objectives

- 1. Land Protection / Recovery
- 2. Sediment Load Reduction
- 3. Water Quality Improvement

#### Solution

- 1. Stable Channel Dimension, Pattern, and Profile
- 2. Bendway Weirs

Overview

History

**Approach** 

Morphology

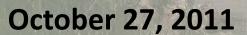
Alternatives

Criteria

Modeling

Construction







November 2, 2015



Overview

History

**Approach** 

Morphology

Alternatives

Criteria

Modeling

Construction





Overview

History

**Approach** 

Morphology

Alternatives

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Overview

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Overview

History

**Approach** 

Morphology

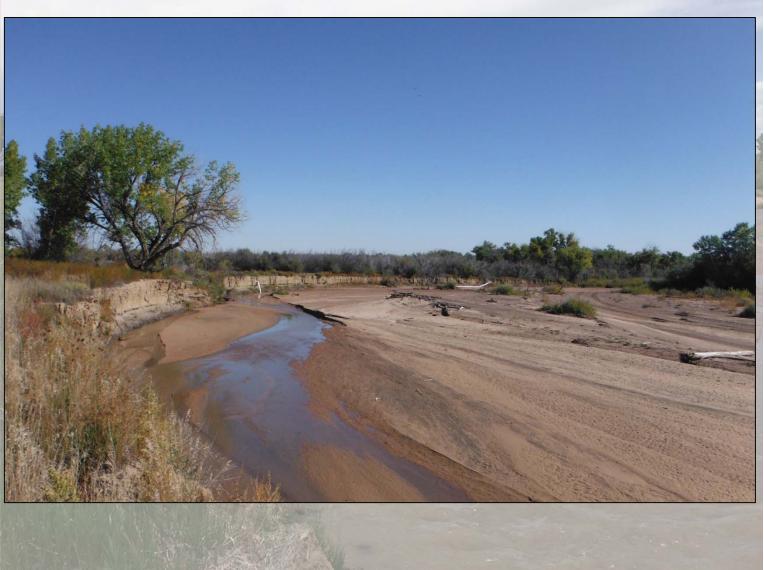
Alternatives

Criteria

Modeling

Construction





# History

**Overview** 

History

**Approach** 

Morphology

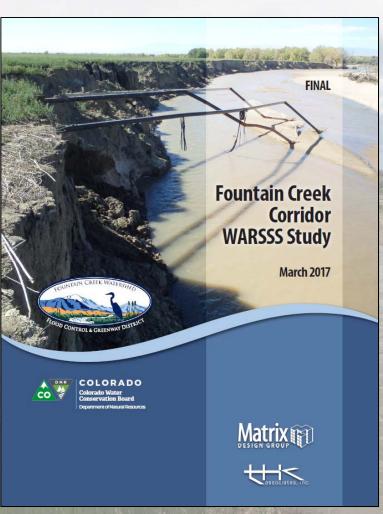
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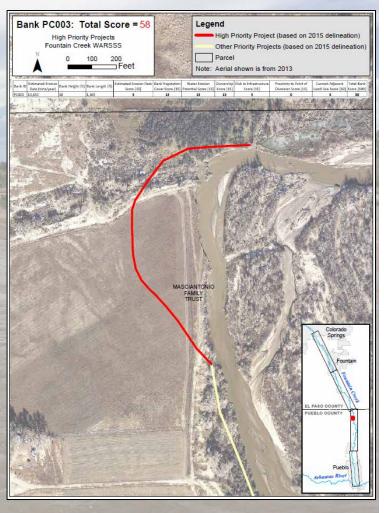
Criteria

Modeling

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Overview

History

#### **Approach**

Morphology

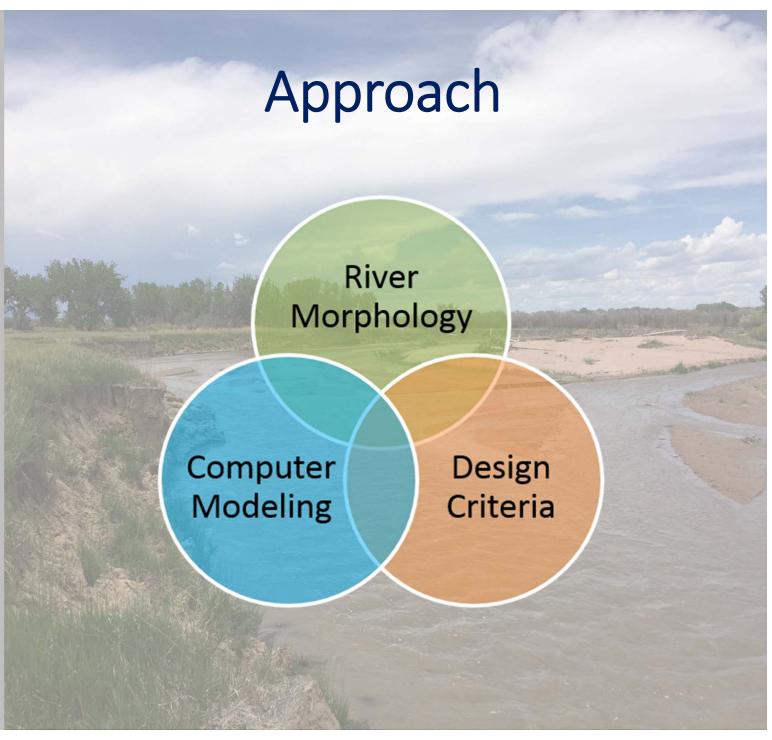
**Alternatives** 

Criteria

Modeling

Construction





# Approach

#### **Data Collection**

**Overview** 

History

#### **Approach**

Morphology

**Alternatives** 

Criteria

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Construction

**Post-Construction** 



- USGS Gage Data
- Fountain CreekWatershed Study
- Survey, LiDAR and Aerial Photos

Hydrology Report for Fountain Creek, El Paso County, CO



Prepared for:

FEMA, Region VIII

Denver Federal Center, Building 710

P.O. Box 25267

Denver, CO 80225

	June 2015 Flood Event
•	Young's Hollow



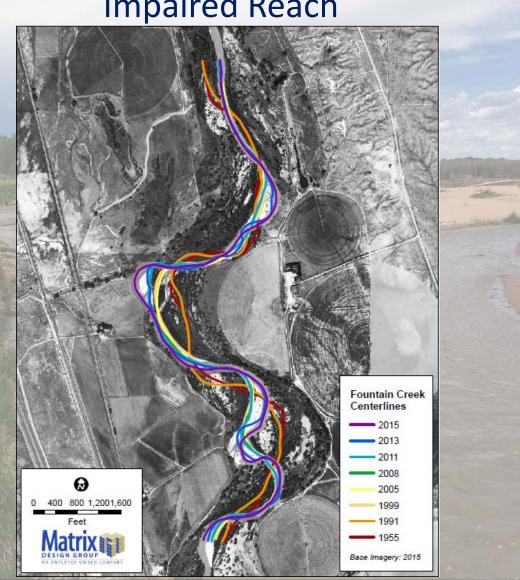
Recurrence Interval	Mean Annual Flow	Bankfull Flow (Matrix)	2-Year	5-Year	10-Year	25-Year (June 16, 2015 Event)	50-Year	100- Year
Discharge (ft³/s)	300	2,700	3,800	7,000	10,700	19,800	24,200	33,300

**Impaired Reach** 

**Overview** 

Morphology





**Impaired Reach** 

Overview

History

Approach

Morphology

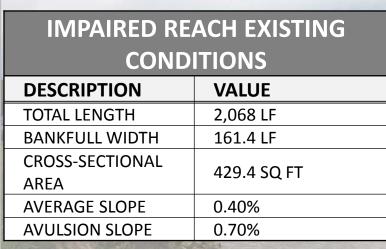
Alternatives

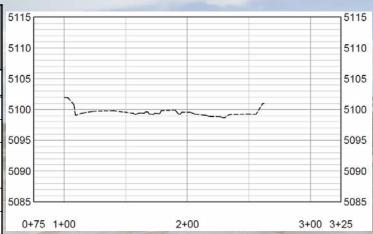
Criteria

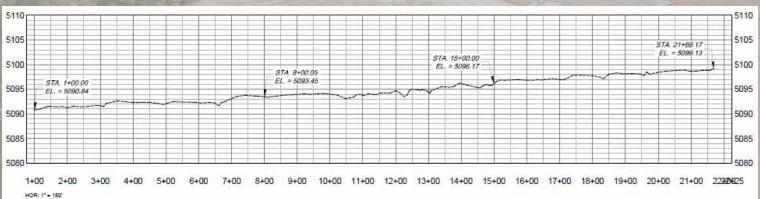
Modeling

Construction









Reference Reach

Overview

History

**Approach** 

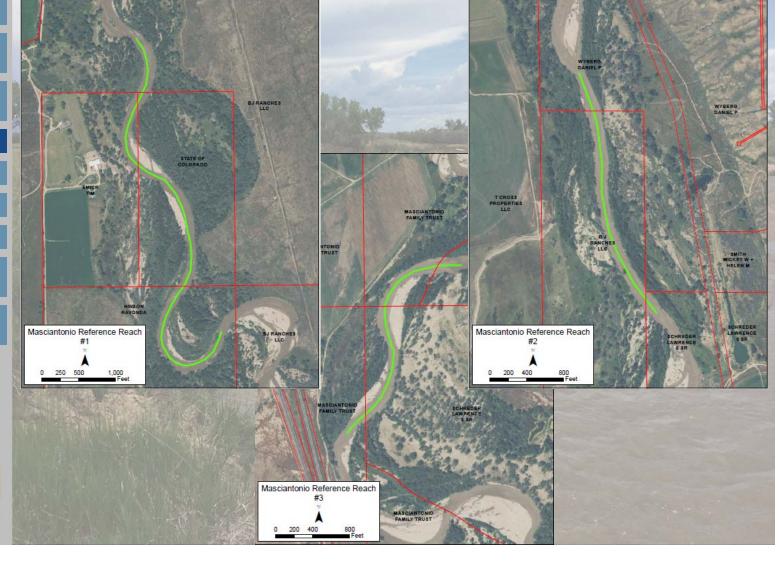
Morphology

Alternatives

Criteria

Modeling

Construction





#### **Departure Analysis**

Overview Dimension:

History

Approach

Morphology

Alternatives

Criteria

Modeling

Construction

**Post-Construction** 

#### **Impaired Reach Reference Reach Parameter** Min Min Avg. Max Avg. Max Area (ft.2) 380 398 639 389 431 505 Width (ft.) 163 145 157 188 213 178 Mean Depth (ft.) 1.8 2.5 2.5 4.4 2.2 3 Max Depth (ft.) 2.9 3.1 3.3 3.7 5.6 W/D (ft./ft.) 65 91.5 118 33 52 71

#### Pattern:

Parameter	Imp	aired Ro	each	Reference Reach			
Parameter	Min	Avg.	Max	Min	Avg.	Max	
Radius of Curvature	375	375	375	520	522	524	
Straight-way length	330	615	900	255	324	373	
Sinuosity	1.7	1.7	1.7	1.2	1.2	1.2	
Belt Width	960	960	960	760	760	760	
Bend-way Length	850	850	850	664	794	923	
Meander Wavelength	1996	1996	1996	1680	1680	1680	
Bend to Bend	1400	1625	1850	1072	1072	1072	

#### Profile:

Parameter	Impaired Reach	Reference Reach			
Bankfull Slope (%)	0.4	0.3			
Water Surface Slope (%)	0.4	0.3			



Overview

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**Alternatives** 

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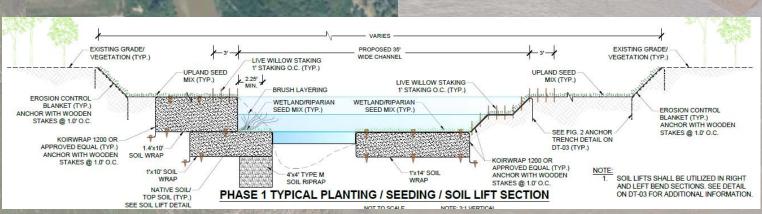
Modeling

Construction









#### **Design Considerations**

Grade Control

Approach

**Overview** 

Morphology

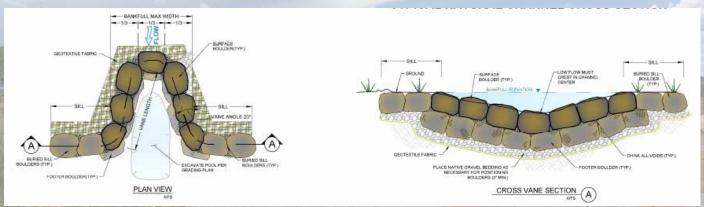
**Alternatives** 

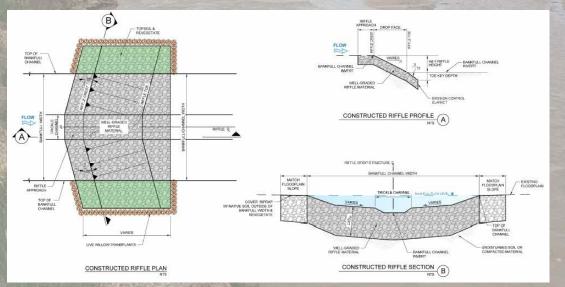
Criteria

Modeling

Construction







**Design Considerations** 

- Bank Protection
  - Bendway Weirs
  - Soil Riprap Toe
  - Grouted Boulder Toe
  - Debris Jams
  - Soil Cement

Revegetation

**Overview** 

History

Approach

Morphology

**Alternatives** 

Criteria

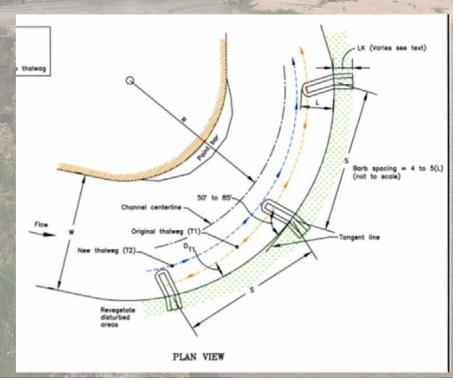
Modeling

Construction



#### Selected Alternative

- Floodplain Grading and Bendway Weirs
- Bendway Weirs: low-elevation structures that are projected into the channel from a bank and angled upstream to redirect flow away from the bank and to control erosion. Typically constructed from rock, large woody debris or a combination of both.



Overview

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**Alternatives** 

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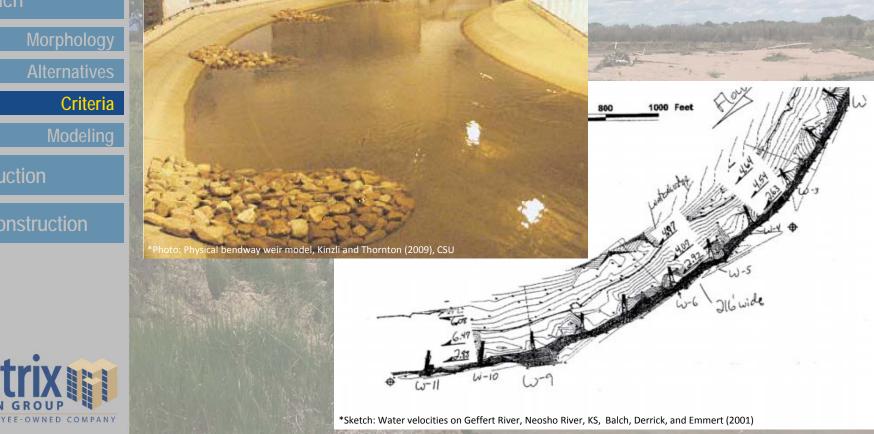
Construction



#### Criteria

**Bendway Weirs** 

Numerous technical references





#### Criteria

#### **Bendway Weirs**

**Overview** 

History

**Approach** 

Morphology

**Alternatives** 

Criteria

Modeling

Construction

**Post-Construction** 



 Wide range of design guidance parameters

- Length
- Height
- Top Width
- Spacing
- Angle
- Transverse Slope

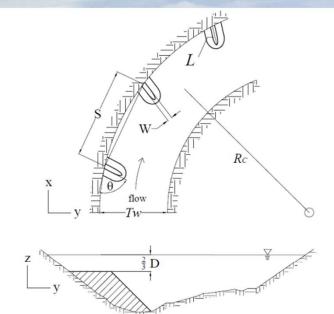


Table 1. Design guidelines for bendway weirs from literature (variables defined in Figure 1)

Source	Length		Height		Top width		Spacing		θ		Transverse slope	
	min	max	min	max	min	max	min	max	min	max	crest slope	transition
NCHRP Report 554, 2005	Tw/3	Tw/2	W/2	w	2D <sub>100</sub>	3D <sub>100</sub>	1.5L	1.5L	80	70	flat	flat
HEC-23, Design Guideline 1, 2009*	Tw/10*	Tw/3*	0.3 BF**	0.5 BF**	2D <sub>100</sub>	$3D_{100}$	4L	5L	60	85	flat	1V:5H
ulien and Duncan, 2003	longer is better		max permitting navigation		none	none	2L	3L	60	60	none	none

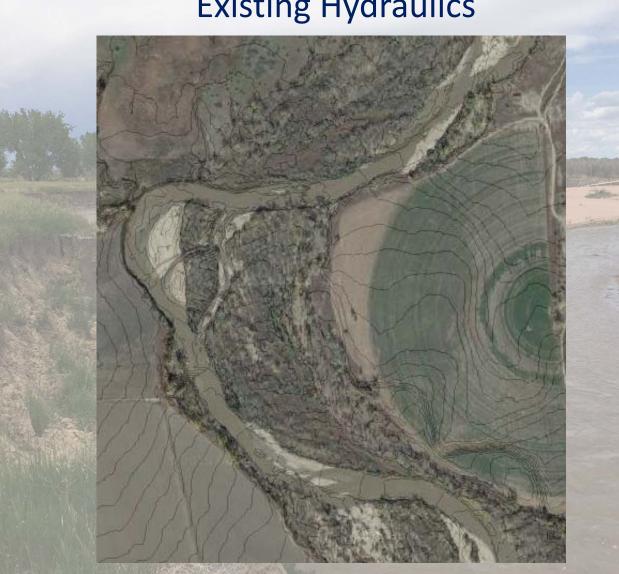
<sup>\*\*</sup>HEC-23 further recommends structure length to cross the stream thalweg

<sup>\*\*</sup>HEC-23 further recommends structure height to fall between annual mean flow and annual low flow water surface elevations

**Existing Hydraulics** 

Modeling





**Existing Hydraulics** 

Overview

History

**Approach** 

Morphology

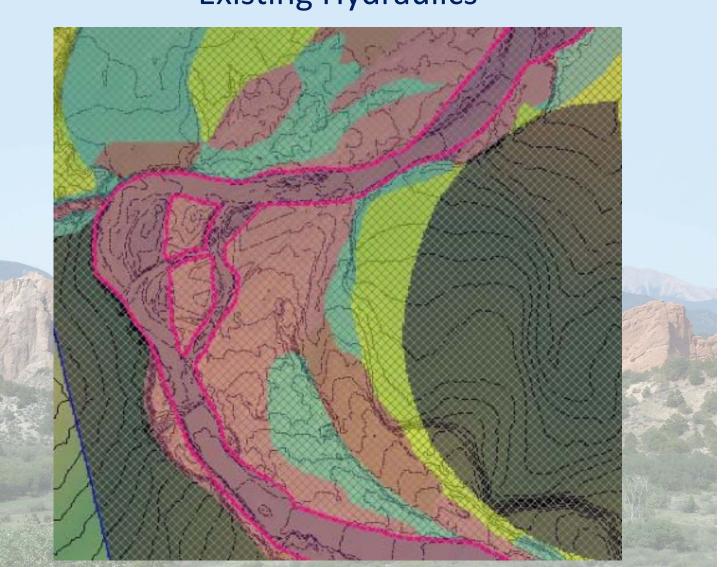
**Alternatives** 

Criteria

Modeling

Construction





**Existing Hydraulics** 

Overview

History

**Approach** 

Morphology

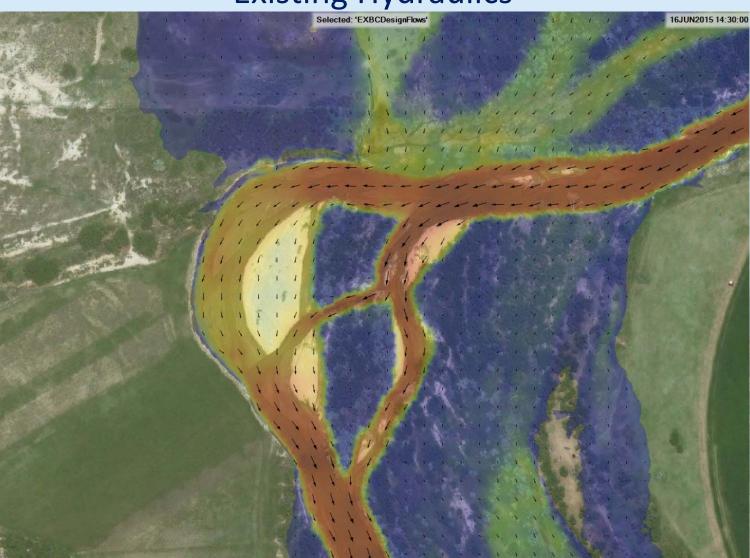
**Alternatives** 

Criteria

Modeling

Construction





**Bendway Weir Analysis** 

**Overview** 

History

Approach

Morphology

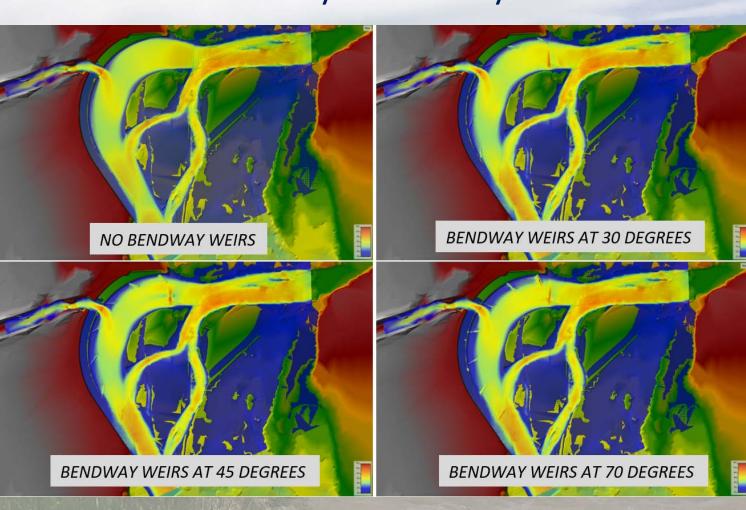
Alternatives

Criteria

Modeling

Construction





#### Bendway Weir Angle Analysis

History

Overview

Approach

Morphology

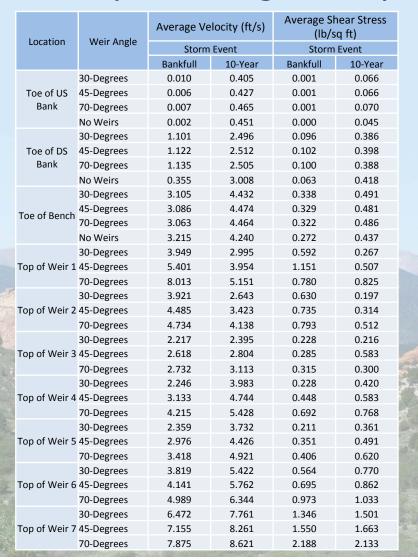
**Alternatives** 

Criteria

**Modeling** 

Construction





**Bendway Weir Length Analysis** 

**Overview** 

History

**Approach** 

Morphology

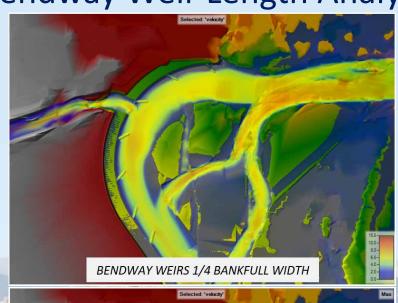
**Alternatives** 

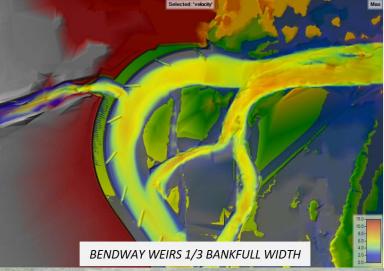
Criteria

Modeling

Construction







**Bendway Weir Height Analysis** 

**Overview** 

History

Approach

Morphology

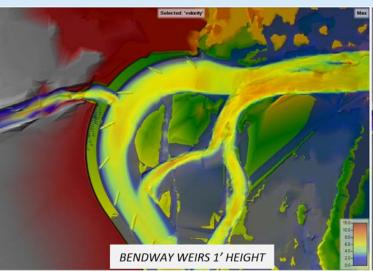
Alternatives

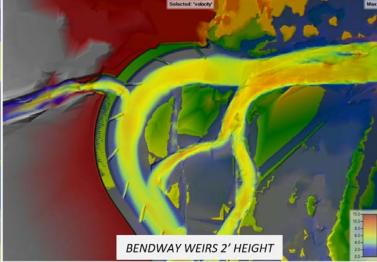
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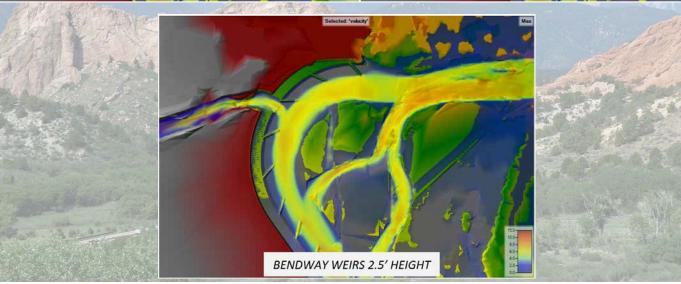
Modeling

Construction









#### **Scour Analysis**

- Bedform Scour (Simons and Richardson 1966)
  - Max = 3.4ft
- Local Scour (Simons and Richardson 1966)
  - Max = 1.2ft









- Max = 15.7ft



Overview

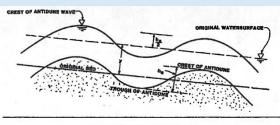
**Approach** 

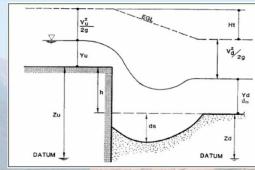
Construction

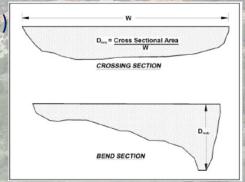
**Post-Construction** 

**Alternatives** 

**Modeling** 

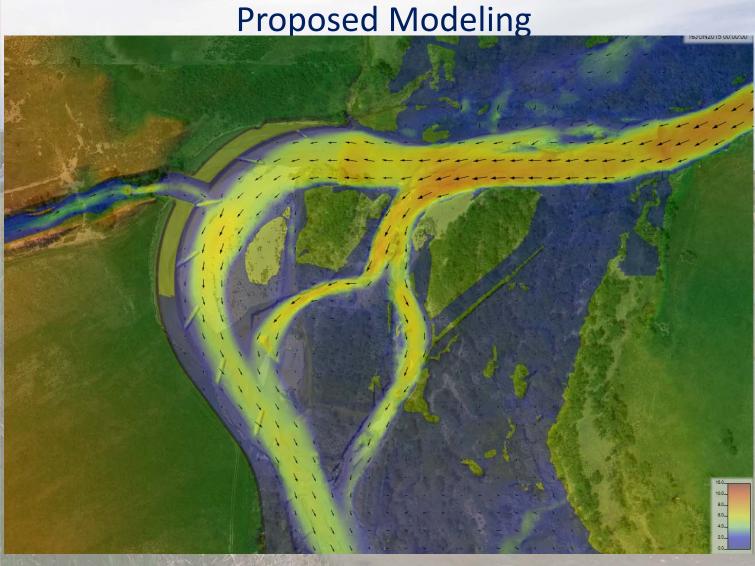






Modeling





**Proposed Design** 

Overview

History

**Approach** 

Morphology

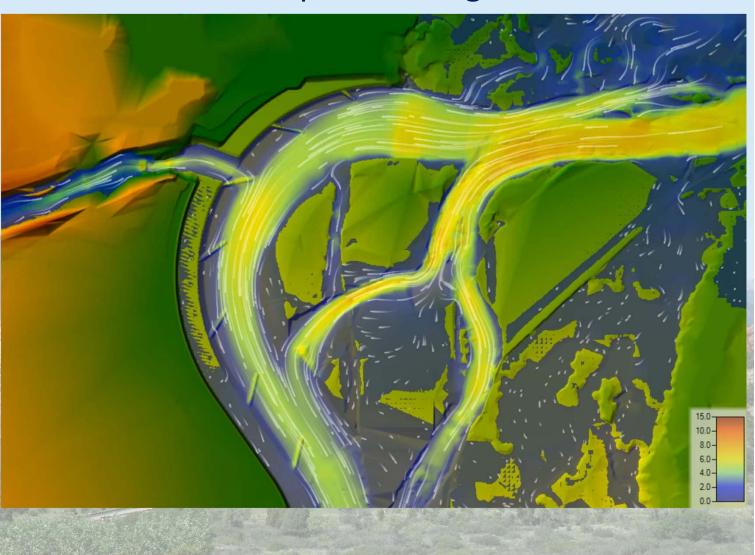
**Alternatives** 

Criteria

Modeling

Construction





# Final Design

Overview

History

**Approach** 

Morphology

**Alternatives** 

Criteria

Modeling

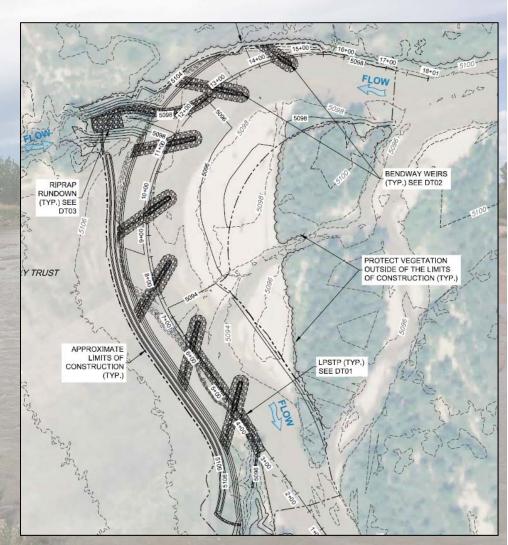
Construction

**Post-Construction** 



#### Design Elements

- Bendway Weirs
  - D50 = 36" Void
  - Filled Riprap
  - Length = 70'
  - Top Width = 6'
  - Spacing = 170'
  - Angle =  $50^{\circ}$
  - TransverseSlope ~1.5%
  - Depth = 9'
- Bankfull Bench
- Longitudinal Peaked Stone Toe Protection



# Final Design

#### Revegetation

- Willow Cuttings 6,000
- Willow Transplants 116
- Cottonwood Poles 76
- Riparian Seeding 1.4 acres
- Upland seeding 1.13 acres

Overview

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#### Overview

- October 2017 through April 2018
- Total Cost: \$1.7 million
- 10,900 Tons of Rock for the Weirs
- 5,300 Willows Planted

Overview

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Overview

History

Approach

Morphology

Alternatives

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Modeling

Construction





Overview

History

**Approach** 

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Overview

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Overview

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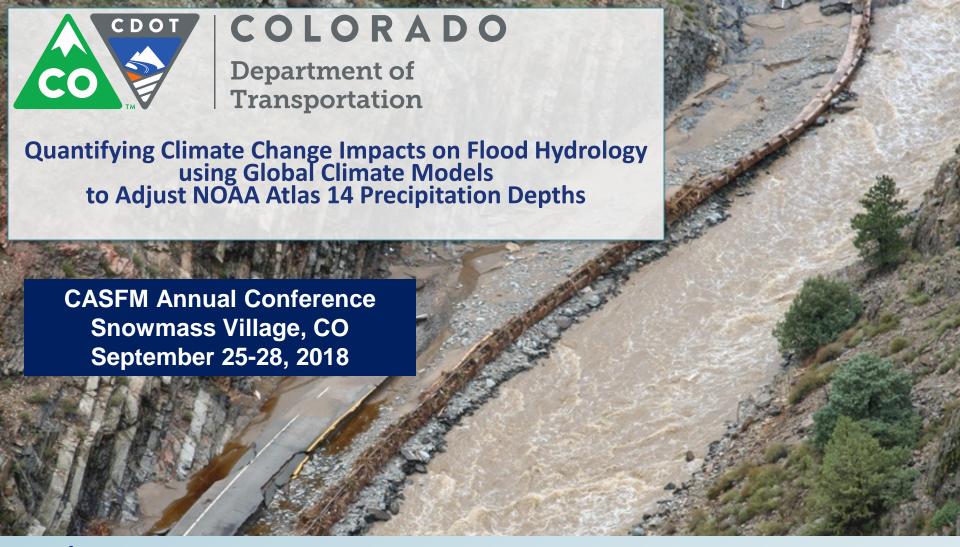
Modeling

Construction









Derek Rapp, P.E., CFM (Muller Engineering, Project Mgr.)

Jim Wulliman, P.E. (Muller Engineering, Program Mgr.)

Brian K. Varrella, P.E., CFM (Colorado DOT Reg. 4 Hydraulics Lead)





#### Climate Change Impacts on Flood Hydrology

#### **Disclaimer:**

This information presented herein is preliminary, and has not been reviewed for quality assurance or control purposes by federal or state partners (Sept. 2018).







#### Climate Change Impacts on Flood Hydrology

#### **Discussion Agenda:**

- 1.CMIP Climate Projections
- 2. Initial Results & Impressions
- 3. HEC-17 Guidance and Tool Development
- 4. CMIP Tool Results
- 5. Summary

Photo: Varrella, 2016





#### Before We Begin; Initial Impressions:



- Complex process!
- Whole new language of terminology and acronyms
- 3. Research is truly international in scope
- 4. Incredible amount of information and different options to sort through
- Results may generate more questions than answers
- 6. No definitive conclusions yet...





#### **Objective:**

The goal of this research project is to understand how to best utilize the climate projection datasets available online when evaluating potential impacts of climate change on infrastructure planning, design and construction. The US DOT CMIP Climate Data Processing Tool along with internally developed spreadsheets (based on HEC-17) guidance) are being used to extract raw climate projection data from various scenarios and to evaluate annual maximum precipitation depths. These results are then being compared with NOAA Atlas 14 point precipitation frequency estimates in an attempt to understand future trends relative to flood events.





#### **Acknowledgements:**

We would like to acknowledge the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the World Climate Research Programme's (WCRP's) Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP's Coupled Model Intercomparison Project (CMIP) Phase 3 and Phase 5 multi-model datasets (CMIP3 and CMIP5). We also thank the climate modeling groups on the next slide for producing and making available their model output. For CMIP the U.S. Department of Energy's PCMDI office provides coordinating support and led the development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

The climate projection datasets were downloaded from the "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" archive at

http://gdo-dcp.ucllnl.org/downscaled\_cmip\_projections/.





#### Acknowledgements: CMIP3 (14 International Models)

Climate Modeling Group

Bjerknes Centre for Climate Research, Norway

Canadian Centre for Climate Modeling and Analysis, Canada

Meteo-France/Centre National de Recherches Meteorologiques, France

Commonwealth Scientific and Industrial Research Organization, Atmospheric Research, Australia

U.S. Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory, USA

NASA/Goddard Institute for Space Studies, USA

Institute for Numerical Mathematics, Russia

Institut Pierre-Simon Laplace, France

Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change, Japan

Meteorological Institute of the University of Bonn, Meteorological Research Institute of the Korean Meteorological Association, Germany/Korea

Max Planck Institute for Meteorology, Germany

Meteorological Research Institute, Japan

National Center for Atmospheric Research, USA

Hadley Centre for Climate Prediction and Research/Met Office UK





#### Acknowledgements: CMIP5 (22 International Models)

Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology, Australia

Beijing Climate Center, China Meteorological Administration

College of Global Change and Earth System Science, Beijing Normal University

Canadian Centre for Climate Modeling and Analysis

National Center for Atmospheric Research

Community Earth System Model Contributors

Centro Euro-Mediterraneo per 1 Cambiamenti Climatici

Centre National de Recherches Meteorologiques/Centre Europeen de Recherche et Formation Avancee en Calcul Scientifique

Commonwealth Scientific and Industrial Research Organization, Queensland Climate Change Centre of Excellence

EC-Earth Consortium, representing 22 academic institutions and meterological services from 10 countries in Europe

Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences

The First Institute of Oceanography, State Oceanic Administration, China

NOAA Geophysical Fluid Dynamics Library

NASA/Goddard Institute for Space Studies, USA

Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)

Institute for Numerical Mathematics

Institut Pierre-Simon Laplace

Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies

Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology

Max-Planck-Institut fur Meteorologie (Max-Plancke-Institute for Meteorology)

Meteorological Research Institute

Norwegian Climate Centre





#### **Background on Climate Projection Models:**

- The online archive contains fine spatial resolution translations of climate projections over the U.S. developed using 3 downscaling techniques (monthly BCSD, daily BCCA, and daily LOCA).
- The archive is meant to provide access to climate projections at spatial and temporal scales relevant to watershed-scale decisions facing water resource managers and planners such as impacts of climate change on flood hydrology.

CMIP - Coupled Model Intercomparison Project

BCSD - Bias-Correction Spatial Disaggregation

BCCA - Bias-Correction Constructed Analogs

**LOCA - Localized Constructed Analogs** 

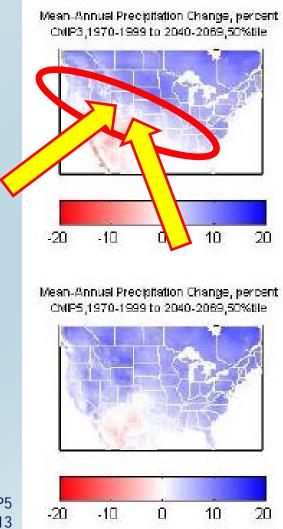




# Mean <u>Annual</u> Precipitation % change between observed and projected

- CMIP3 (Phase 3 released 2007)
- CMIP5 (Phase 5 released 2013)
- Observed Period (1970-1999)
- Projected Period (2040-2069)
- Southwest U.S. differs in Phases 3 and 5
- Colorado is on the boundary (white area)

Bureau of Reclamation, Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections, *Tech rep.*, *May* 2013

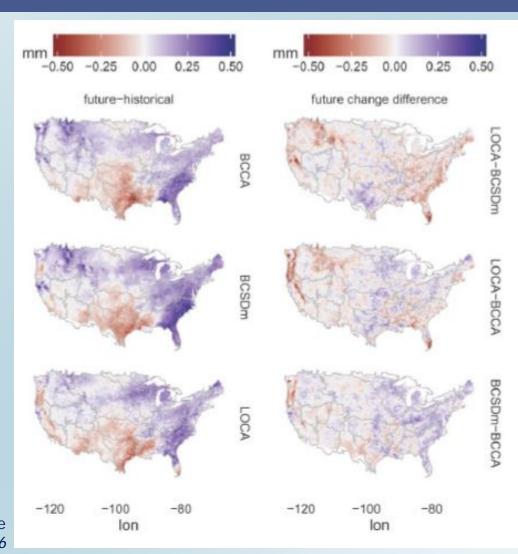






#### **Mean Daily Precipitation:**

- Observed Period (1970-1999)
- Projected Period (2040-2069)
- BCCA vs. BCSD vs. LOCA
- Slight variations throughout the country but Colorado is consistent in all projections.



Bureau of Reclamation, Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections - Addendum, *Tech rep., Sept 2016* 

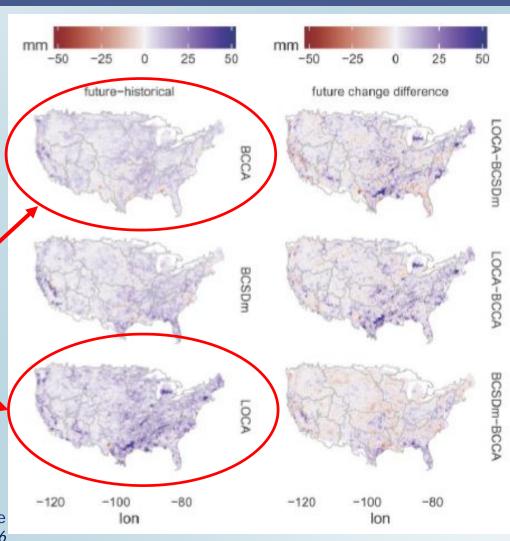




# Maximum Daily Precipitation

- Observed Period (1970-1999)
- Projected Period (2040-2069)
- BCCA vs. BCSD vs. LOCA
- BCCA does not show much change in max depth
- LOCA able to project more extreme precipitation events.

Bureau of Reclamation, Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections - Addendum, *Tech rep., Sept 2016* 







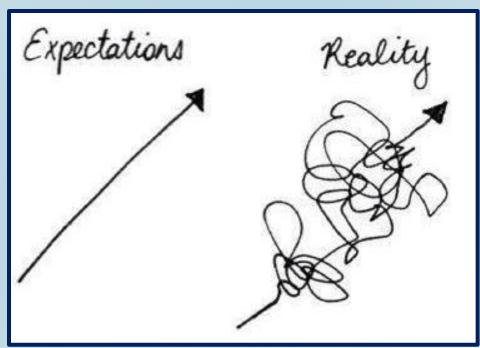
#### Climate Change Impacts on Flood Hydrology

#### **Discussion Agenda:**

- 1. CMIP Climate Projections
- 2. Initial Results & Impressions

Doodle by Jessica Hagy, @JessicaHagy, 2014

- 3. HEC-17 Guidance and Tool Development
- 4. CMIP Tool Results
- 5. Summary





#### ■ New Acronyms and Terminology

<u>CMIP</u> - Coupled Model Inter-comparison Project (primary dataset)

WGCM - Working Group on Coupled Modeling (source of dataset)

CDPT - Climate Data Processing Tool (excel spreadsheet)

BCSD - Bias-Correction Spatial Disaggregation (monthly data - not used)

BCCA - Bias-Correction Constructed Analogs (daily data - CMIP3, CMIP5)

CMIP3 - CMIP Phase 3 dataset (released 2007, 14 international models)

CMIP5 - CMIP Phase 5 dataset (released 2013, 22 international models)

LOCA - Localized Constructed Analogs (promising data, but can't import)

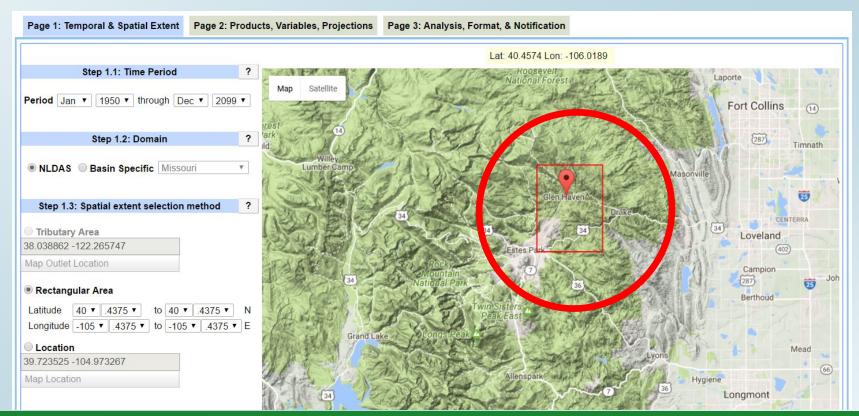
RCP - Representative Concentration Pathways (emission scenarios)





#### Request Process – Select Location

- Select location on 12 km X 12 km grid
- 1 grid per request only

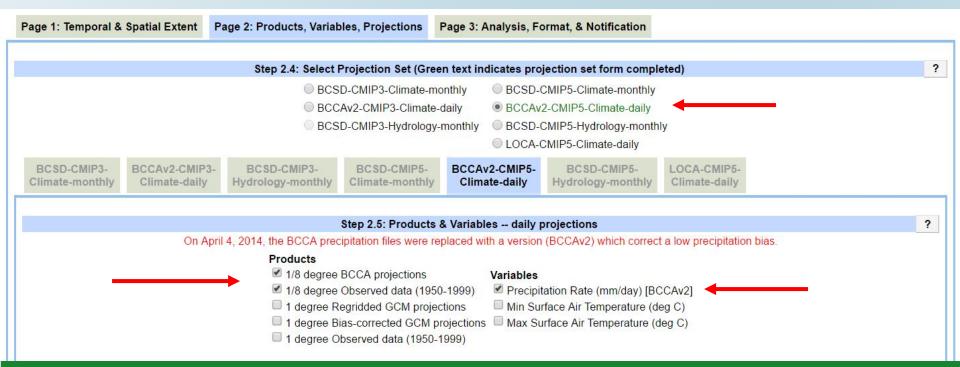






#### Request Process – Select Projection Set (1 per Request)

- 1. Select Phase CMIP3 or CMIP5
- 2. Select Projection Set BCSD (monthly), BCCA (daily), LOCA (daily)
- 3. Products Observed and Projected, Precipitation and Temperature







#### **Select Emissions Scenario and Climate Model**

	The original GCM output files f	Step 2.6: Emissions Scenarios, Climate for the BNU-ESM model were discovered to		a place-holder
De-select all runs	None	None	None	None
Select all runs	All	All	All	All
Climate Models:	Emissions Path: RCP2.6	Emissions Path: RCP4.5	Emissions Path: RCP6.0	Emissions Path: RCP8.5
access1-0				
bcc-csm1-1				Ø 0 0 0 0 0 0 0 0 0 0
onu-esm				
canesm2				
ccsm4				<b>2</b>
cesm1-bgc		000000000000		
cnrm-cm5	000000000000	000000000000		
csiro-mk3-6-0	00000000000	000000000000		
gfdl-cm3	00000000000	000000000000		
gfdl-esm2g				
gfdl-esm2m				
i <mark>nmcm4</mark>				Ø
ipsl-cm5a-lr				
ipsl-cm5a-mr				Ø
miroc-esm		000000000000		Ø
miroc-esm-chem				Ø 100000000
miroc5		0000000000000		
mpi-esm-lr				
mpi-esm-mr				<b>v</b>
mri-cgcm3				<b>Ø</b>
noresm1-m				





#### ☐ Incredible breadth of data

**Emissions Scenario & Climate Model Selection:** 

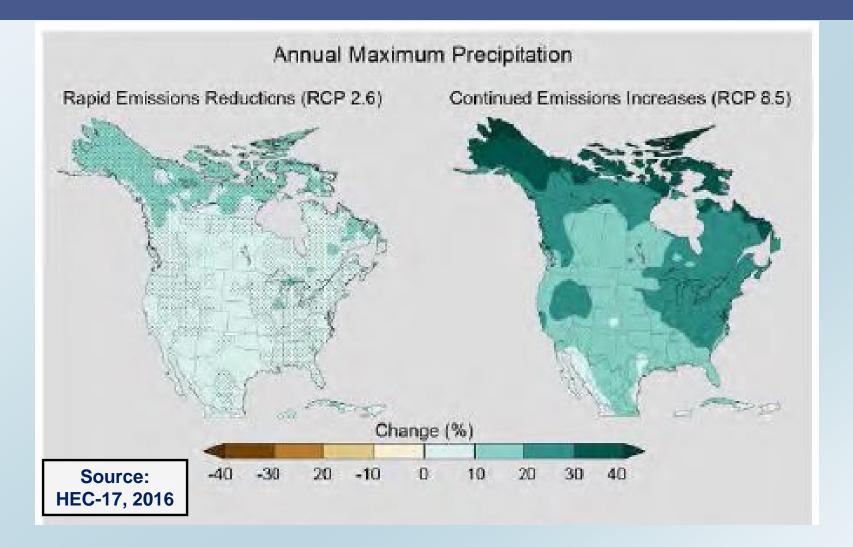
- 3 Daily Projection Sets
- 2 to 4 Emissions Scenarios
- 8 to 32 Climate Models

ORGANIZE YOUR FILES!!

Phase	Projection Set	Emissions Scenario	Emissions Description	# of Climate Models
		B1	LOW, lower emissions technology, declining global population	9
СМІРЗ	BCCA A1b		MEDIUM, rapid economic growth, declining global population	8
		A2	9	
			population growth	
		2.6	LOW, substantial and sustained emissions reductions to 475 ppm CO2	16
CAMIDE	DCCA.	4.5	MEDIUM-LOW Stabilized CO2 at 630 ppm	19
CMIP5	BCCA	6.0	MEDIUM-HIGH Stabilized CO2 at 800 ppm	12
		8.5	HIGH, high emissions continue 1313 ppm CO2	20
CMUDE	LOCA	4.5	MEDIUM-LOW Stabilized CO2 at 630 ppm	32
CMIP5	LOCA	8.5	HIGH, high emissions continue 1313 ppm CO2	32



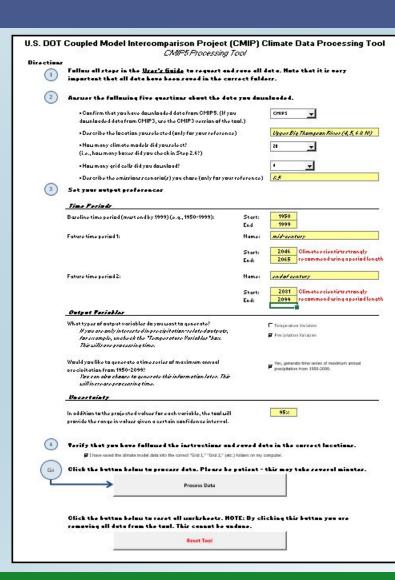








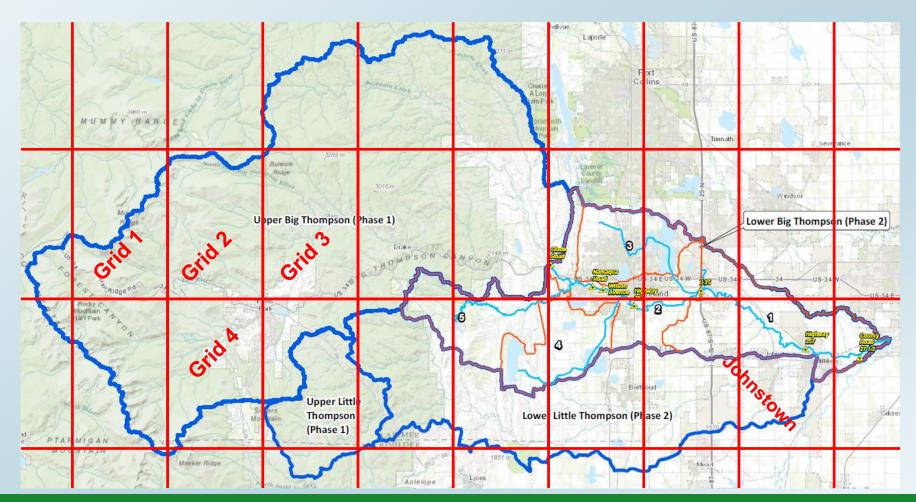
- CMIP3 and CMIP5 Spreadsheet Tools developed by U.S. DOT
- Imports ASCII (.csv) files into Excel
- Can process up to 4 separate grids
- Determines Annual Maximum Time Series from daily data
- Currently not capable of processing LOCA datasets due to NetCDF file format







#### Colorado Test Case: Big Thompson River Watershed

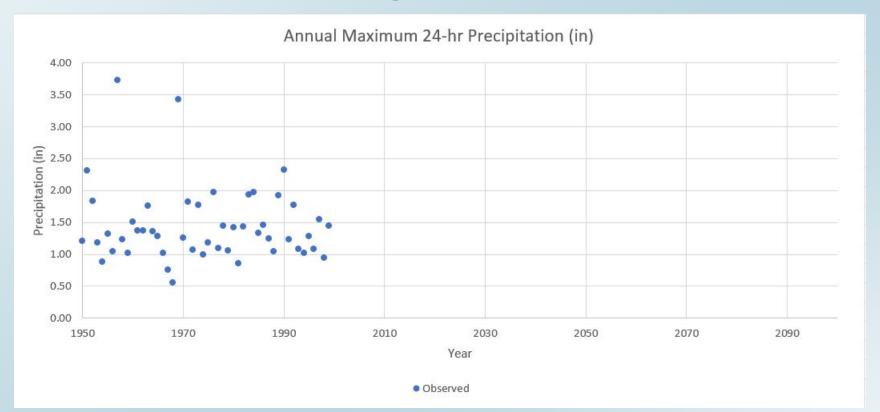






#### Observed Annual Max. Precip. (1950 – 2000)

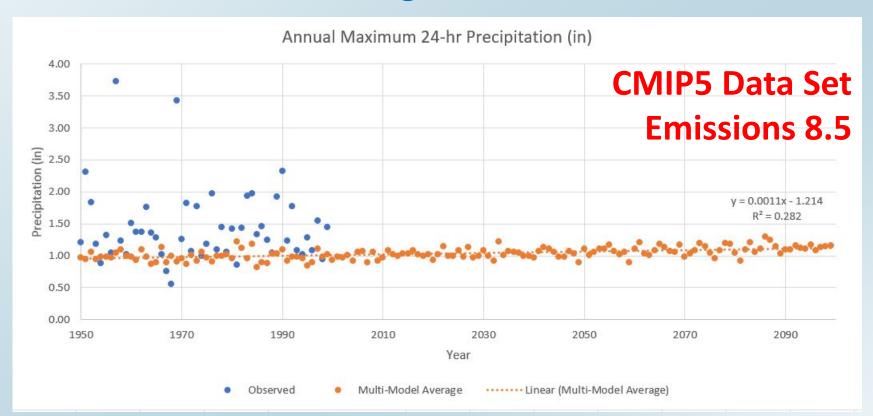
#### **Average of 4 Grids**





#### Projected Annual Max. Precip. (1950-2100):

#### **Multi-Model Average of 20 Climate Models**

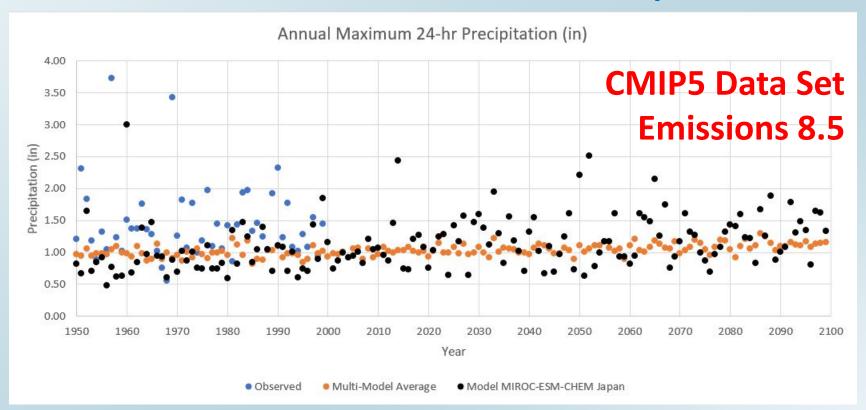






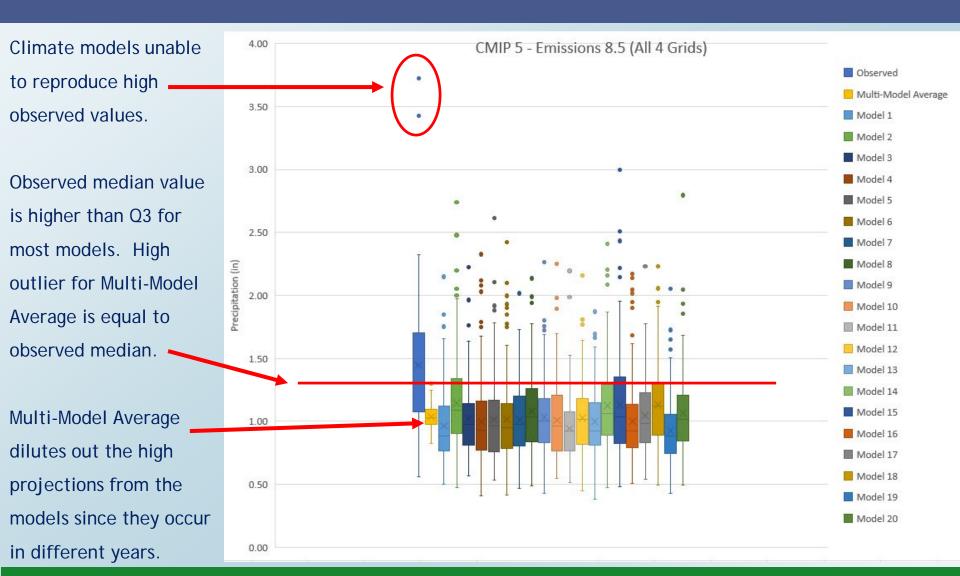
#### Projected Annual Max. Precip. (1950-2100):

#### Model 15, MIROC-ESM-CHEM Japan













#### Climate Change Impacts on Flood Hydrology

#### **Discussion Agenda:**

- 1. CMIP Climate Projections
- 2. Initial Results & Impressions
- 3.HEC-17 Guidance and Tool Development
- 4. CMIP Tool Results
- 5. Summary







Roger T. Kilgore, et al., Kilgore Consulting and Management

Hydraulic Engineering Circular Number 17, 2<sup>nd</sup> edition

# Highways in the River Environment

Floodplains, Extreme Events, Risk, and Resilience

June 2016

Publication No. FHWA-HIF-16-018

- Ch. 4 Nonstationarity and Climate Change
- Ch. 5 Climate Modeling (Downscaling/Emission Scenarios)
- Ch. 7 Analysis Framework (12 Step Procedure)





HEC-17 Analysis Framework provides guidance for State DOTs when asked to consider extreme events and climate change.

Intended to help identify data uncertainty in climate models and hydrologic models by considering the resilience of designs over a range of potential peak discharges.

5 Levels of Analysis depending on the project service life and evaluation of risks (criticality, vulnerability, and cost).





- Level 1 standard model based on historical data
- Level 2 standard model with additional evaluation of upper and lower confidence limits (LU, precip, discharge)
- Level 3 Level 2 analysis plus incorporation of projected precipitation estimates
- Level 4 Level 3 analysis plus evaluation of confidence limits on projected precipitation estimates.
- Level 5 Involve expanded expertise from other fields.

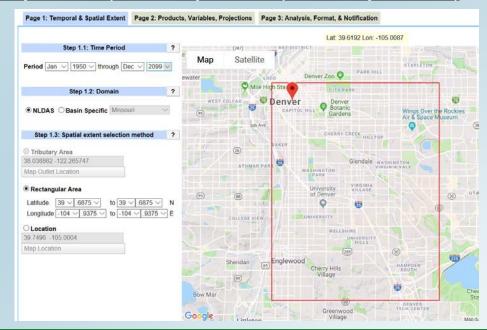




Obtain existing <u>NOAA Atlas 14 Annual Maximum Series (AMS)</u>
 <u>Quantiles</u> (e.g. 2yr-24hr through 500yr-24hr)

	AMS-based	precipitatio	n frequency	estimates v	vith 90% cor	nfidence inte	ervals (in inc	ches) <sup>1</sup>	
Duration	Duration Annual exceedance probability (1/years)								
Duration	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
24-hr	1.61 (1.34-1.94)	<b>2.22</b> (1.83-2.68)	<b>2.71</b> (2.22-3.28)	3.39 (2.70-4.24)	3.93 (3.06-4.97)	<b>4.50</b> (3.38-5.80)	<b>5.10</b> (3.67-6.71)	<b>5.93</b> (4.10-7.96)	<b>6.58</b> (4.42-8.91)

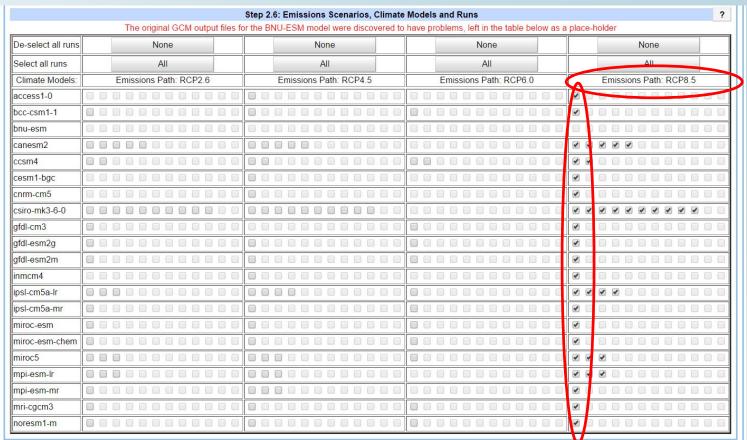
Identify downscaled
 GCM grids to cover
 area of interest
 (recommend minimum of 3)







 Download CMIP precipitation for selected emission scenario and GCMs for each grid







4. Extract AMS for each emission scenario, GCM and grid.

Then adjust with point (1.04) and unconstrained 24-hr

(1.12) correction factors

1950	1	1	0	0.014	Emissions Scenario	8.5 - Grid 1									
1950	1	2	0.051	0	Observe			AND DESCRIPTION OF THE PARTY OF	rojections						
		2	NOTE THAT THE PARTY OF THE PART	0.000	2007102	/laximum		Annual N	/laximum 24	-					
1950	1	3	0.072	0.009	24-hr Pre	cipitation (	in)		Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Me
1950	1	4	0	0.02	Year	Observed		Year	ess1-0.1.rd	csm1-1.1.r	esm2.1.rc	sm4.1.rcp	n1-bgc.1.rd	n-cm5.1.rd	mk:
1950	1	5	0.008	157	1950	1.67		1950	0.81	0.75	1.05	0.85	1.60	1.36	į.
	-	-	0.000		1951	1.63		1951	0.69	0.88	1.07	0.82	1.27	0.75	(
1950	1	6	0	0	1952	1.40		1952	1.12	1.06	0.66	0.89	1.28	1.65	
1950	1	7	0.002	0.266	253	1.35		1953	1.47	1.51	0.87	0.99	0.94	1.61	- 1
1950	1	8	0	0	1954	0.51		1954	0.82	0.86	0.57	0.70	0.71	0.82	- 1
	-				1955	1.45		1955	0.46	0.97	1.76	1.10	0.80	1.25	(
1950	1	9	0.019	0.065	1956	1.28		1956	0.79	1.07	0.51	1.71	0.89	1.34	(
1950	1	10	0.063	0	1957	2.19		1957	0.92	1.61	1.32	1.28	0.90	0.97	
					1958	1.25		1958	0.81	1.52	0.51	1.49	0.64	0.93	3
.csv file	e of c	lailv			1959	0.84	1	1959	0.69	0.57	0.84	0.89	1.20	0.85	
					1960	1.17		1960	0.91	0.80	1.11	0.60	0.40	0.83	(
precip	itatio	n (m	m)		1961	1.59		1961	0.82	1.29	1.07	0.52	1.40	1.06	
hi ceih	itatio	(111	· · · · /		1962	0.63		1962	0.69	0.90	0.58	0.91	1.30	0.64	(

1.89

1.01

1.50

1963

1964

1965

Excel file of AMS, converted to inches, and adjusted for area/point and 24-hr period

1.00

0.45

0.63

0.45

0.92

0.88

1.14

1.52

1.38

0.92

0.77

0.85

1963

1964

1965





0.48

0.73

0.90

1.48

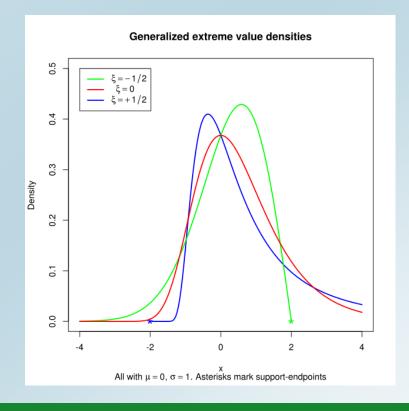
0.80

0.85

- 5. Select <u>Baseline Period</u> for analysis (e.g. 1950-1999)
- 6. Select Future Period for analysis (e.g. 2020-2099)

Time Perious	
Future Peri	od
Start Year	2020
End Year	2099
(e.g. 2020 to	2099)
	Start Year End Year

7. Extract Baseline Period AMS from Step 4 and compute Baseline 10yr-24hr Quantile by fitting GEV distribution







8. Extract Future Period AMS from Step 4 and compute

Projected 10yr-24hr Quantile
by fitting GEV distribution

GEV Distri	bution (EasyFitXL	)						
Observed	Baseli	ne Pe	eriod (195	io - 1999)				
N/A	Mo	del	1	2	3	4	5	6
-0.1679	GEV shape	e, k	0.1422	-0.0958	0.0468	0.1398	0.0517	-0.0147
0.4426	GEV Scale	2, σ	0.2645	0.2887	0.2935	0.2814	0.2816	0.2566
1.1874	GEV Location	η, μ	0.7611	0.9141	0.9029	0.8171	0.8121	0.8665
0.90	10-yr probability	y, P	0.90	0.90	0.90	0.90	0.90	0.90
2.02	10yr, 24hr Quan	tile	1.46	1.50	1.60	1.56	1.48	1.43
	Future	Peri	iod (2020	- 2099)				
	Mo	del	1	2	3	4	5	6
	GEV shape	e, k	0.1131	-0.0398	0.1452	-0.0723	0.1037	0.1185
	GEV Scale	2, σ	0.2511	0.3723	0.2759	0.2709	0.2879	0.2989
	GEV Location	η, μ	0.8316	1.0179	0.8763	0.8184	0.8598	0.9045
	10-yr probability	y, P	0.90	0.90	0.90	0.90	0.90	0.90
-	10yr, 24hr Quan	tile	1.47	1.82	1.61	1.38	1.59	1.68
	10-yr,	24-hi	RPB (Rat	io of proje	cted to bas	seline)		
	Mo	del	1	2	3	4	5	6
	RPB (10yr, 24	lhr)	1.01	1.21	1.01	0.88	1.07	1.17

Repeat Steps 3-8 for eachGCM in emission scenario

CMIP Tool can handle all GCMs simultaneously





10. Compute Ratio of Projected

to Baseline (RPB) 10yr-24hr

Quantiles and assess ratios

Select an Appropriate RPB for each Emission Scenario

Emission		RPB	
Scenario	Mean	Lower CL	<b>Upper CL</b>
2.6	1.02	0.81	1.28
4.5	1.03	0.83	1.28
6.0	1.03	0.89	1.20
8.5	1.04	0.87	1.24

90% Confidence Limits								
MEAN	Lower CL	Upper CL						
1.04	0.89	1.22						
1.04	0.87	1.22						
1.04	0.87	1.22						
1.05	0.88	1.24						
MEAN	Lower CL	Upper CL						
1.04	0.87	1.24						

- 3	1	2	3	4	5	6
Grid 1	1.46	1.50	1.60	1.56	1.48	1.43
Grid 2	1.53	1.57	1.73	1.61	1.55	1.50
Grid 3	1.43	1.47	1.52	1.53	1.43	1.38
Grid 4	1.44	1.54	1.59	1.52	1.47	1.39
MEAN	1.47	1.52	1.61	1.56	1.48	1.42
	10-yr, 24-l	nr Quantile	for Future	Period (2	020 - 2099)	

	1	2	3	4	5	6
Grid 1	1.47	1.82	1.61	1.38	1.59	1.68
Grid 2	1.52	1.90	1.75	1.49	1.68	1.76
Grid 3	1.45	1.79	1.57	1.34	1.58	1.64
Grid 4	1.48	1.84	1.67	1.43	1.62	1.70
MEAN	1.48	1.84	1.65	1.41	1.62	1.70
1						

10-yr, 24-hr RPB (Ratio of Projected to Baseline)

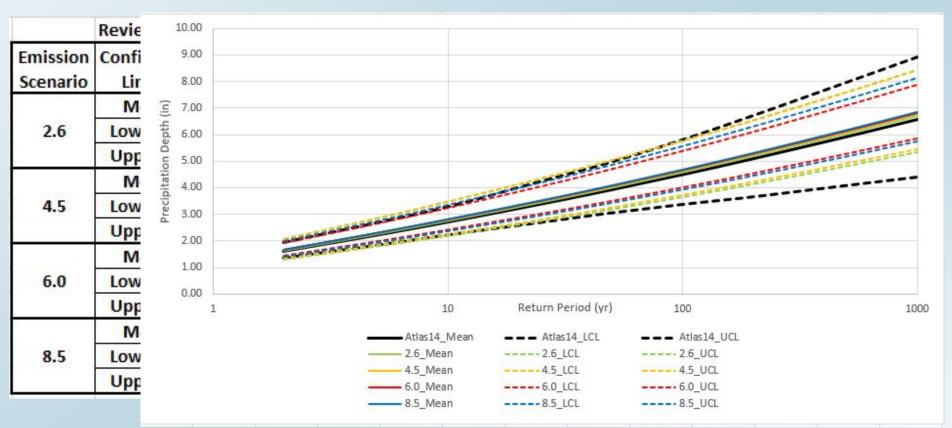
		111 172 1	- 111 (6)			
	1	2	3	4	5	6
Gri 1	1.01	1.21	1.01	0.88	1.07	1.17
Grid ?	0.99	1.21	1.01	0.93	1.09	1.18
Grid .	1.01	1.22	1.04	0.87	1.11	1.19
Grid 4	1.03	1.19	1.05	0.94	1.10	1.23
MEAN	1.01	1.21	1.03	0.91	1.09	1.19
ower CL	0.99	1.19	1.01	0.87	1.07	1.17
Jpper Cl	1.02	1.22	1.05	0.94	1.11	1.22





#### 11. Adjust Atlas 14 Quantiles (Step 1) with selected RPBs

to estimate Projected Future Quantiles







12. Repeat Steps 3-11 for each future emissions scenario

CMIP Tool can handle all emission scenarios simultaneously

**Evaluate Climate Change Indicator (CCI)** 

Scenario 2.6 4.5	1/2 0.08	1/5 0.08	1/10	1/25	1/50	4/400		N1 N2	
200 0000	0.08	0.08			1,30	1/100	1/200	1/500	1/1000
4.5			0.08	0.07	0.06	0.06	0.05	0.05	0.05
	0.15	0.15	0.15	0.12	0.12	0.11	0.10	0.09	0.09
6.0	0.16	0.16	0.16	0.13	0.13	0.12	0.11	0.10	0.09
8.5	0.20	0.20	0.20	0.17	0.16	0.14	0.13	0.12	0.12
	CCI < 0.4 (I	_evel 2 Ana	a <mark>l</mark> ysis is sut	ficient)					
1	0.4 < CCI <	0.8 (Desig	n Team to	determine	appropria	ite level of	analysis)		
1	0.8 < CCI (L	evel 4 Ana	alysis Reco	mmended	)		300 000		





#### Climate Change Impacts on Flood Hydrology

#### **Discussion Agenda:**

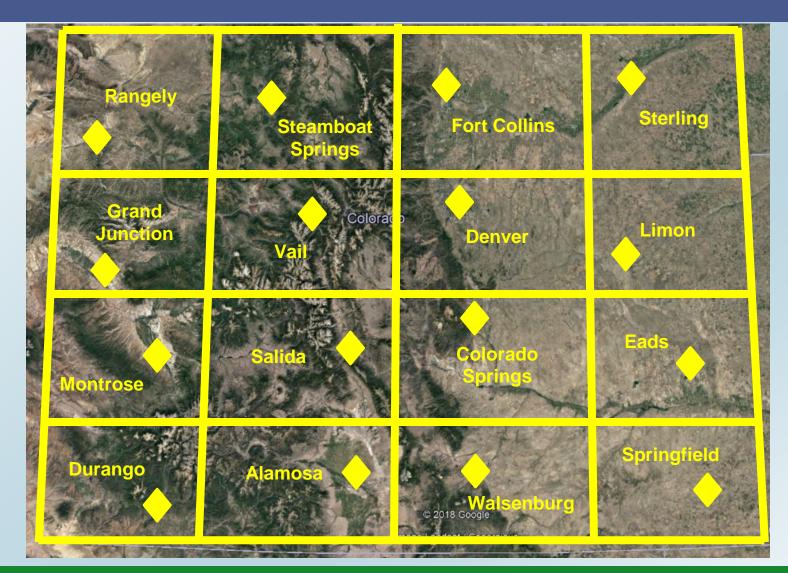
- 1. CMIP Climate Projections
- 2. Initial Results & Impressions
- 3. HEC-17 Guidance and Tool Development
- 4.CMIP Tool Results
- 5. Summary



Source: Rapp, 2008











# **Eastern Plains**

Mean RPB

Min 1.03 Max 1.11

						•							
4 Sterling													
Emission	D CONTROL	RPB		Emission						cator (CCI)			
Scenario	Mean	Lower CL	Upper CL	Scenario	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
2.6	1.04	0.90	1.20	2.6	0.22	0.23	0.22	0.18	0.17	0.15	0.14	0.12	0.12
4.5	1.07	0.94	1.30	4.5	0.37	0.37	0.36	0.29	0.28	0.25	0.23	0.20	0.20
6.0	1.10	0.96	1.27	6.0	0.49	0.49	0.48	0.38	0.37	0.33	0.30	0.27	0.26
8.5	1.04	0.90	1.19	8.5	0.21	0.22	0.21	0.17	0.16	0.14	0.13	0.12	0.11
8 Limon													
Emission		RPB		Emission				Climate C	hange Indi	icator (CCI)			
Scenario	Mean	Lower CL	Upper CL	Scenario	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
2.6	1.04	0.92	1.17	2.6	0.17	0.16	0.16	0.12	0.12	0.11	0.10	0.09	0.09
4.5	1.06	0.88	1.21	4.5	0.25	0.24	0.23	0.19	0.18	0.16	0.14	0.13	0.13
6.0	1.11	0.98	1.24	6.0	0.46	0.45	0.43	0.34	0.33	0.30	0.27	0.24	0.24
8.5	1.06	0.92	1.26	8.5	0.24	0.23	0.22	0.18	0.17	0.15	0.14	0.13	0.12
12 Eads													
Emission		RPB		Emission									
Scenario	Mean	Lower CL	<b>Upper CL</b>	Scenario	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
2.6	1.09	0.96	1.30	2.6	0.56	0.55	0.55	0.44	0.42	0.38	0.34	0.31	0.31
4.5	1.10	1.01	1.22	4.5	0.60	0.59	0.58	0.47	0.44	0.40	0.37	0.33	0.33
6.0	1.11	1.04	1.24	6.0	0.67	0.66	0.65	0.53	0.50	0.45	0.41	0.37	0.37
8.5	1.07	0.92	1.27	8.5	0.42	0.41	0.41	0.33	0.31	0.28	0.26	0.23	0.23
16 Springfi	eld	10000000											
Emission	20	RPB		Emission						cator (CCI)			
Scenario	Mean	Lower CL	Upper CL	Scenario	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
2.6	1.06	0.94	1.20	2.6	0.27	0.26	0.26	0.20	0.19	0.17	0.16	0.14	0.14
4.5	1.05	0.98	1.22	4.5	0.22	0.21	0.21	0.16	0.16	0.14	0.13	0.12	0.12
6.0	1.03	0.89	1.20	6.0	0.14	0.13	0.13	0.10	0.10	0.09	0.08	0.07	0.07
8.5	1.07	0.93	1.19	8.5	0.30	0.29	0.28	0.22	0.21	0.19	0.17	0.16	0.16





# Front Range

Mean RPB

Min 1.02 Max 1.08

Emission		RPB		Emission				Climate C	hange Indi	cator (CCI)	r (CCI)			
Scenario	Mean	Lower CL	Upper CL	Scenario	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000	
2.6	1.03	0.90	1.22	2.6	0.17	0.16	0.16	0.11	0.10	0.09	0.08	0.07	0.07	
4.5	1.04	0.90	1.24	4.5	0.20	0.20	0.19	0.13	0.12	0.11	0.10	0.09	0.09	
6.0	1.04	0.89	1.16	6.0	0.22	0.21	0.21	0.14	0.13	0.12	0.11	0.10	0.09	
8.5	1.06	0.88	1.25	8.5	0.37	0.36	0.35	0.23	0.23	0.20	0.18	0.16	0.16	
7 Denver														
Emission	0 0 11111	RPB		Emission		V2	)/ )/-	Climate C	hange Indi	cator (CCI)	y2. III. III.	V2	N.	
Scenario	Mean	Lower CL	Upper CL	Scenario	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/100	
2.6	1.02	0.81	1.28	2.6	0.08	0.08	0.08	0.07	0.06	0.06	0.05	0.05	0.05	
4.5	1.03	0.83	1.28	4.5	0.15	0.15	0.15	0.12	0.12	0.11	0.10	0.09	0.09	
6.0	1.03	0.89	1.20	6.0	0.16	0.16	0.16	0.13	0.13	0.12	0.11	0.10	0.09	
8.5	1.04	0.87	1.24	8.5	0.20	0.20	0.20	0.17	0.16	0.14	0.13	0.12	0.12	
	lo Coringe													
11 Colora	L Colora o Springs													
11 Colora Emission	io springs	RPB		Emission		X		Climate C	hange Indi	cator (CCI)	6. IFIELD .	X3. 111 11 14		
	Mean	RPB Lower CL	Upper CL	Emission Scenario	1/2	1/5	1/10	Climate C 1/25	hange Indi 1/50	cator (CCI) 1/100	1/200	1/500	1/100	
Emission	e mana		Upper CL 1.15		1/2 0.38	1/5 0.37	1/10 0.36				1/200 0.20	1/500 0.18		
Emission Scenario	Mean	Lower CL	A CONTRACTOR OF THE PARTY OF TH	Scenario		720000000000000000000000000000000000000		1/25	1/50	1/100			0.18	
Emission Scenario 2.6 4.5 6.0	Mean 1.07 1.05 1.07	0.98 0.90 0.87	1.15	Scenario 2.6 4.5 6.0	0.38 0.26 0.38	0.37 0.25 0.37	0.36 0.24 0.36	1/25 0.26 0.18 0.26	1/50 0.25	1/100 0.22 0.15 0.22	0.20 0.13 0.20	0.18 0.12 0.18	0.18 0.12 0.18	
Emission Scenario 2.6 4.5	Mean 1.07 1.05	0.98 0.90	1.15 1.20	Scenario 2.6 4.5	0.38 0.26	0.37 0.25	0.36 0.24	1/25 0.26 0.18	1/50 0.25 0.17	1/100 0.22 0.15	0.20	0.18 0.12	0.18 0.12 0.18	
Emission Scenario 2.6 4.5 6.0	Mean 1.07 1.05 1.07 1.04	0.98 0.90 0.87	1.15 1.20 1.22	Scenario 2.6 4.5 6.0	0.38 0.26 0.38	0.37 0.25 0.37	0.36 0.24 0.36	1/25 0.26 0.18 0.26	1/50 0.25 0.17 0.25	1/100 0.22 0.15 0.22	0.20 0.13 0.20	0.18 0.12 0.18	1/100 0.18 0.12 0.18 0.10	
Emission Scenario 2.6 4.5 6.0 8.5	Mean 1.07 1.05 1.07 1.04	0.98 0.90 0.87	1.15 1.20 1.22	Scenario 2.6 4.5 6.0	0.38 0.26 0.38	0.37 0.25 0.37	0.36 0.24 0.36	1/25 0.26 0.18 0.26 0.15	1/50 0.25 0.17 0.25 0.15	1/100 0.22 0.15 0.22	0.20 0.13 0.20	0.18 0.12 0.18	0.18 0.12 0.18	
Emission Scenario 2.6 4.5 6.0 8.5	Mean 1.07 1.05 1.07 1.04	0.98 0.90 0.87 0.93	1.15 1.20 1.22	Scenario 2.6 4.5 6.0 8.5	0.38 0.26 0.38	0.37 0.25 0.37	0.36 0.24 0.36	1/25 0.26 0.18 0.26 0.15	1/50 0.25 0.17 0.25 0.15	1/100 0.22 0.15 0.22 0.13	0.20 0.13 0.20	0.18 0.12 0.18	0.18 0.12 0.18	
Emission Scenario 2.6 4.5 6.0 8.5	Mean 1.07 1.05 1.07 1.04 burg	0.98 0.90 0.87 0.93	1.15 1.20 1.22 1.16	Scenario 2.6 4.5 6.0 8.5	0.38 0.26 0.38 0.23	0.37 0.25 0.37 0.22	0.36 0.24 0.36 0.21	1/25 0.26 0.18 0.26 0.15	1/50 0.25 0.17 0.25 0.15	1/100 0.22 0.15 0.22 0.13	0.20 0.13 0.20 0.12	0.18 0.12 0.18 0.11	0.18 0.12 0.18 0.10	
Emission Scenario 2.6 4.5 6.0 8.5 L5 Walser Emission Scenario	Mean 1.07 1.05 1.07 1.04 burg Mean	0.98 0.90 0.87 0.93 RPB	1.15 1.20 1.22 1.16	Scenario 2.6 4.5 6.0 8.5 Emission Scenario	0.38 0.26 0.38 0.23	0.37 0.25 0.37 0.22	0.36 0.24 0.36 0.21	1/25 0.26 0.18 0.26 0.15 Climate C 1/25	1/50 0.25 0.17 0.25 0.15	1/100 0.22 0.15 0.22 0.13 cator (CCI) 1/100	0.20 0.13 0.20 0.12	0.18 0.12 0.18 0.11	0.18 0.12 0.18 0.10	
Emission Scenario 2.6 4.5 6.0 8.5  15 Walser Emission Scenario 2.6	Mean 1.07 1.05 1.07 1.04 burg Mean 1.08	0.98 0.90 0.87 0.93 RPB Lower CL	1.15 1.20 1.22 1.16 Upper CL 1.20	Scenario 2.6 4.5 6.0 8.5 Emission Scenario 2.6	0.38 0.26 0.38 0.23	0.37 0.25 0.37 0.22 1/5 0.42	0.36 0.24 0.36 0.21 1/10 0.40	1/25 0.26 0.18 0.26 0.15 Climate C 1/25 0.29	1/50 0.25 0.17 0.25 0.15 0.15	1/100 0.22 0.15 0.22 0.13 cator (CCI) 1/100 0.23	0.20 0.13 0.20 0.12	0.18 0.12 0.18 0.11 1/500 0.18	0.18 0.12 0.18 0.10 1/100 0.17	





High Mountains

Mean RPB

Min 1.05 Max 1.13

2 Steamb	oc <mark>at Spring</mark> .												
Emission		RPB		Emission				Climate C	hange Indi	cator (CCI)		99/2101	
Scenario	Mean	Lower CL	Upper CL	Scenario	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
2.6	1.08	0.99	1.16	2.6	0.39	0.38	0.37	0.28	0.26	0.23	0.20	0.18	0.17
4.5	1.06	0.95	1.15	4.5	0.27	0.27	0.26	0.20	0.18	0.16	0.14	0.13	0.12
6.0	1.10	1.00	1.19	6.0	0.45	0.45	0.44	0.32	0.31	0.27	0.24	0.21	0.20
8.5	1.13	0.97	1.26	8.5	0.60	0.59	0.58	0.43	0.40	0.36	0.31	0.28	0.27
									1				
6 Vail													
Emission	n	RPB		Emission		43	40 0000	Climate C	hange Indi	cator (CCI)	Si Carlo		
Scenario	Mean	Lower CL	<b>Upper CL</b>	Scenario	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
2.6	1.08	0.94	1.19	2.6	0.28	0.28	0.27	0.21	0.20	0.18	0.16	0.15	0.14
4.5	1.05	0.94	1.16	4.5	0.19	0.19	0.18	0.14	0.14	0.12	0.11	0.10	0.10
6.0	1.09	0.95	1.22	6.0	0.34	0.34	0.32	0.26	0.24	0.22	0.19	0.18	0.17
8.5	1.11	0.96	1.25	8.5	0.43	0.42	0.40	0.32	0.30	0.27	0.24	0.22	0.22
10 Salida													
Emission	1	RPB		Emission						cator (CCI)		-	
Scenario	Mean	Lower CL		Scenario	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
2.6	1.08	0.94	1.23	2.6	0.37	0.35	0.35	0.28	0.27	0.24	0.21	0.19	0.18
4.5	1.06	0.90	1.17	4.5	0.28	0.27	0.26	0.21	0.20	0.18	0.16	0.14	0.14
6.0	1.07	0.96	1.22	6.0	0.32	0.31	0.30	0.25	0.23	0.21	0.18	0.16	0.16
8.5	1.09	0.96	1.24	8.5	0.43	0.42	0.41	0.33	0.31	0.28	0.25	0.22	0.21
14 Alamo	The state of the s				9								
Emission	1,340	RPB		Emission						cator (CCI)			
Scenario		Lower CL		Scenario	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
2.6	1.09	0.93	1.24	2.6	0.53	0.52	0.50	0.43	0.38	0.34	0.31	0.27	0.26
4.5	1.05	0.89	1.23	4.5	0.32	0.31	0.30	0.26	0.23	0.21	0.19	0.16	0.16
6.0	1.08	0.94	1.28	6.0	0.50	0.49	0.47	0.41	0.36	0.32	0.29	0.25	0.24
8.5	1.08	0.93	1.24	8.5	0.51	0.50	0.48	0.42	0.37	0.33	0.30	0.26	0.25





# Western Slope

Mean RPB

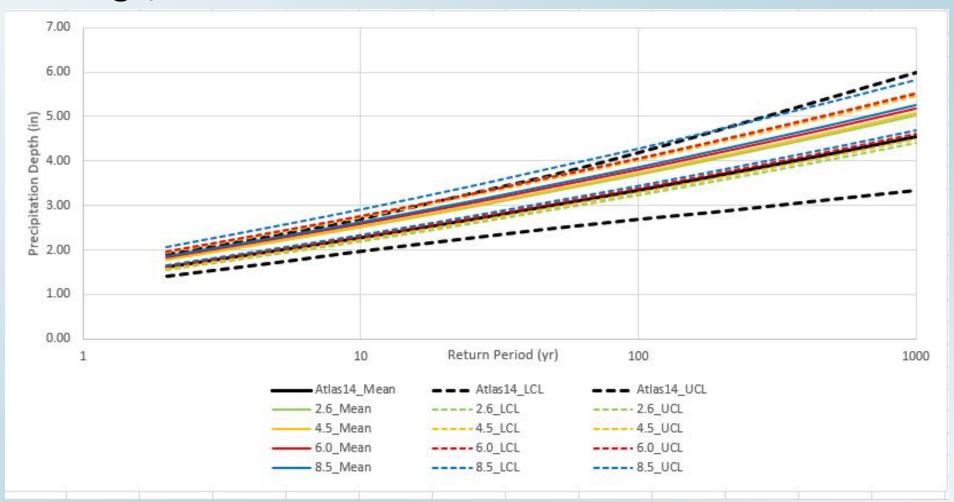
Min 1.08 Max 1.16

1 Rangely				11111									
Emission		RPB		Emission				Climate C	hange Indi	cator (CCI)			
Scenario	Mean	Lower CL	Upper CL	Scenario	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
2.6	1.15	0.95	1.34	2.6	0.71	0.69	0.66	0.55	0.51	0.45	0.40	0.36	0.34
4.5	1.13	0.94	1.31	4.5	0.61	0.59	0.57	0.48	0.44	0.39	0.35	0.31	0.29
6.0	1.13	1.00	1.30	6.0	0.64	0.61	0.59	0.50	0.46	0.40	0.36	0.32	0.30
8.5	1.15	0.95	1.28	8.5	0.72	0.70	0.67	0.56	0.52	0.46	0.41	0.36	0.35
5 Grand Ju	nction												
Emission		RPB		Emission				Climate C	hange Indi	cator (CCI)			
Scenario	Mean	Lower CL	Upper CL	Scenario	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
2.6	1.08	0.97	1.19	2.6	0.39	0.38	0.37	0.31	0.29	0.26	0.24	0.21	0.21
4.5	1.09	0.98	1.20	4.5	0.40	0.39	0.38	0.32	0.30	0.27	0.24	0.22	0.21
6.0	1.11	1.01	1.22	6.0	0.51	0.51	0.48	0.41	0.38	0.35	0.31	0.28	0.27
8.5	1.13	0.97	1.23	8.5	0.59	0.59	0.56	0.48	0.44	0.41	0.36	0.32	0.31
9 Montro	e												
Emission		RPB		Emission				Climate C	hange Indi	cator (CCI)			
Scenario	Mean	Lower CL	Upper CL	Scenario	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
2.6	1.12	1.02	1.28	2.6	0.55	0.55	0.52	0.43	0.39	0.34	0.30	0.27	0.25
4.5	1.10	1.01	1.21	4.5	0.49	0.49	0.47	0.39	0.35	0.31	0.27	0.24	0.22
6.0	1.13	1.00	1.26	6.0	0.62	0.62	0.59	0.49	0.45	0.38	0.34	0.30	0.28
8.5	1.14	1.00	1.28	8.5	0.66	0.66	0.63	0.52	0.48	0.41	0.36	0.32	0.30
13 Durang													
Emission	,	RPB		Emission				Climate	hange Indi	cator (CCI)			
Scenario	Mean	Lower CL	Upper CL	Scenario	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
2.6	1.10	0.97	1.22	2.6	0.59	0.58	0.56	0.48	0.46	0.41	0.37	0.34	0.33
4.5	1.11	0.98	1.20	4.5	0.65	0.64	0.61	0.52	0.50	0.45	0.41	0.37	0.36
6.0	1.14	1.01	1.21	6.0	0.80	0.78	0.75	0.64	0.61	0.55	0.50	0.46	0.44
8.5	1.16	1.03	1.28	8.5	0.89	0.88	0.84	0.72	0.69	0.62	0.56	0.51	0.49





#### Durango, CO







## **HEC-17 Guidance and Tool Development**

1,491 Stations from the HCDN (1948-2007)

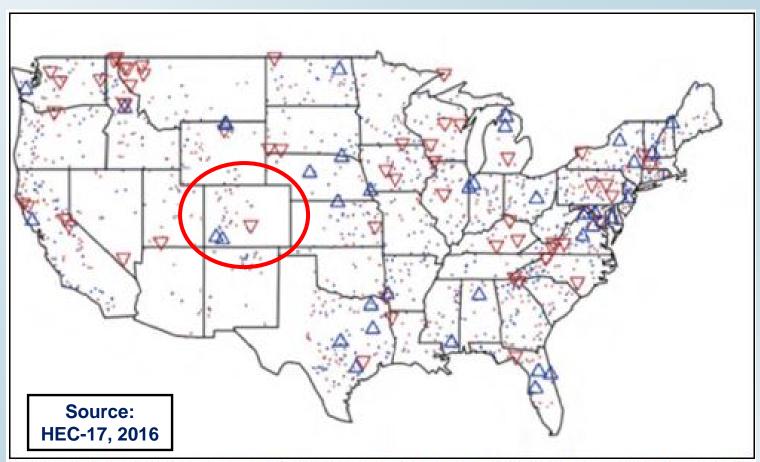


Figure 4.4. Trends in annual instantaneous peak streamflow (from Lins and Cohn, 2011).

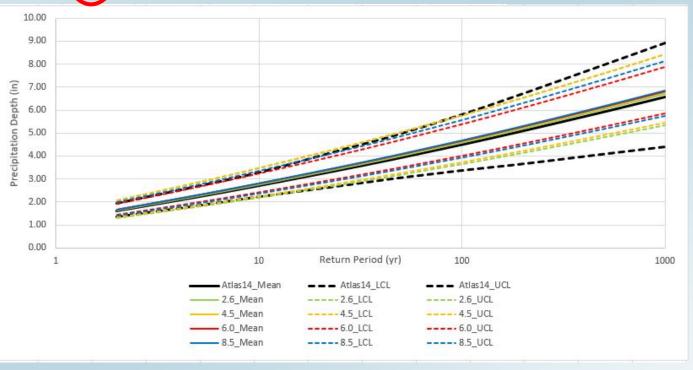




#### Denver, CO (Average of All GCMs)

Select an Ap	propriate	RPB for ea	ch Emission Scen	ario on the Quant	tile Summa	ry worksheet						
Emission	111	RPB										
Scenario	Mean	Lower CL	Upper CL	Avg			Max			Min		
2.6	1.02	0.81	1.28	1.02	0.81	1.28	1.30	1.28	1.31	0.79	0.78	0.80
4.5	1.03	0.83	1.28	1.03	0.83	1.28	1.30	1.25	1.34	0.78	0.76	0.79
6.0	1.03	0.89	1.20	1.03	0.89	1.20	1.19	1.18	1.21	0.87	0.85	0.89
8.5	1.04	0.87	1.24	1.04	0.87	1.24	1.24	1.21	1.27	0.88	0.86	0.91

Emission	10.7			
Scenario	1/2	1/5		
2.6	0.08	0.08		
4.5	0.15	0.15		
6.0	0.16	0.16		
8.5	0.20	0.20		
	CCI < 0.4 (	Level 2 A		
	0.4 < CCI <	0.8 (Des		
	0.8 < CCI (	Level 4 A		



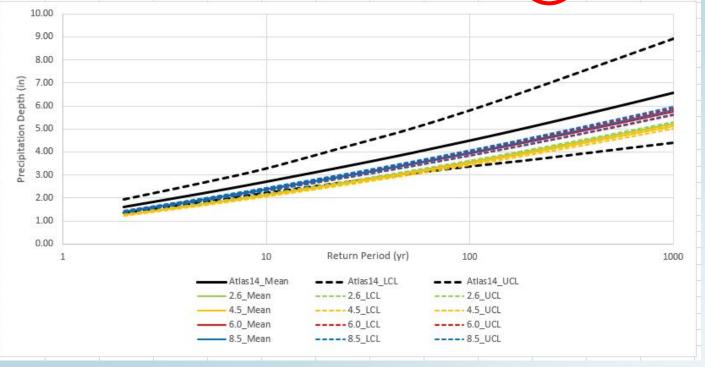




#### Denver, CO (Minimum GCM)

Emission	111	RPB										
Scenario	Mean	Lower CL	Upper CL	Avg			Max			Min		
2.6	1.02	0.81	1.28	1.02	0.81	1.28	1.30	1.28	1.31	0.79	0.78	0.80
4.5	1.03	0.83	1.28	1.03	0.83	1.28	1.30	1.25	1.34	0.78	0.76	0.79
6.0	1.03	0.89	1.20	1.03	0.89	1.20	1.19	1.18	1.21	0.87	0.85	0.89
8.5	1.04	0.87	1.24	1.04	0.87	1.24	1.24	1.21	1.27	0.88	0.86	0.91

Emission			
Scenario	1/2	1/5	
2.6	-1.01	-1.00	
4.5	-1.07	-1.06	
6.0	-0.62	-0.61	
8.5	-0.58	-0.57	





0.4 < CCI < 0.8 (Desig

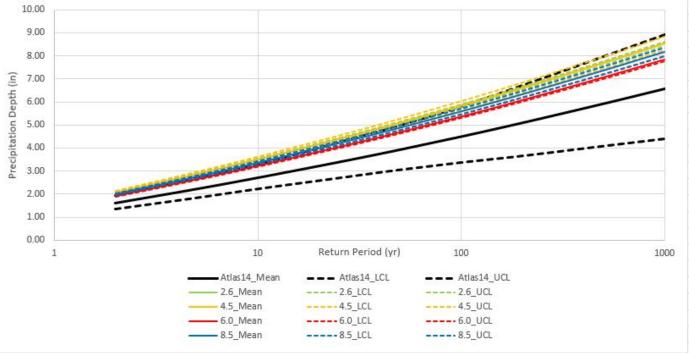
0.8 < CCI (Level 4 And



#### Denver, CO (Maximum GCM)

Emission		RPB										
Scenario	Mean	Lower CL	Upper CL	Avg			Max			Min		
2.6	1.02	0.81	1.28	1.02	0.81	1.28	1.30	1.28	1.31	0.79	0.78	0.80
4.5	1.03	0.83	1.28	1.03	0.83	1.28	1.30	1.25	1.34	0.78	0.76	0.79
6.0	1.03	0.89	1.20	1.03	0.89	1.20	1.19	1.18	1.21	0.87	0.85	0.89
8.5	1.04	0.87	1.24	1.04	0.87	1.24	1.24	1.21	1.27	0.88	0.86	0.91

Emission		
Scenario	1/2	1/5
2.6	1.44	1.43
4.5	1.44	1.43
6.0	0.95	0.94
8.5	1.19	1.18
	CCI < 0.4 (	Level 2 An
	0.4 < CCI <	0.8 (Desig
	0.8 < CCI (	Level 4 An













#### Ratio of Projected to Baseline (RPB)

Source: Varrella, 2012

Results	below	organized	based	on	USA Map	

Results bei	ow organ	lized based	on USA IVIAP
Seattle	Billings	Minneapolis	Augusta
Tahoe City	Denver	St Louis	Washington
San Diego	Tuscon	Houston	Miami
Scenario 4	.5 RPB M	ean	
1.13	1.11	1.12	1.10
1.09	1.03	1.10	1.10
1.07	1.11	1.04	1.06
Scenario 8	.5 RPB M	ean	
1.17	1.18	1.11	1.13
1.17	1.04	1.14	1.06
1.13	1.13	1.06	1.09





## Climate Change Impacts on Flood Hydrology

#### **Discussion Agenda:**

- 1. CMIP Climate Projections
- 2. Initial Results & Impressions
- 3. HEC-17 Guidance and Tool Development
- 4. CMIP Tool Results
- 5.Summary







## Summary

- Complex process!
- 2. New language of terms
- 3. International dataset
- 4. Myriad of info and options
- Downscaling limitations and dampening of extremes (LOCA?)

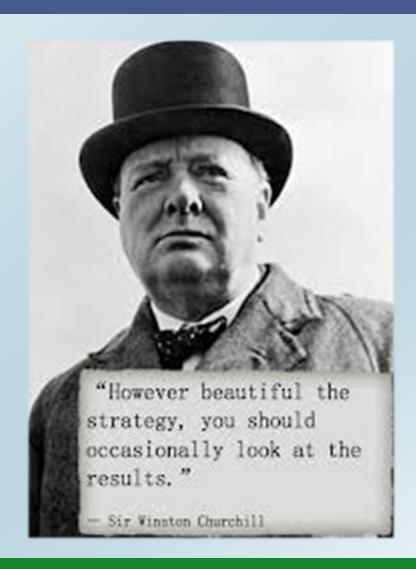


- 6. Difficult to select appropriate GCMs without bias
- 7. Wide NOAA Atlas 14 Confidence limits often envelope results
- 8. No definitive conclusions but will press on!



## Summary

Final Thought...





## **Climate-Modified Hydrology**



#### **Questions?**

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@COriverDude





Evolution of the 2-D Base Level Engineering Across FEMA Region VIII and a Case Study from Garfield County, Colorado

Eli Gruber, PE Garrett Sprouse, EIT David Sutley, PE





## **Project Acknowledgments**



#### **FEMA Region 8 Staff:**

- David Sutley, PE
- Dawn Brabenec, PE

#### **CWCB Staff:**

Thuy Patton, MPA, CFM

#### **Anderson Consulting Engineers**

- Travis Rounsaville, PE
- Michelle Martin, PE

#### **Terrain Data Sources:**

- USGS National Elevation Dataset
- CWCB Colorado Hazard Mapping Program





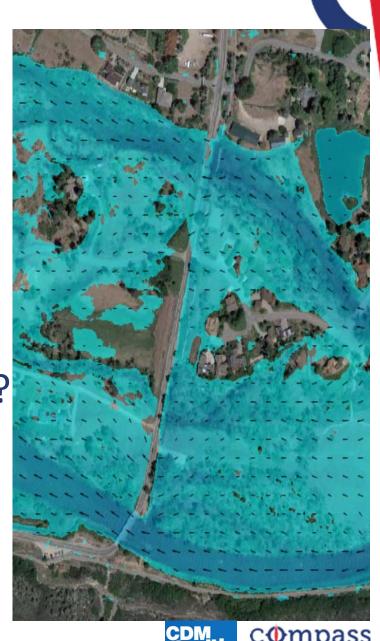






#### **Overview**

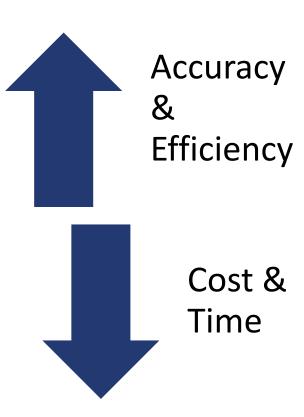
- What is 2D Base Level Engineering (BLE)?
- Garfield County BLE
  - Process refinements
  - Issues and Limitations
- Where do we go from here?
- Research and Development



## **2D Base Level Engineering (BLE)**



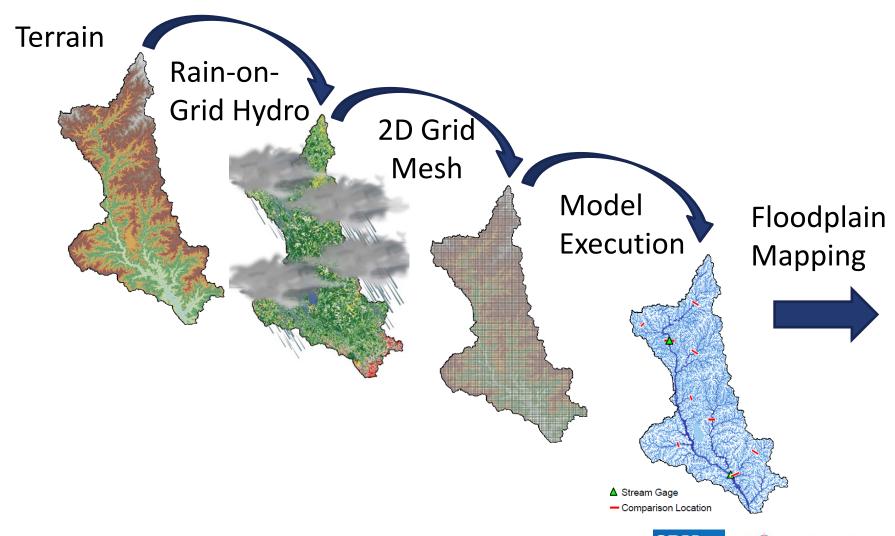
- What is 2D BLE?
  - Watershed-level hydraulic modeling and floodplain mapping
  - Automated processes
- HEC-RAS 5.0
- Produce results for previously unmapped areas and/or nonmodel backed SFHAs
- Help drive scoping decisions for future detailed studies (scalable)





## **2D BLE Modeling Concepts**





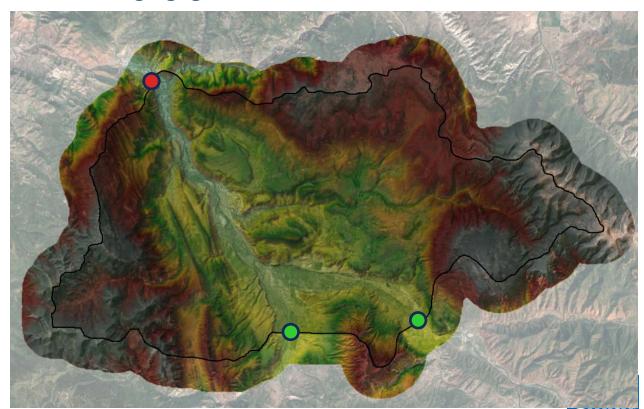




#### **Model Area Delineation**



- Main considerations for model areas:
  - 1. SIZE: Max model area ~ 1,300 sq mi
  - 2. **DRAINAGE**: Account for all contributing basin area (Rain-on-Grid + external inflows)
  - 3. DATA: Leverage gage data for inflows and calibration

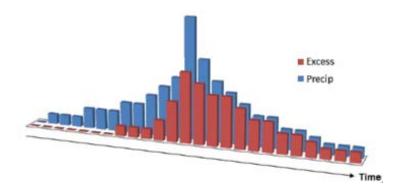


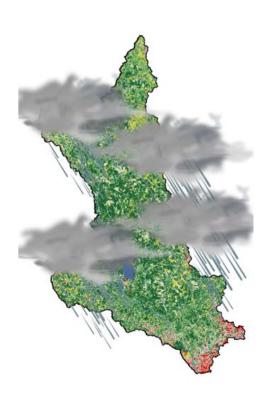


## **BLE Rain-on-Grid Hydrology**



- Applied directly to 2D Mesh
- No hydrologic losses in HEC-RAS 5.0
  - Simple HMS model
    - SCS CN Method 24-hour storm
    - NOAA Atlas 14 precip raster
    - NRCS Soils + NLCD = Average CN
- Excess Precipitation Hyetograph



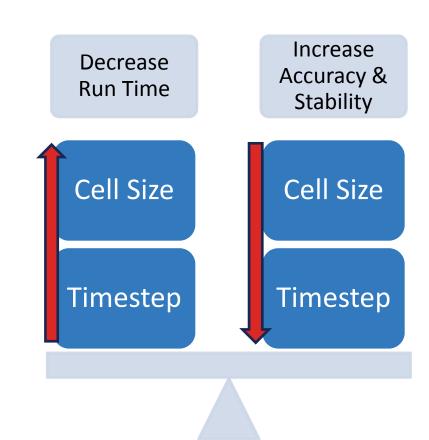




## **HEC-RAS 5.0 Hydraulic Parameters**



- Grid cell mesh
  - 200-foot nominal cell size
- Manning's n
  - NLCD 2011 spatial coverage
- Boundary Conditions
- Computational options
  - Diffusion Wave Equation
  - Timestep options

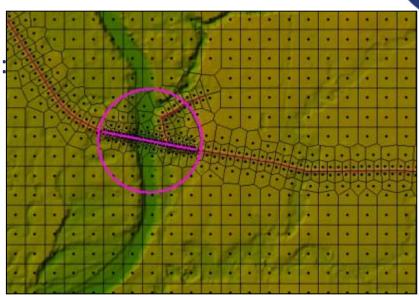




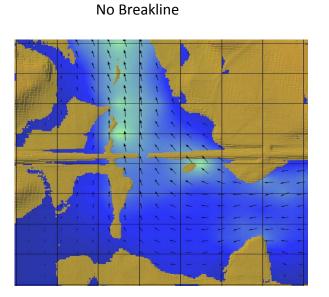


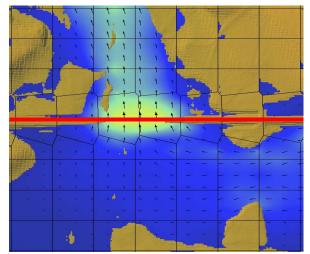
#### **Breaklines**

- Used to refine grid and represent:
  - Road embankments
  - Structures
  - Levees
  - Dams
  - Other Terrain Features



With Breakline



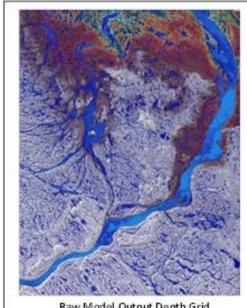




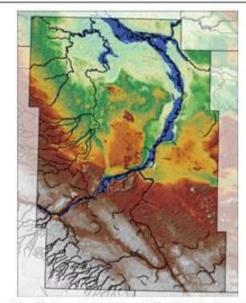
#### **BLE Outputs**

- Provide county-wide floodplain data for 7 recurrence intervals
- Mapped SFHA data for 1% and 0.2% **ACE** events
- Final BLE models and reports

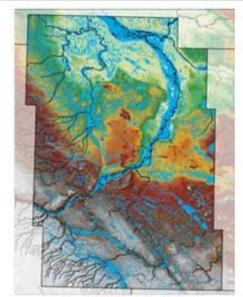
Annual Chance Exceedance	H&H Modeling	Floodplain Mapping
10%		
4%		
2%		
1%-minus		
1%-plus		
1%	<b>✓</b>	$\overline{\checkmark}$
0.20%	$\overline{\checkmark}$	$\overline{\checkmark}$







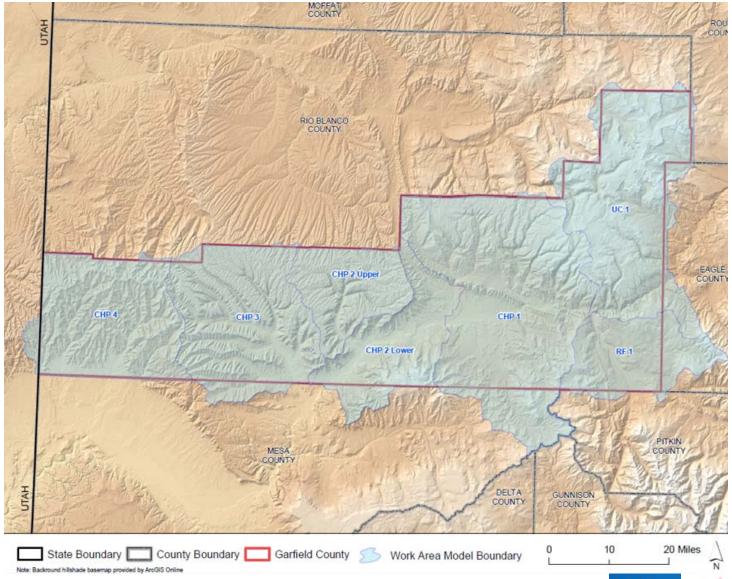
Identify County, CNMS and Effective Flood Zones



Floodplain Mapping Applied



# **Garfield County, CO 2D BLE**



Smith.



# **Garfield County Model Background**



- LiDAR data from CWCB
- Produced floodplain data for full county
- Gage analysis for three major external inflows:
  - Colorado River
  - Roaring Fork
  - Crystal River
- Highly variable <u>terrain</u> and <u>hydrologic conditions</u>



Photo from Glenwood Springs Chamber of Commerce





## **Hydrologic Conditions**



#### **Challenge:**

- Represent variable hydrologic conditions
  - Small streams and washes < 8,000' controlled cloudburst rainfall events
  - Larger basins driven by snowmelt or rain-on-snow

#### **Solution:**

- Model "calibration"
  - Calculate target 100-yr peak flows (gage or regional regression) at various points in model
  - Compare model values to target values
  - Adjust rain-on-grid hydrology and re-run model until best match at most points

September 27, 2018

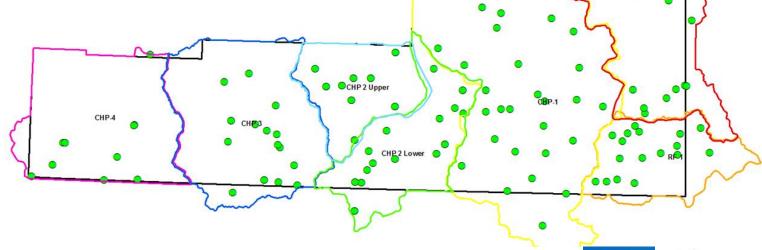


### "Calibration" Results



Model Area	Within 1-Sep	Within 2-Sep	Outside 2-Sep
UC-1	69%	31%	0%
RF-1	76%	24%	0%
CHP-1	81%	19%	0%
CHP-2 (Lower)	73%	27%	0%
CHP-2 (Upper)	100%	0%	0%
CHP-3	88%	12%	0%
CHP-4	93%	7%	0%

Standard Error +/- 35% to 75%



## **Steep & Variable Channel Slopes**



#### **Challenge:**

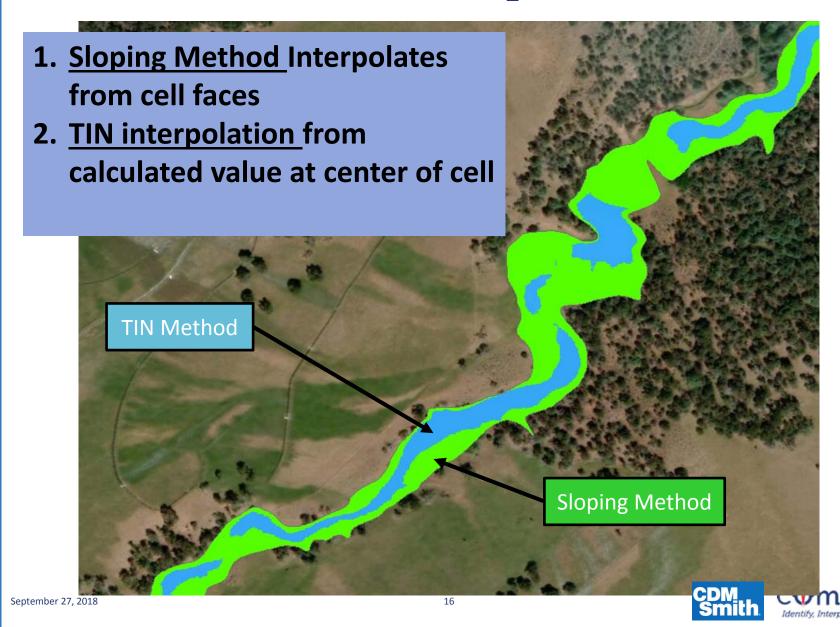
- Disconnected mapped floodplains
  - Map rendering issues in steep streams (>3%) with low discharge

#### **Solution**

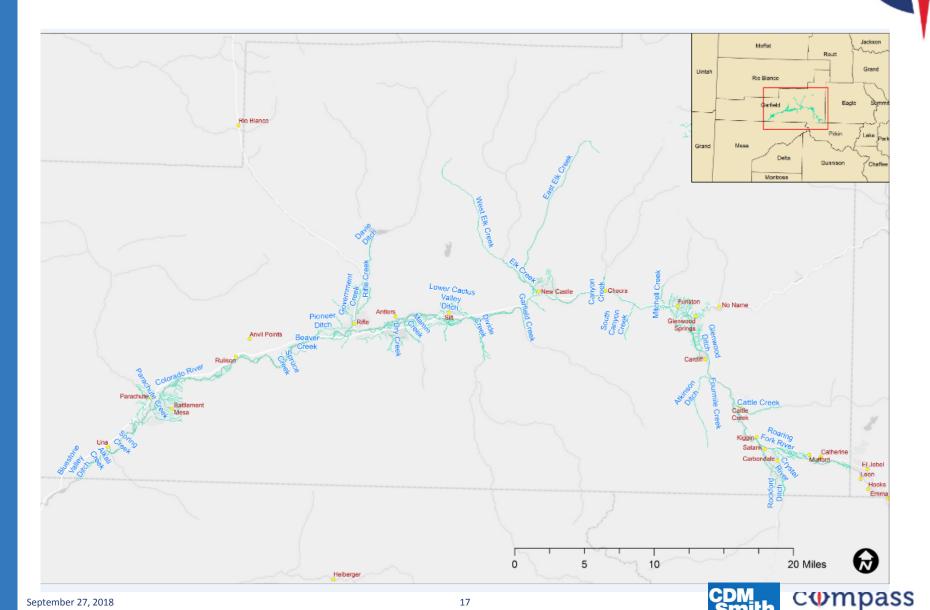
- Targeted grid cell mesh refinement
  - Streams with existing/prelim FEMA data and/or within municipal boundaries
  - Decrease cell size from 200ft to 40ft along stream centerline

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## **Garfield Results Examples**

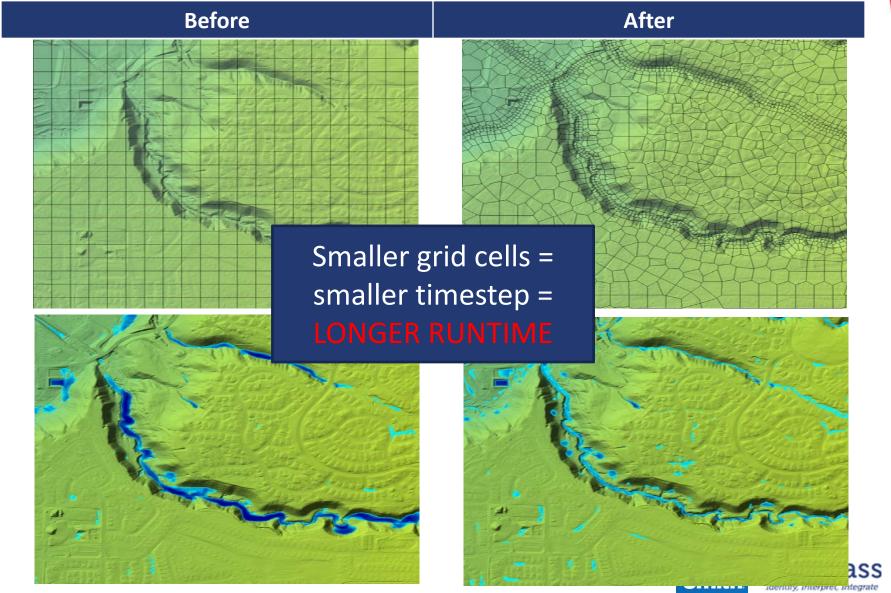


## **Refinement Areas**



#### **Mesh Refinement Results**

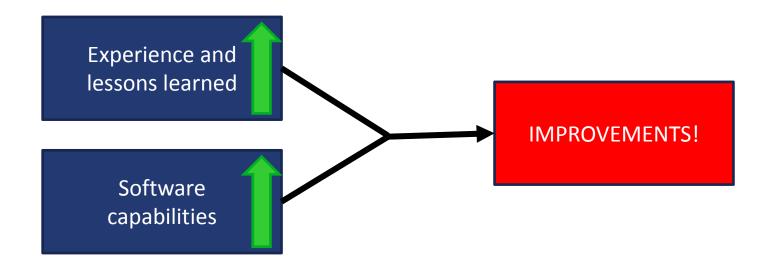




## Where do we go from here?



- 2D BLE process is capable of producing approximate Zone A floodplains in most areas
- Garfield County highlights some challenges to address



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# **Ongoing Research & Development**



Evaluate current BLE process

Document major limitations

Identify opportunities for improvement

Develop innovative solutions

Smith.



## **Ongoing R&D Activities**

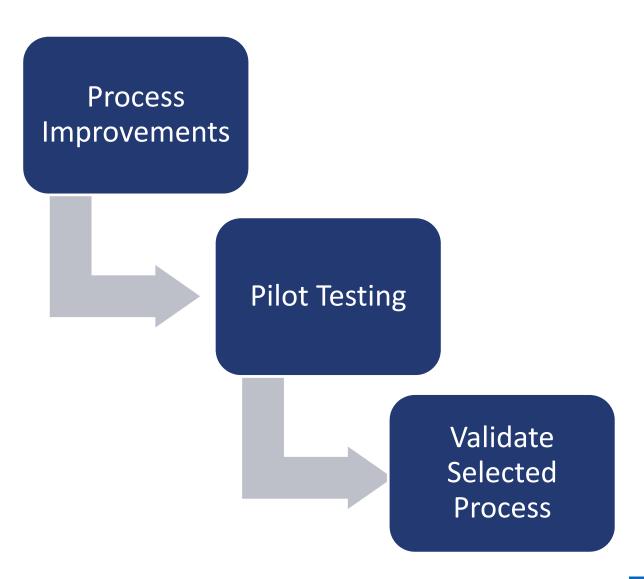


- Pre-project watershed evaluation process
- Testing sensitivity to <u>slope</u> vs <u>grid cell size</u> vs <u>discharge</u>
- Sub-basin specific hydrologic parameters
  - -Rainfall distribution/Precip/CN
- Methods for representing structures
- Improving results rendering and mapping

COmpass Smith. Compass

## **R&D Next Steps?**





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## **Key Takeaways**

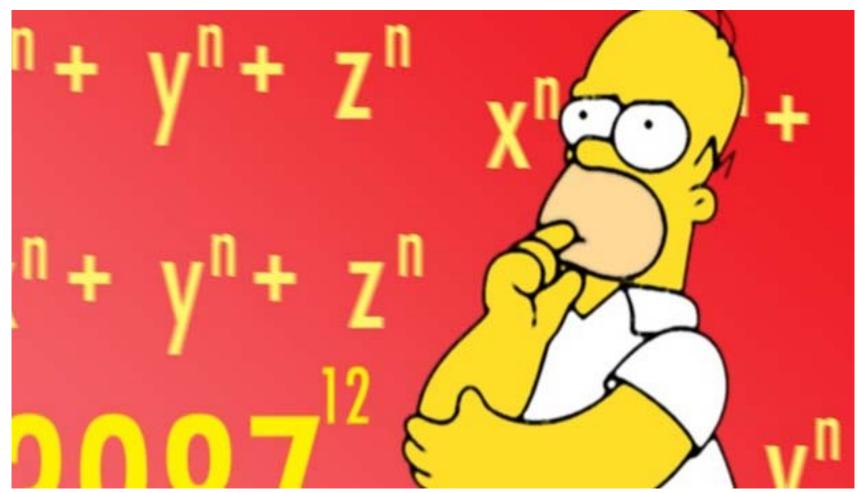


- 2D BLE is an efficient and (relatively) accurate method for producing floodplains
- Engineers should evaluate whether method can achieve desired project outcome
- Process limitations provide opportunities to improve....stay tuned!

COmpass Identify, Interpret, Integrate

# **Questions?**









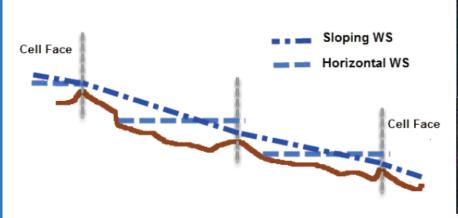


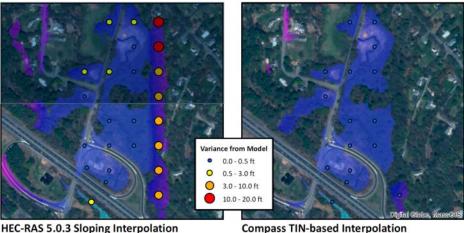


## **Map Rendering Options**



- Sloping Interpolates from cell faces; tendency to overestimate
- Compass TIN Method: TIN interpolation from calculated value at center of cell





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September 27, 2018

