The Homestake Project's Arkansas River Diversion Rehabilitation

HOMESTAKE WATER PROJECT

AURORA WATER

Colorado Springs Utilities

Tiered Hydraulic Modeling Applied to a Recreational, In-Channel Project

CASFM 2019 Conference, September 26, 2019

Brian McCormick, P.E., CFM, CSU Sr. Project Engineer

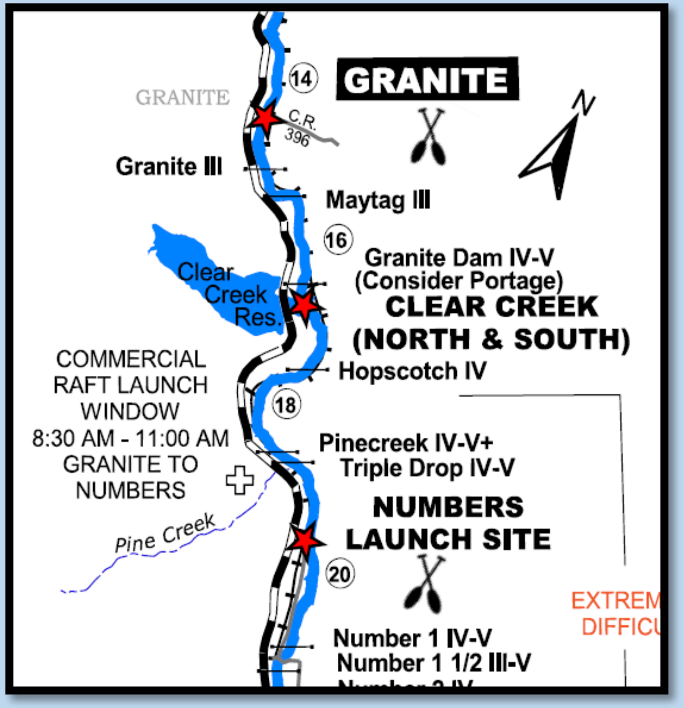
Homestake Arkansas River Diversion

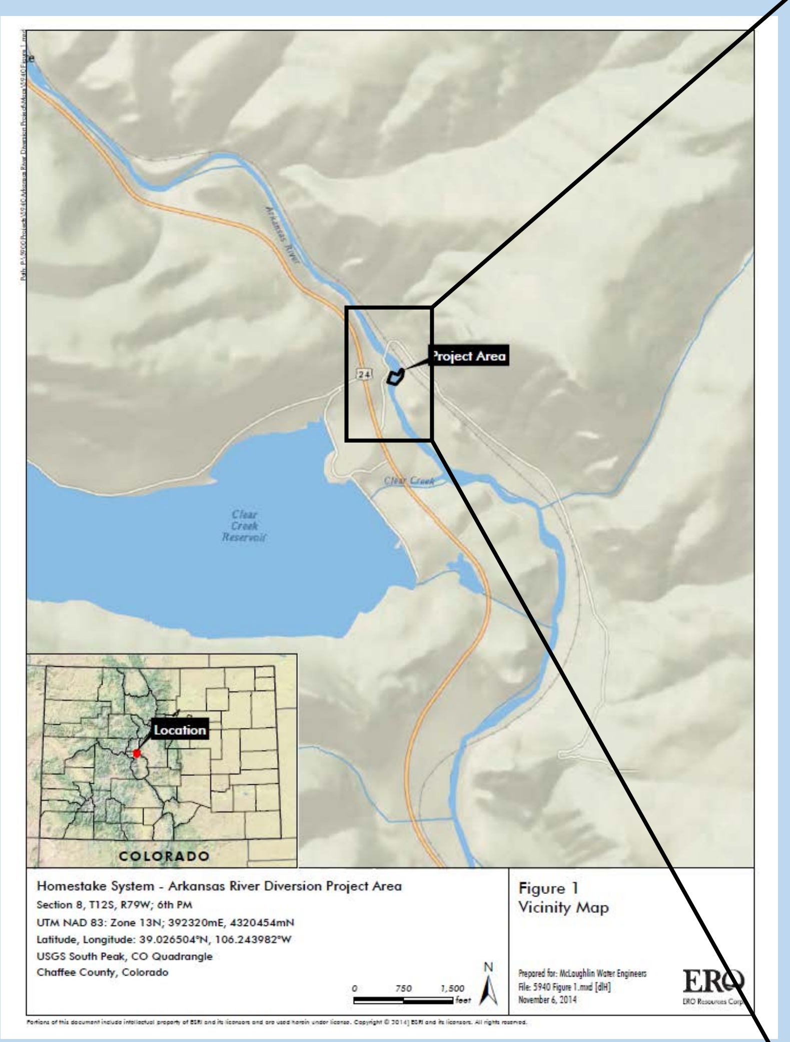
- The Homestake Project is a partnership between the Cities of Colorado Springs and Aurora.
- The Homestake Project moves water from Homestake Creek and other Eagle River tributaries to the Cities via a series of reservoirs, tunnels, pipelines, and the Otero Pump Station north of Buena Vista, CO.
- The Arkansas River Diversion (ARD) constructed c. 1965
  - ARD was the original intake for the Otero Pump Station
  - In the 1980s, the Intake Pipeline was extended to Twin Lakes (~400’ higher) and the ARD became a backup facility
  - The ARD had issues with sediment, debris, and in its deteriorated state, was not a reliable facility
  - The ARD was not designed as a navigable structure and was considered non-navigable in its pre-project condition.
- Design of a repair was challenging due to
  - Site conditions (12-13’ of drop and two sharp bends)
  - Multiple Objectives: Intake, Navigability, Fish Passage, Sediment and Debris Management

HOMESTAKE WATER PROJECT

AURORA WATER Colorado Springs Utilities

Project Location



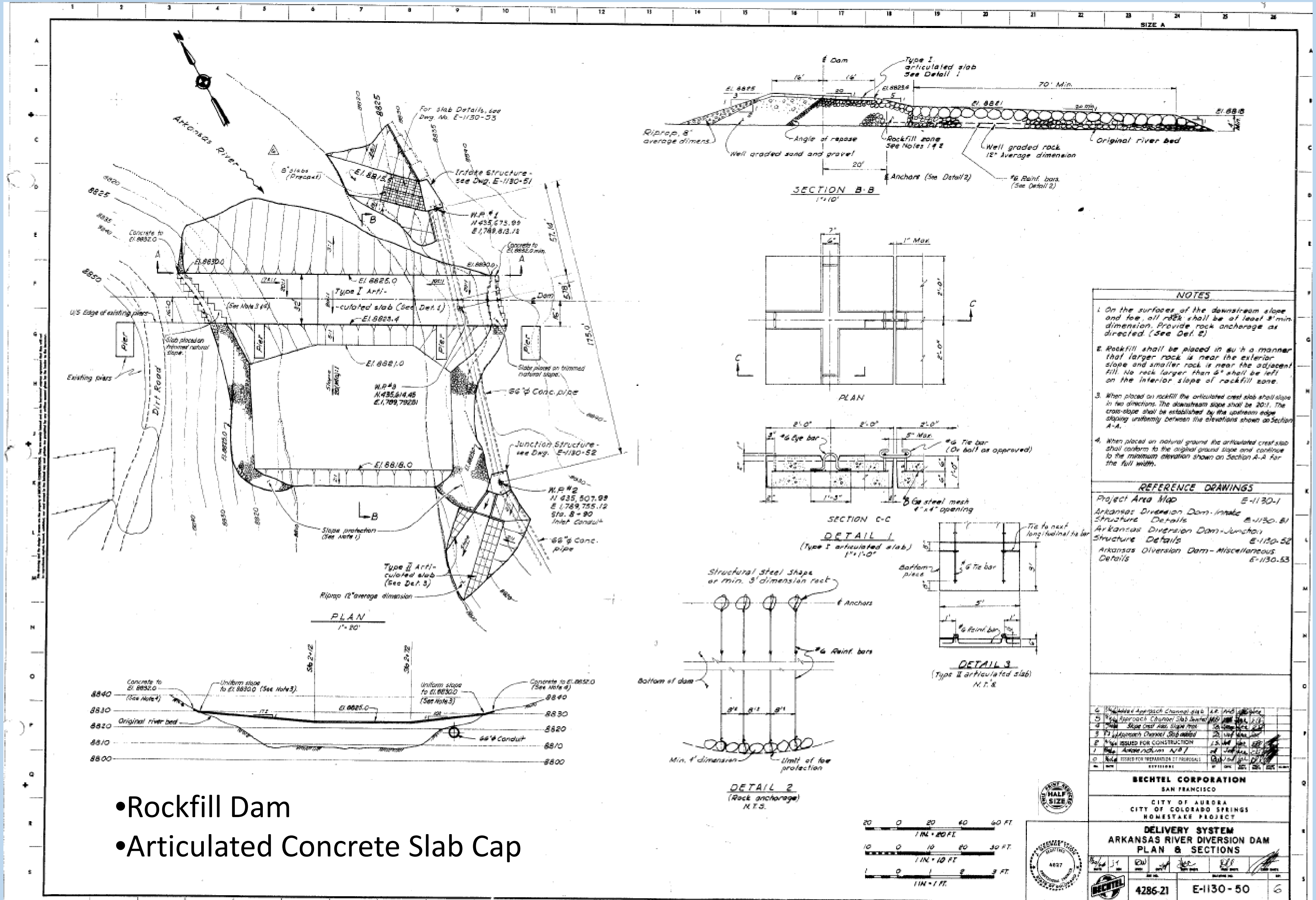


HOMESTAKE WATER PROJECT

AURORA WATER

Colorado Springs Utilities

Original Design Intent, Bechtel c. 1965



- Rockfill Dam
- Articulated Concrete Slab Cap

Pre-Project Conditions

Pre-Project Conditions

HOMESTAKE WATER PROJECT

AURORA WATER

Colorado Springs Utilities

Pre-Project Conditions

HOMESTAKE WATER PROJECT

AURORA WATER

Colorado Springs Utilities

Pre-Project Conditions

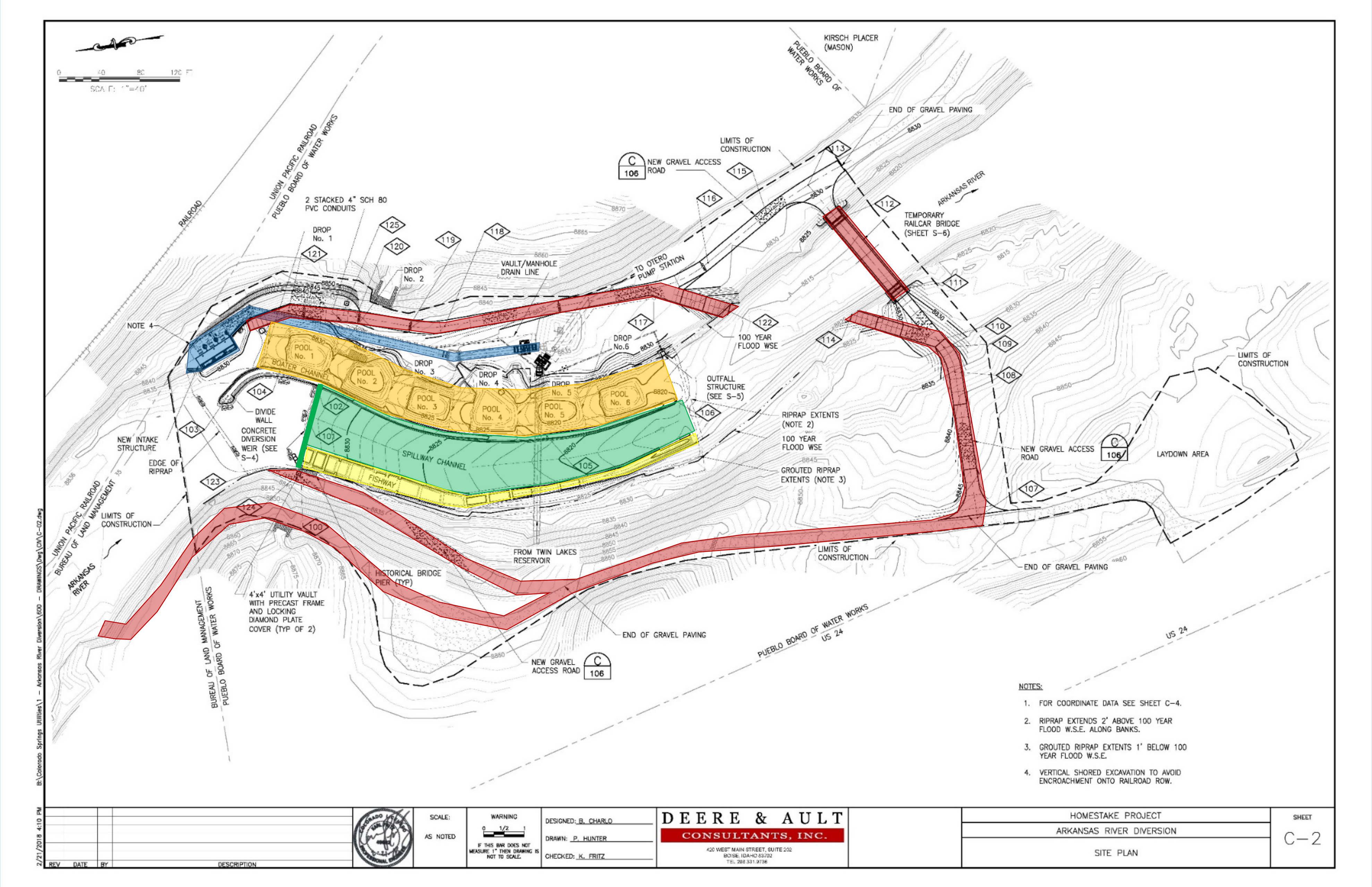
HOMESTAKE WATER PROJECT

AURORA WATER

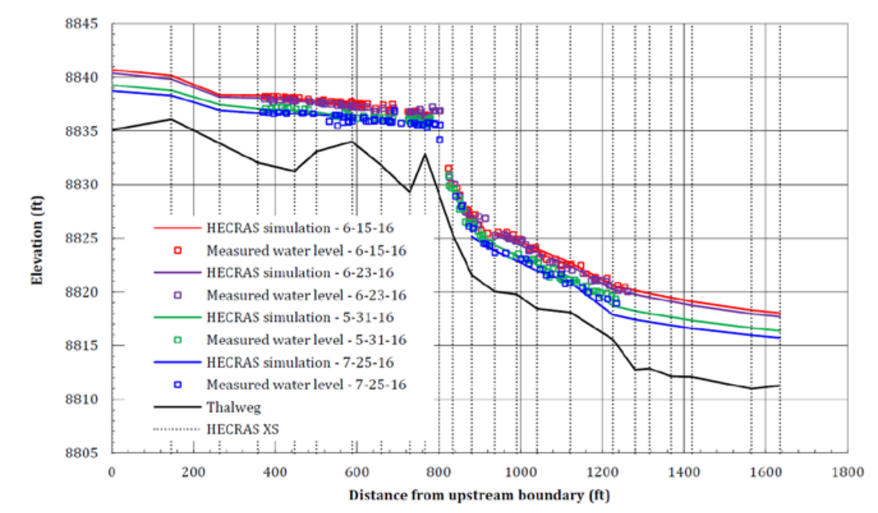
Colorado Springs Utilities

Site Plan and Key Project Elements

- Diversion Weir
- Intake and Pipeline Connection
- Spillway
- Fishway
- Boat Chute
- Site Access (Temporary Bridge)
- Portage Landings and Paths



Design Process



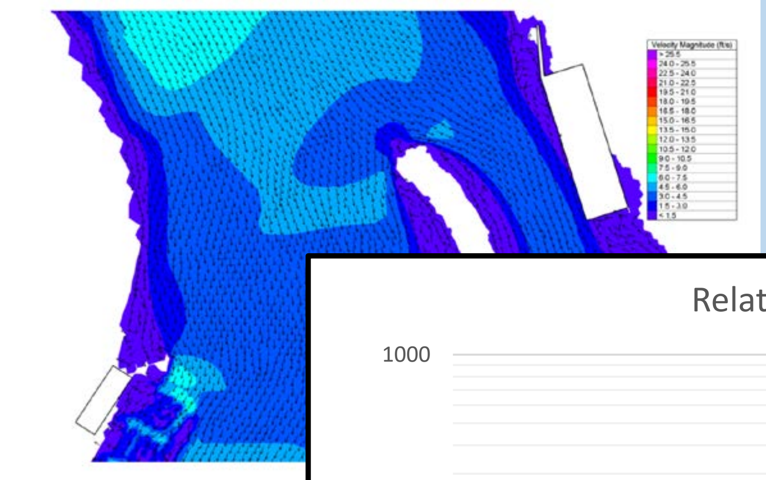
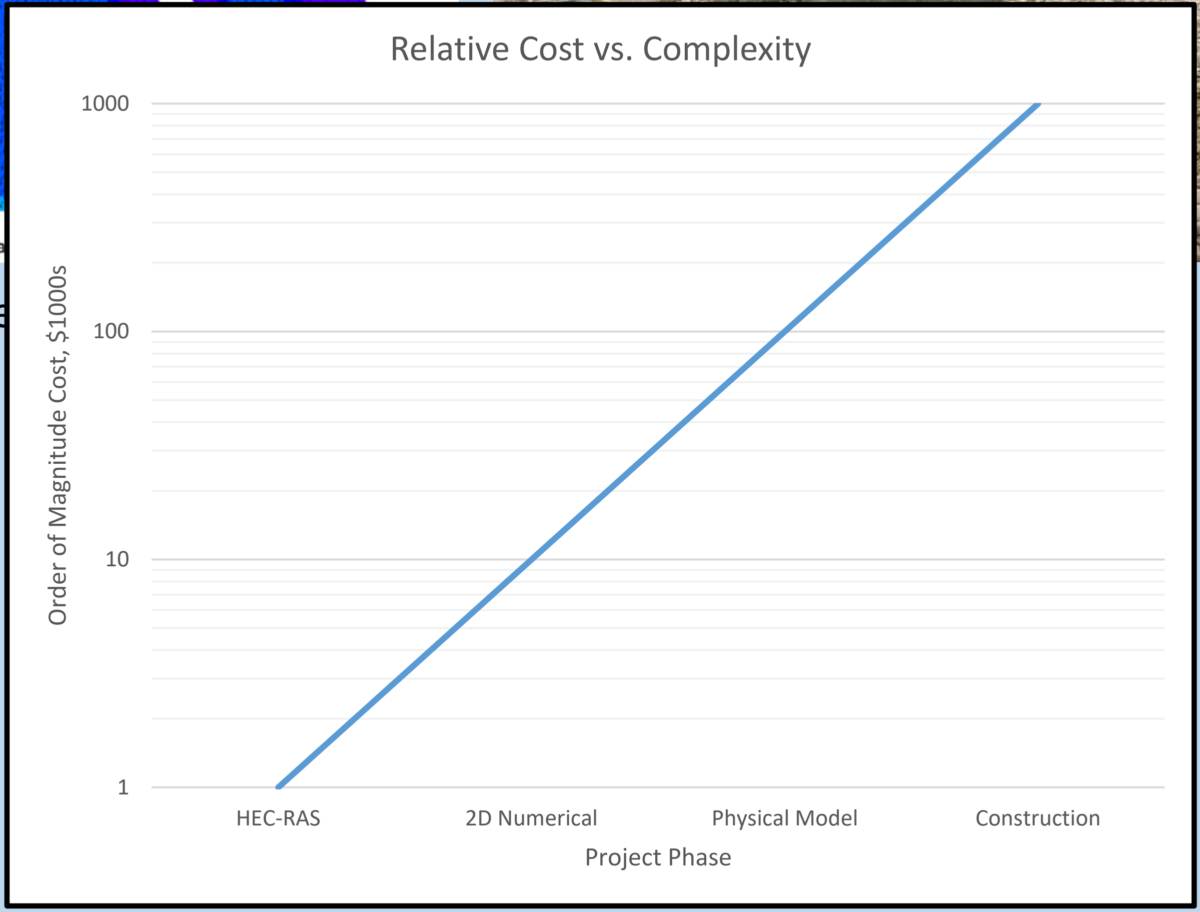
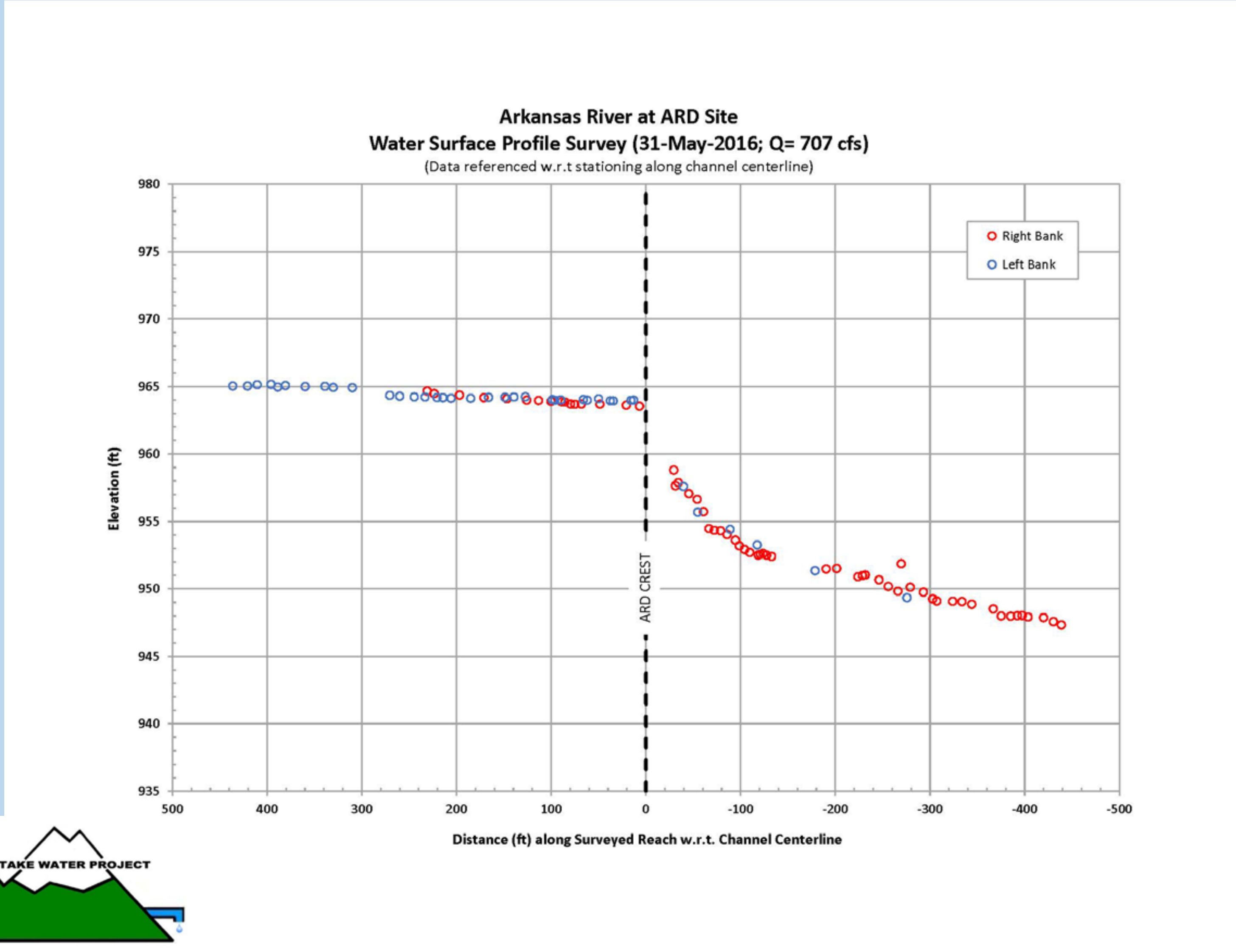


Figure 7: Depth Average Velocity Ma



- Objective: satisfy risk tolerance of owner and partne recreational, in-channel project
- Utilized tiered hydraulic modeling with design refine
  - Site Survey, Water Surface Profiles
  - 1D, HEC-RAS to establish boundary conditions
  - Preliminary layout and site grading
  - 2D, TELEMAC-2D
  - Refine layout and site grading
  - 1/12th scale Physical Model
  - Refine layout and site grading
  - Construction
    - Commissioning and Testing
    - Final Adjustments as necessary
  - Open for Public Use

Water Surface Elevation Survey and Profiles

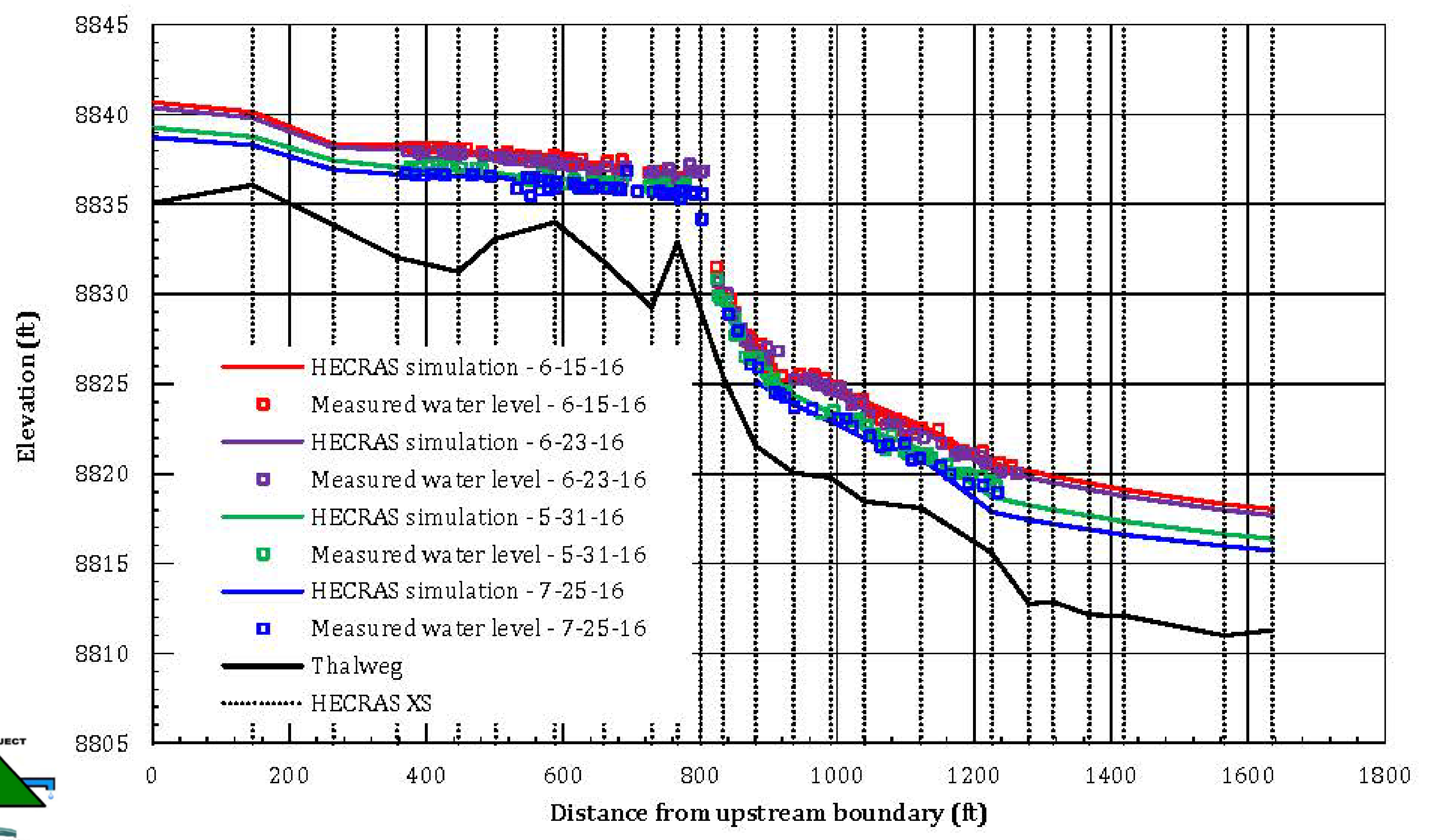


HOMESTAKE WATER PROJECT

AURORA WATER

Colorado Springs Utilities

1-Dimensional Hydraulic Modeling



HOMESTAKE WATER PROJECT

AURORA WATER Colorado Springs Utilities

2-Dimensional Numerical Modeling

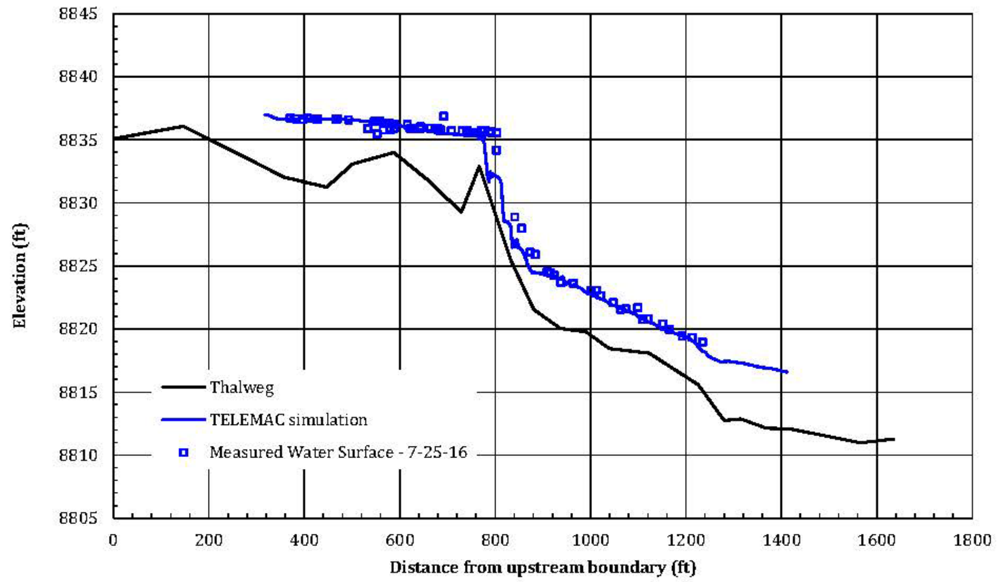


Figure 2: Two Dimensional Simulated Water Surface Profile

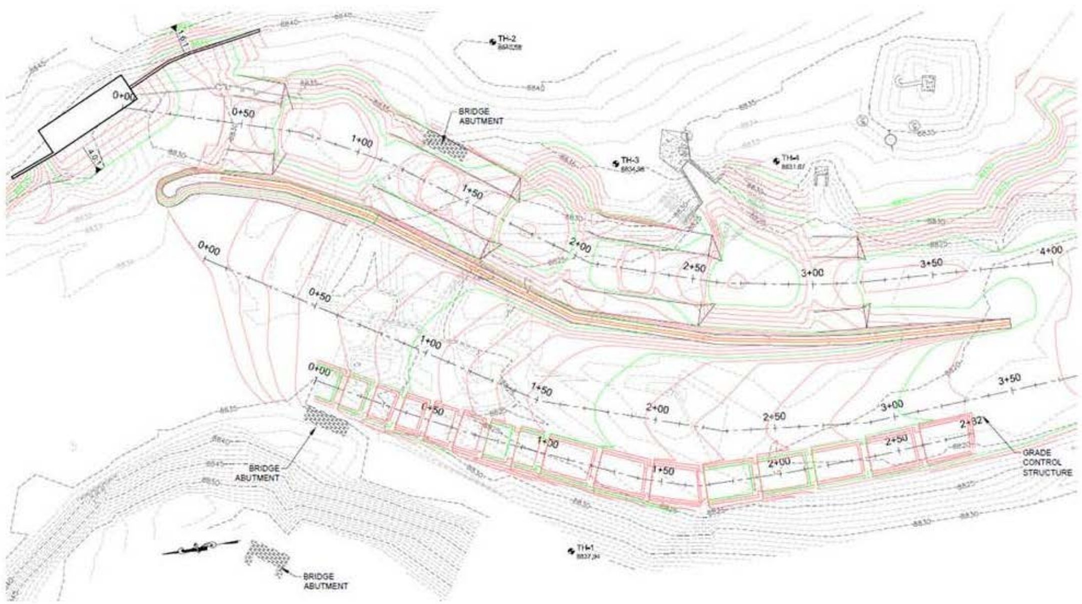


Figure 3: Layout of Initial Conceptual Design on Existing Contours

- Model TELEMAC-2D, Frontend Blue Kenue
- Existing conditions model - Mesh size 1-2m
- Bed roughness calibrated to June 2016 observations (1680 cfs)
- First iteration of design, evaluated using 2D model and refined

HOMESTAKE WATER PROJECT

AURORA WATER

Colorado Springs Utilities

Boat Chute Refinements

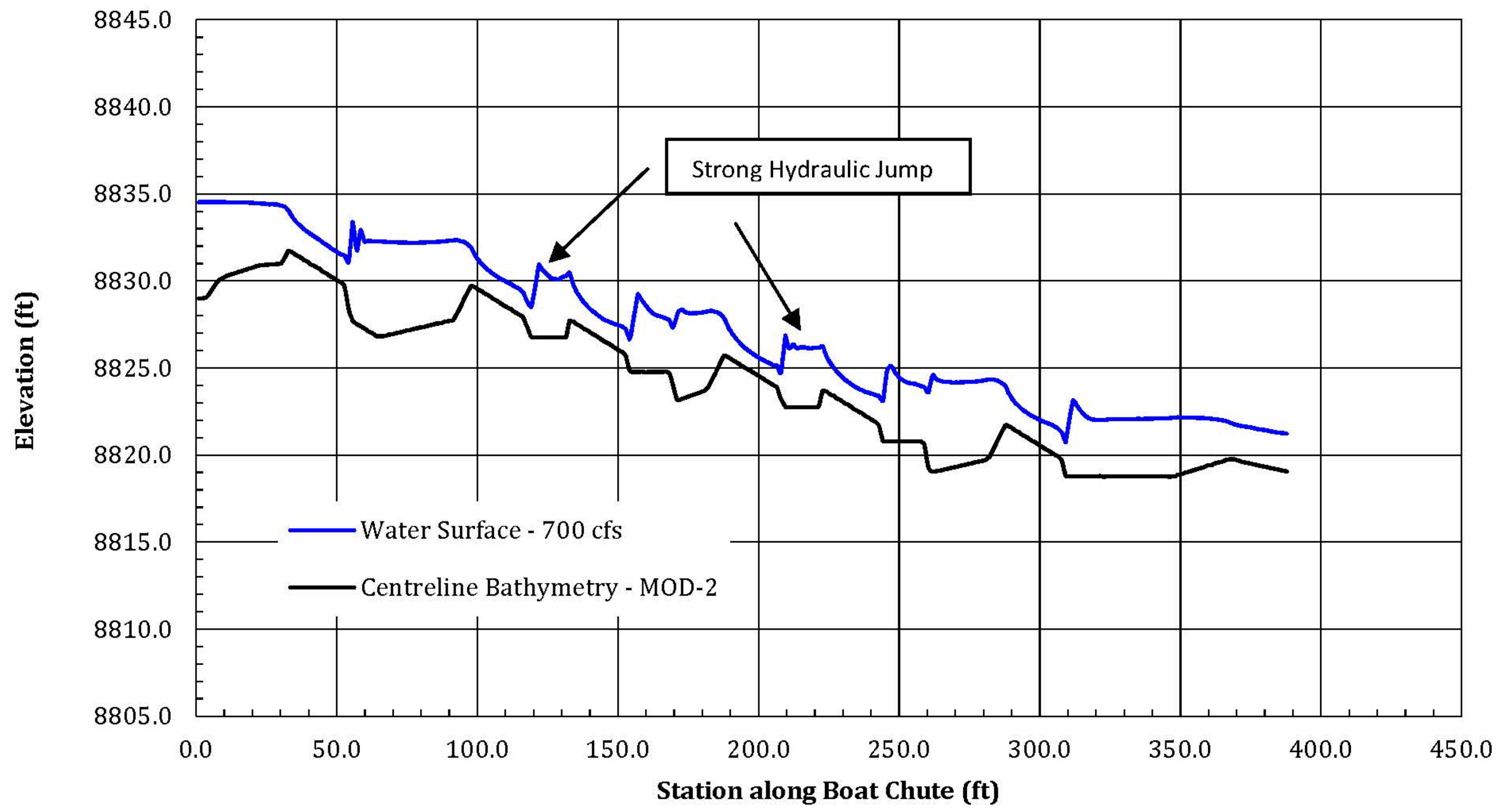


Figure 6: Simulated Boat Chute Water Surface Profile for 700 cfs

HOMESTAKE WATER PROJECT

AURORA WATER Colorado Springs Utilities

Intake refinements from 2D modeling

Figure 4: Depth Avera
700 cfs.

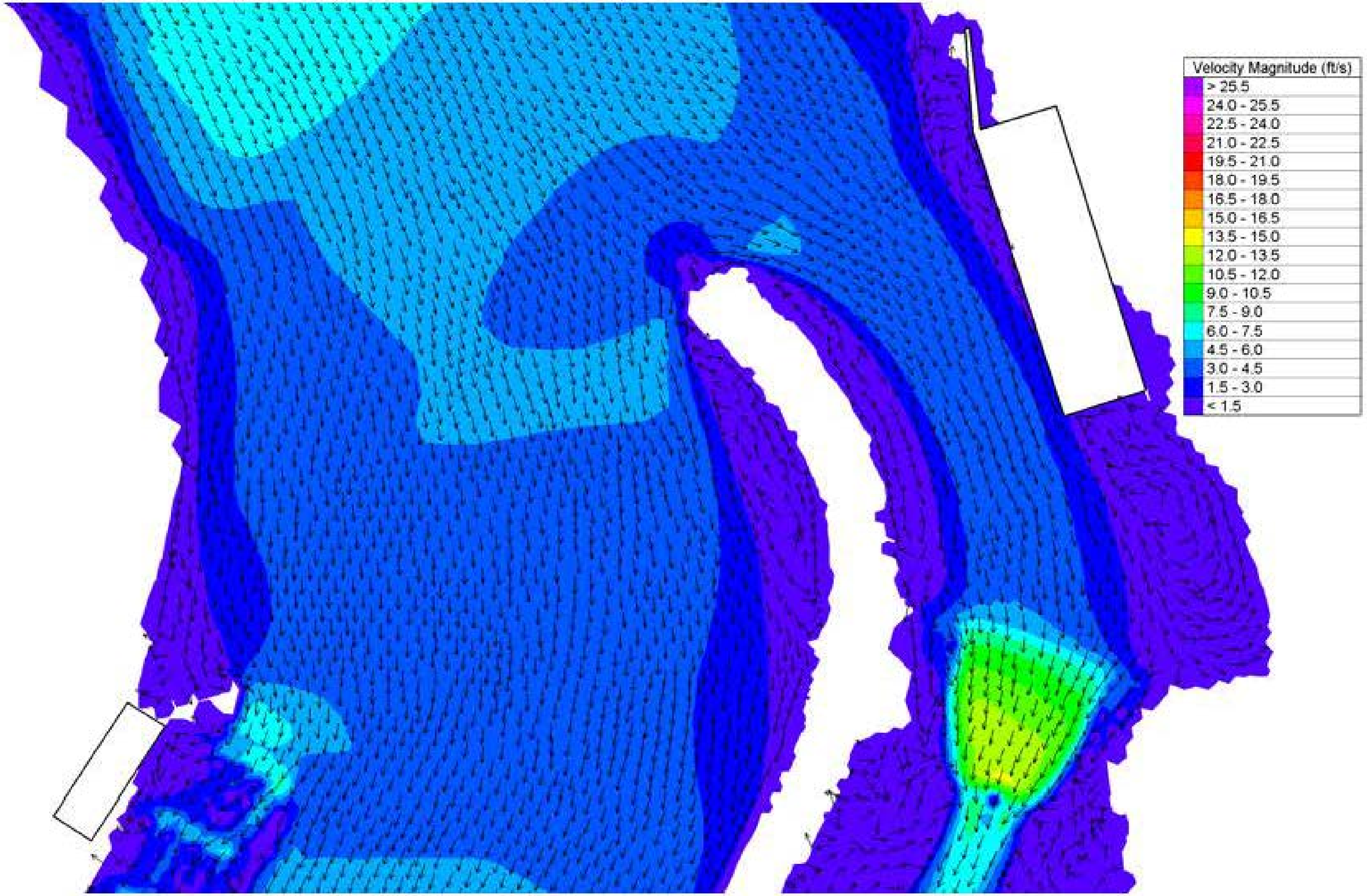
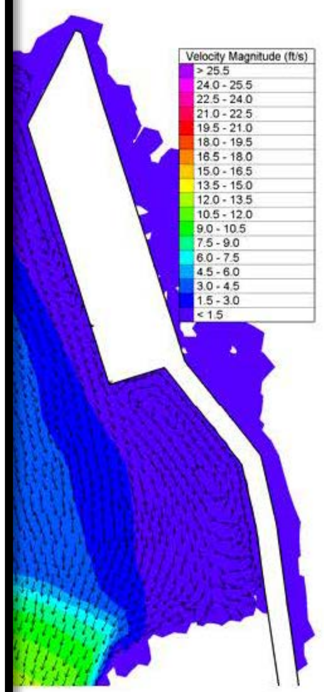


Figure 7: Depth Average Velocity Magnitude and Unit Vectors for MOD-3 Design at 700 cfs.



r MOD-1 Design at 700 cfs

Scaled Physical Modeling

- Similitude: For a free surface (open channel flow) inertial and gravitational forces are dominant. Froude number therefore must be equal between model and prototype.
- $Fr = \frac{Fm}{Fp} = 1, F = \frac{U}{\sqrt{gL}}$
  - F = Froude number
  - U = characteristic velocity
  - g = gravitational acceleration
  - L = characteristic length

Parameter	Relation	Ratio
Length	Lr	1:12
Velocity, Time	Lr^1/2	1:3.46
Discharge	Lr^5/2	1:498.8
Manning's n	Lr^1/6	1:1.51

Model Construction and Refinement

HOMESTAKE WATER PROJECT

AURORA WATER

Colorado Springs Utilities

Hydraulic Performance, 200-4175cfs

HOMESTAKE WATER PROJECT
AURORA WATER
Colorado Springs Utilities

~4000 cfs

HOMESTAKE WATER PROJECT

AURORA WATER

Colorado Springs Utilities

Refinements: Boat Chute, 700cfs

Hydraulic Performance, Sediment Management, Navigability

HOMESTAKE WATER PROJECT

AURORA WATER

Colorado Springs Utilities

Initial Intake Performance

Flow = 700 cfs; Intake withdrawal = 185 cfs

HOMESTAKE WATER PROJECT

AURORA WATER

Colorado Springs Utilities

Intake Performance, Scour

HOMESTAKE WATER PROJECT

AURORA WATER

Colorado Springs Utilities

Physical Model Results

- Good Hydraulic Performance
- Robust, flushing wave shapes (non-retentive)
- low sensitivity to changes upstream and downstream
- Effective Flow split
- Fish passage in conformance with design criteria
- Spillway and boat chute in conformance with design criteria
- Acceptable self scouring performance in front of intake
- Overall, an effective design that meets all objectives and satisfies risk tolerance.

HOMESTAKE WATER PROJECT

AURORA WATER

Colorado Springs Utilities

Physical modeling provided good insight into the performance of the design and allowed the development and testing of multiple improvements to the original design.

Lessons Learned

- Each “D” adds an order of magnitude to the cost
- Scaled physical modeling provided opportunities for refinement / improvement not available from 2D model
- Physical model cost is small compared to the cost (and risk to users) resulting from poor performance and need to make adjustments in the future.
- The tiered approach allowed the Owner to minimize risk (risk to recreational users and risk of un-expected re-construction)

Thanks to:

- Homestake Project (Owner)
  - City of Aurora
  - Colorado Springs Utilities
- SG1 Water Consulting (Owners Rep)
- Design Team
  - Deere and Ault (Lead Engineer)
  - Recreation Engineering and Planning
  - Northwest Hydraulics Corporation
- Partners and Stakeholders
  - CPW, AHRA
  - CWCB
  - USACE
  - Chaffee County
  - Board of Water Works of Pueblo, CO

HOMESTAKE WATER PROJECT

AURORA WATER

Colorado Springs Utilities



A New Look to Manning ‘n’ Values

Craig Jacobson, PE, CFM, ICON Engineering

Jennifer Bousselot, Ph.D., Colorado State University

Colorado State University

ICON ENGINEERING, INC.

Introduction

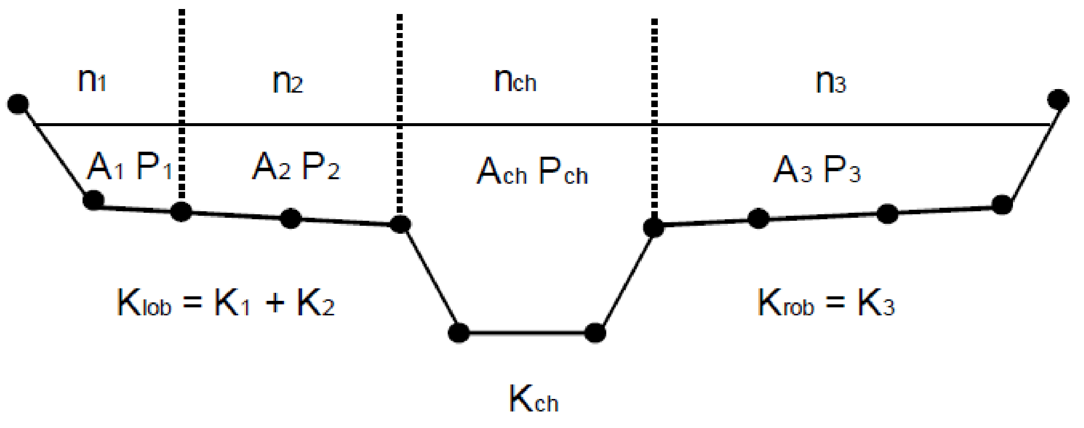
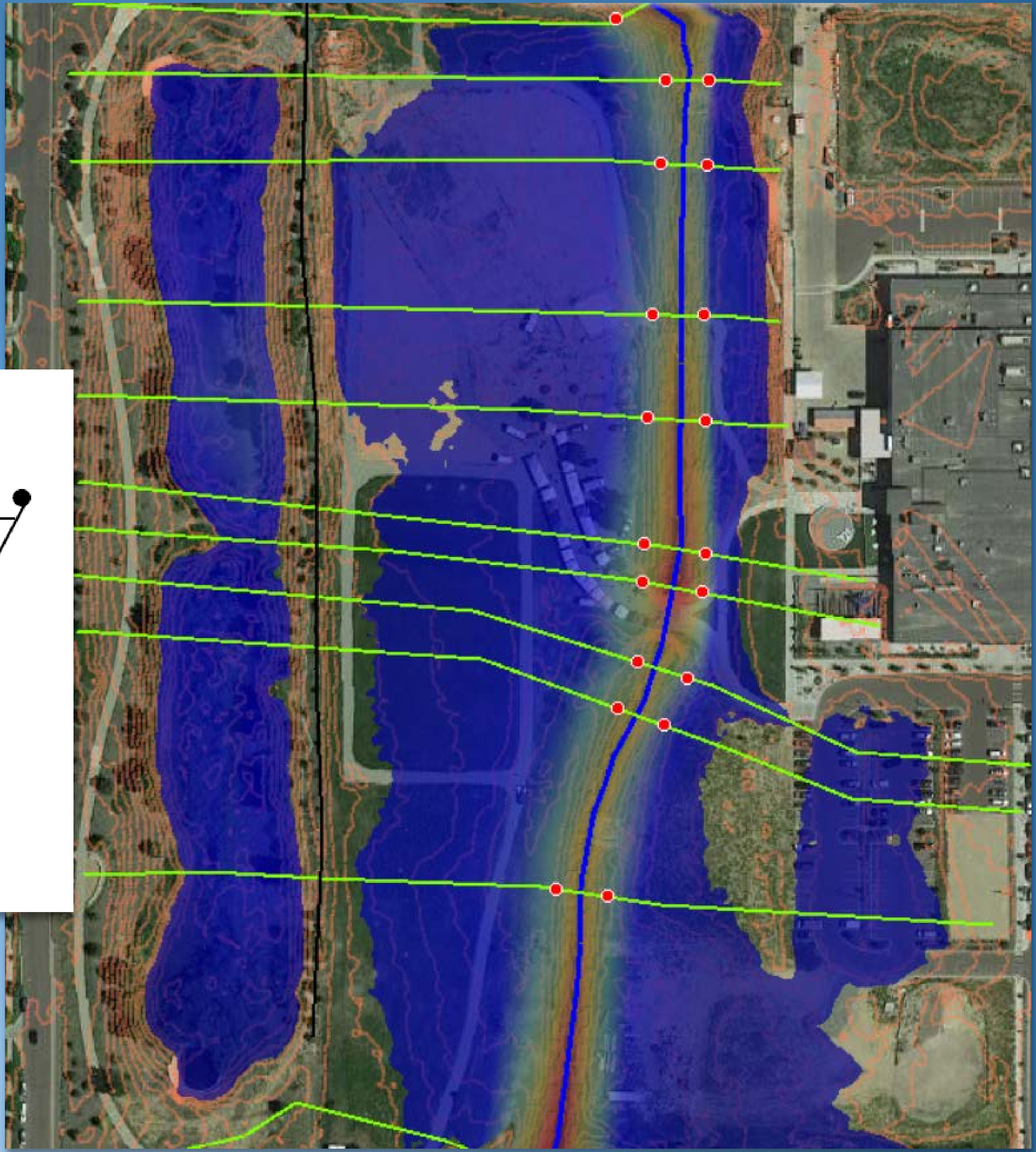


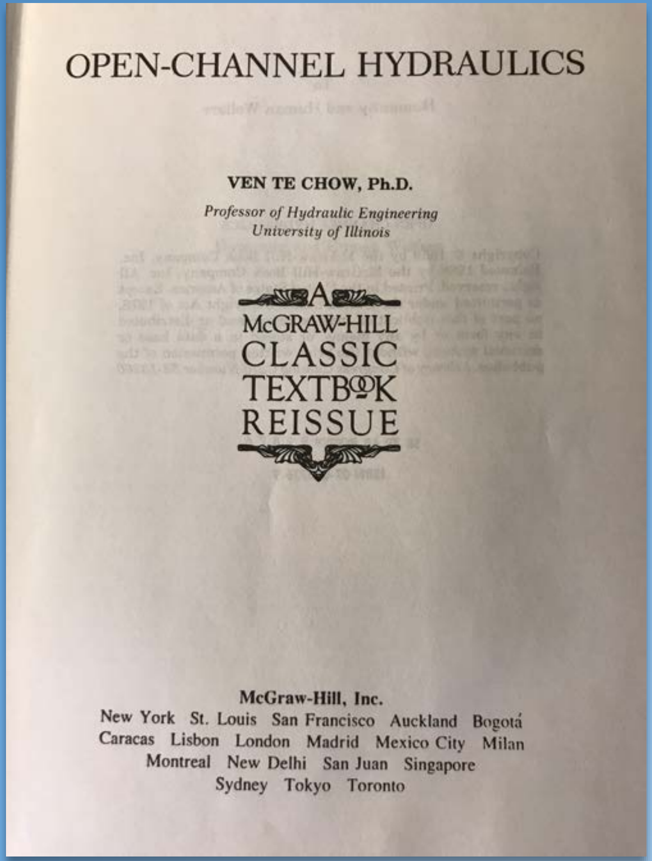
Figure 2-2 HEC-RAS Default Conveyance Subdivision Method



ICON ENGINEERING, INC.

Introduction

- **Chow 1959 – Open Channel Hydraulics**



Type of Channel and Description	Minimum	Normal	Maximum
A. *Natural Streams*			
1. **Main Channels**			
a. Clean, straight, full, no rifts or deep pools	0.025	0.030	0.033
b. Same as above, but more stones and weeds	0.030	0.035	0.040
c. Clean, winding, some pools and shoals	0.033	0.040	0.045
d. Same as above, but some weeds and stones	0.035	0.045	0.050
e. Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. Same as "d" but more stones	0.045	0.050	0.060
g. Sluggish reaches, weedy. deep pools	0.050	0.070	0.080
h. Very weedy reaches, deep pools, or floodways with heavy stands of timber and brush	0.070	0.100	0.150
2. **Flood Plains**			
a. Pasture no brush			
1. Short grass	0.025	0.030	0.035
2. High grass	0.030	0.035	0.050
b. Cultivated areas			
1. No crop	0.020	0.030	0.040
2. Mature row crops	0.025	0.035	0.045
3. Mature field crops	0.030	0.040	0.050
c. Brush			
1. Scattered brush, heavy weeds	0.035	0.050	0.070
2. Light brush and trees, in winter	0.035	0.050	0.060
3. Light brush and trees, in summer	0.040	0.060	0.080
4. Medium to dense brush, in winter	0.045	0.070	0.110
5. Medium to dense brush, in summer	0.070	0.100	0.160
d. Trees			
1. Cleared land with tree stumps, no sprouts	0.030	0.040	0.050
2. Same as above, but heavy sprouts	0.050	0.060	0.080
3. Heavy stand of timber, few down trees, little undergrowth, flow below branches	0.080	0.100	0.120
4. Same as above, but with flow into branches	0.100	0.120	0.160
5. Dense willows, summer, straight	0.110	0.150	0.200
3. **Mountain Streams, no vegetation in channel, banks usually steep, with trees and brush on banks submerged**			
a. Bottom: gravels, cobbles, and few boulders	0.030	0.040	0.050
b. Bottom: cobbles with large boulders	0.040	0.050	0.070

Introduction

- **Cowans Procedure 1956**

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m \qquad (3\text{-}1)$$

Where: n_b = Base value for n for a straight uniform, smooth channel in natural materials

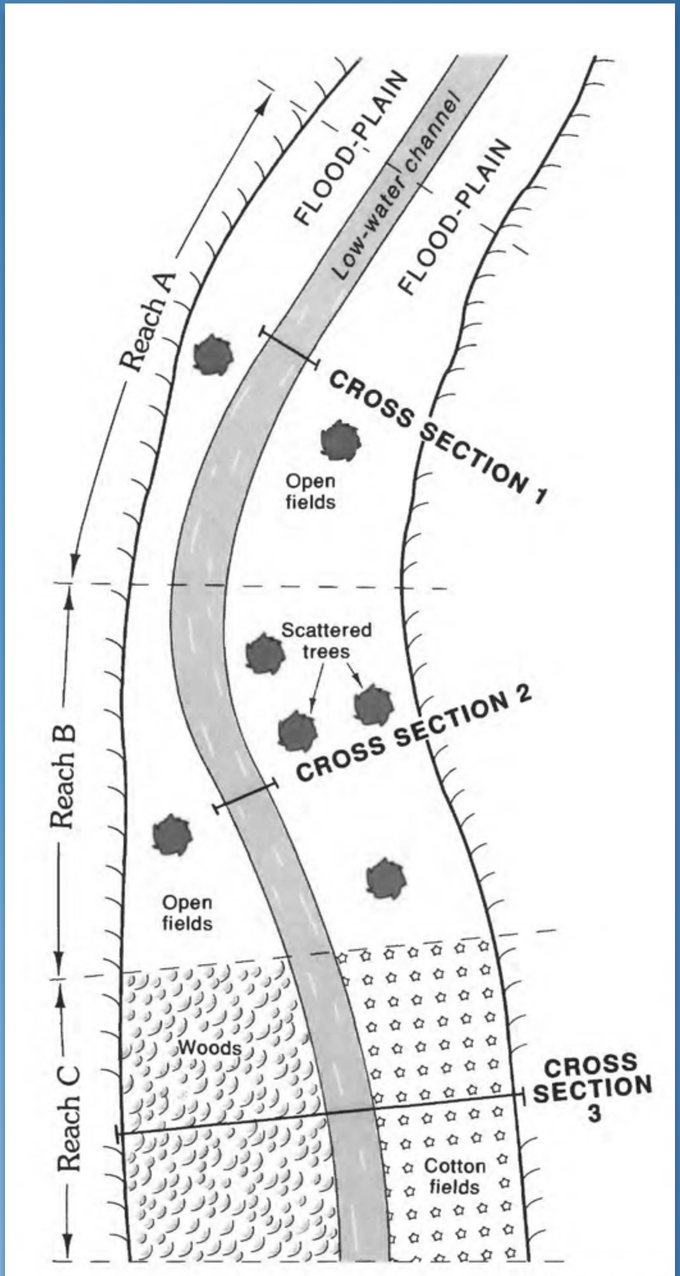
n_1 = Value added to correct for surface irregularities

n_2 = Value for variations in shape and size of the channel

n_3 = Value for obstructions

n_4 = Value for vegetation and flow conditions

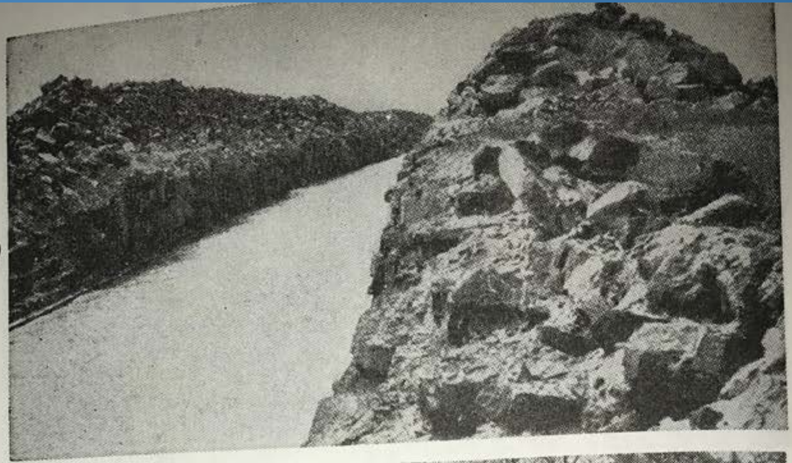
m = Correction factor to account for meandering of the channel



(22)

(23)

(24)



(19)

(20)

(21)

(Chow 1959)

(22)

n = 0.11

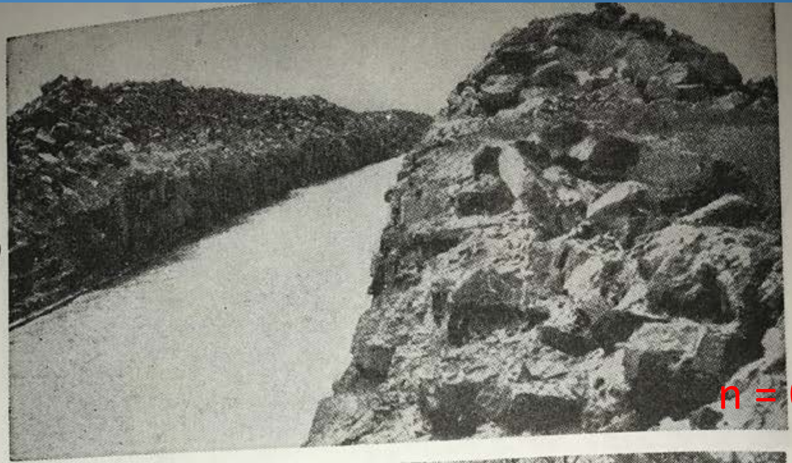
(23)

n = 0.125

(24)

n = 0.15

(19)



n = 0.05

(20)

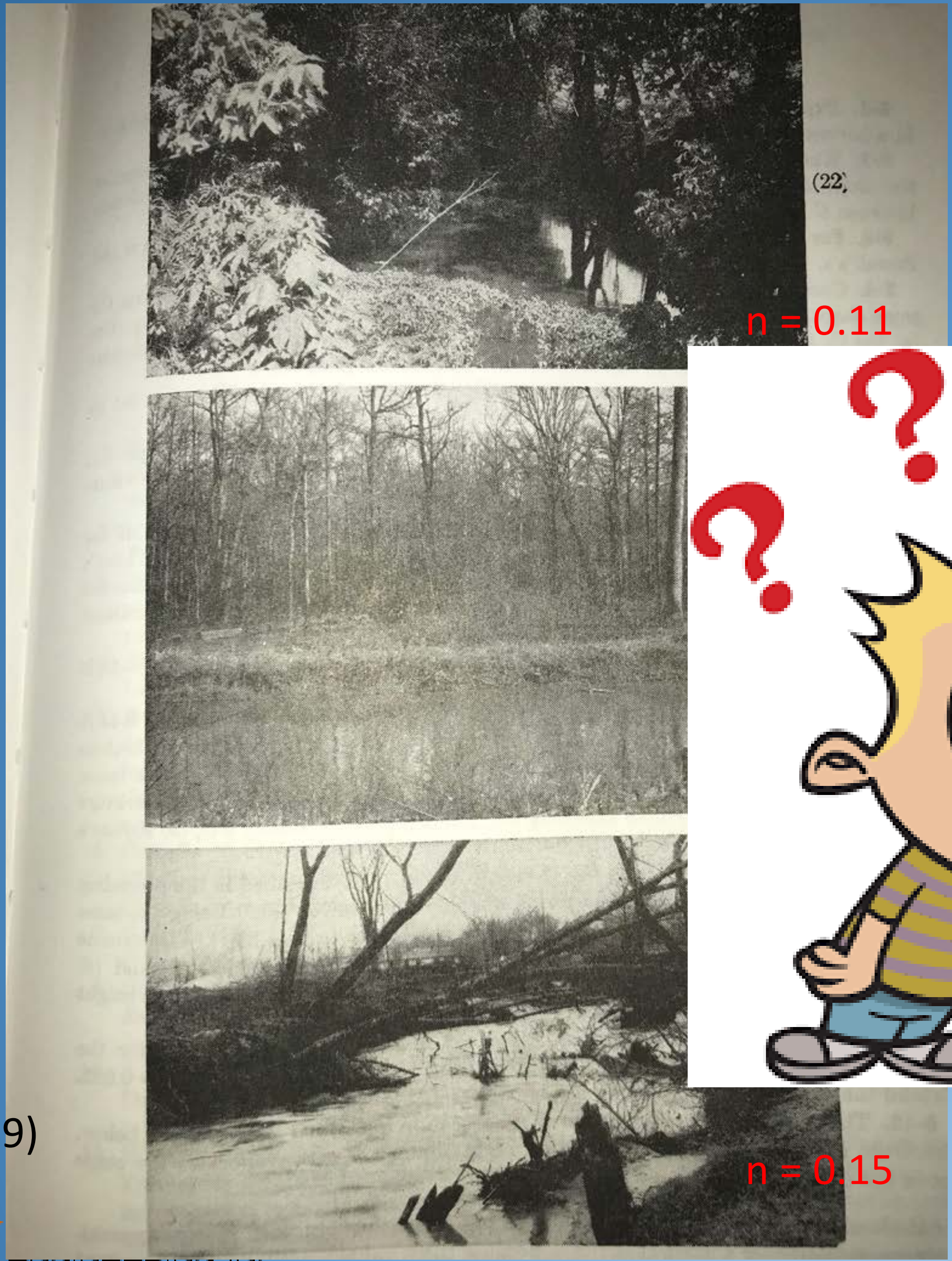
n = 0.06

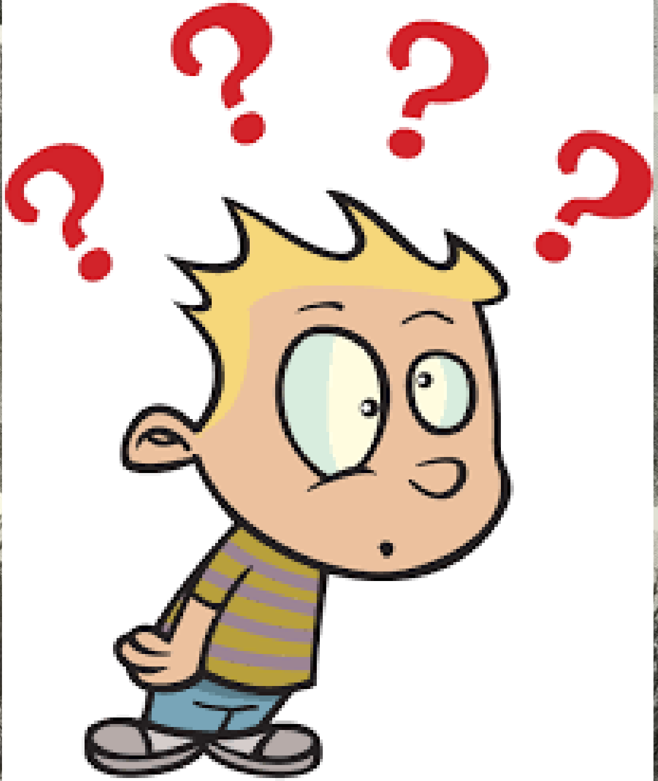
(21)

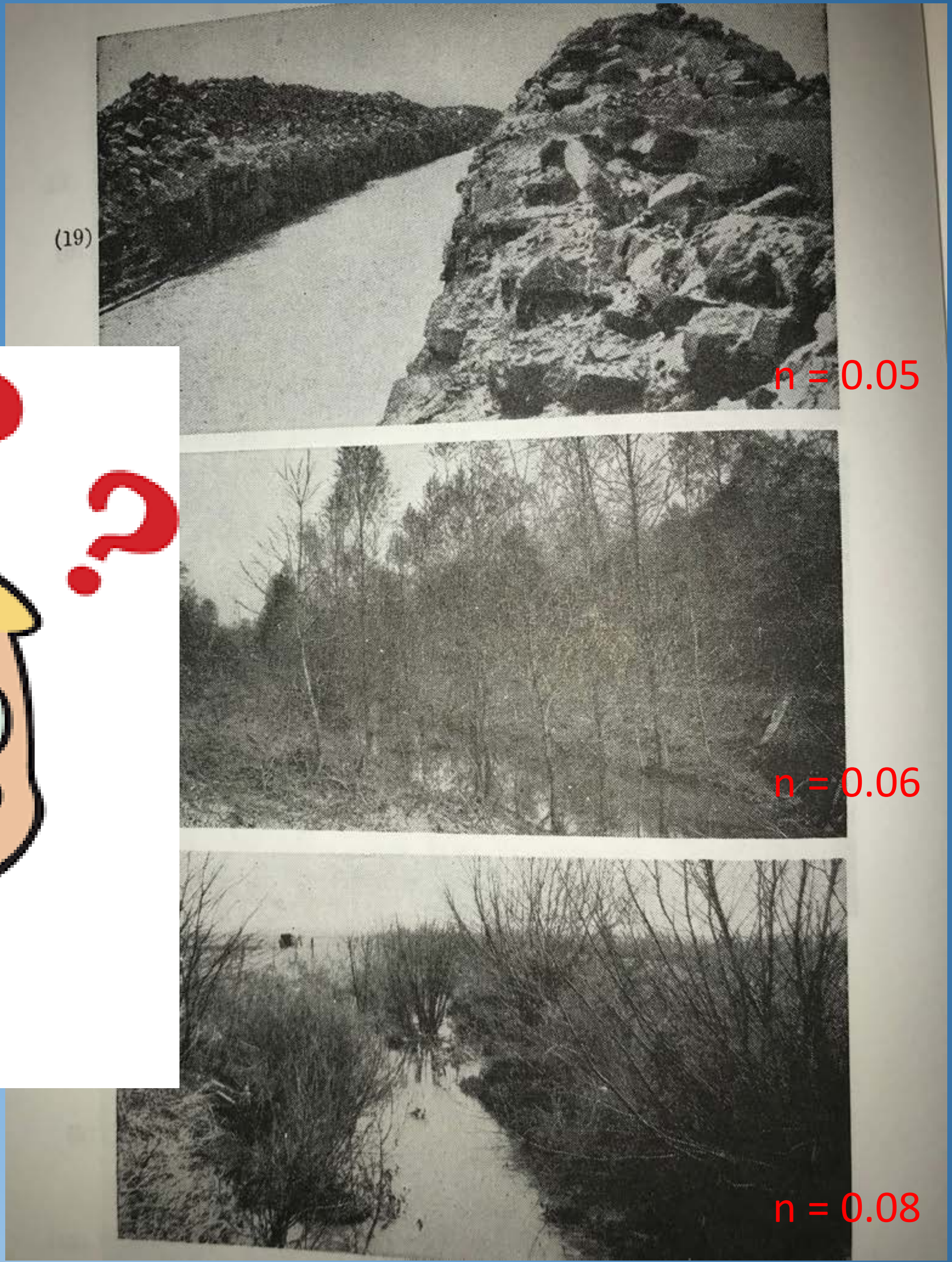
n = 0.08

(Chow 1959)

ICON ENGINEERING, INC.



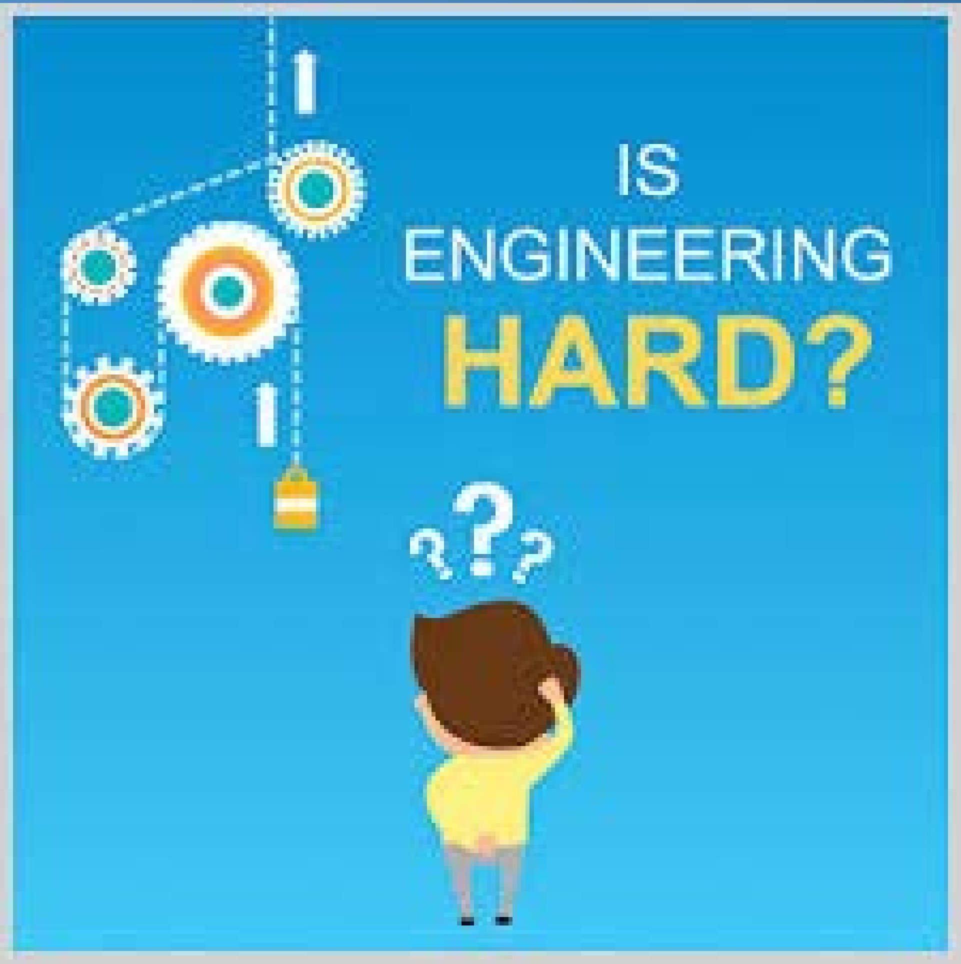




(Chow 1959)

Introduction

- **Engineering Judgement**
- **Rules of Thumb**



ICON ENGINEERING, INC.

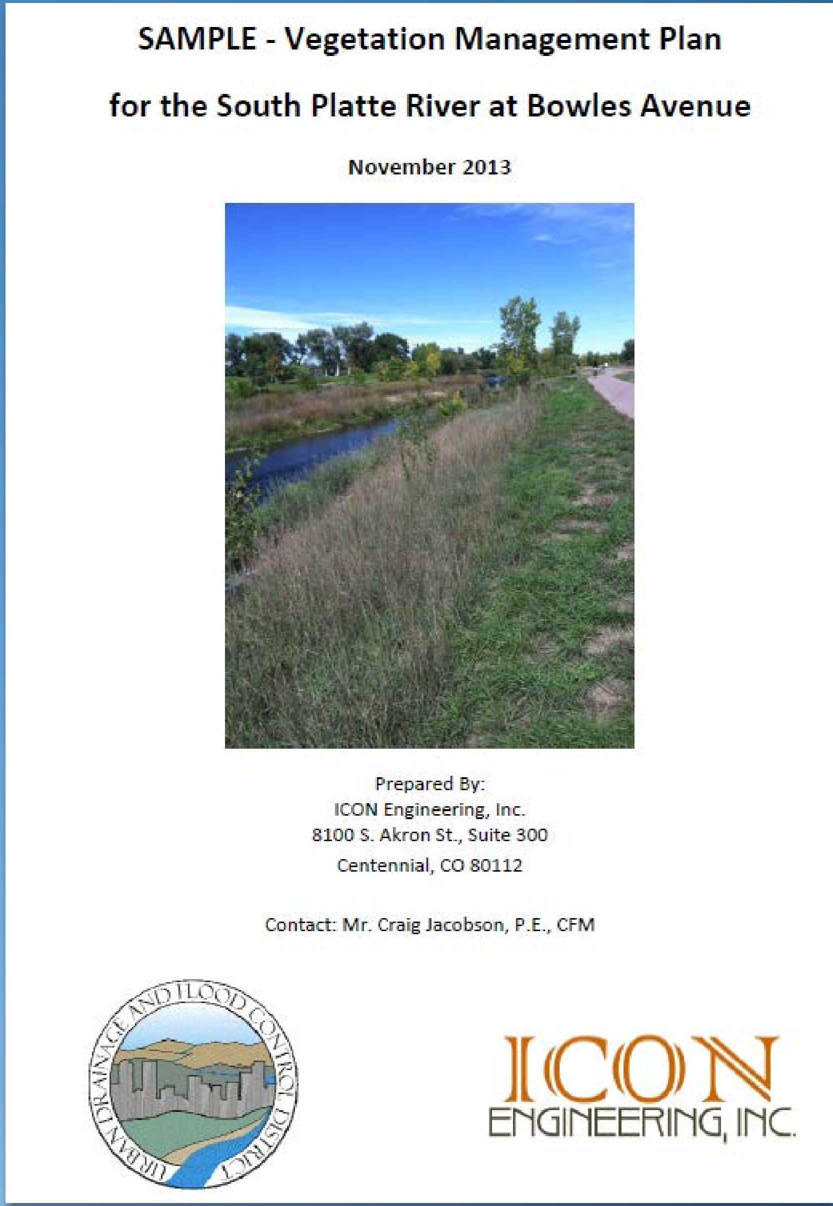
Introduction

Introduction

ICON ENGINEERING, INC.

Project Approach

- **Document Review**
  - **COE Documentation**
  - **USGS Documentation**
- **Identification of Technical Approach**
- **Field Review**
  - **Characteristics of vegetation**
- **Relationship of Manning's n to:**
  - **Specific local vegetation communities,**
  - **Guidance for varying inundation depths**



SAMPLE - Vegetation Management Plan

for the South Platte River at Bowles Avenue

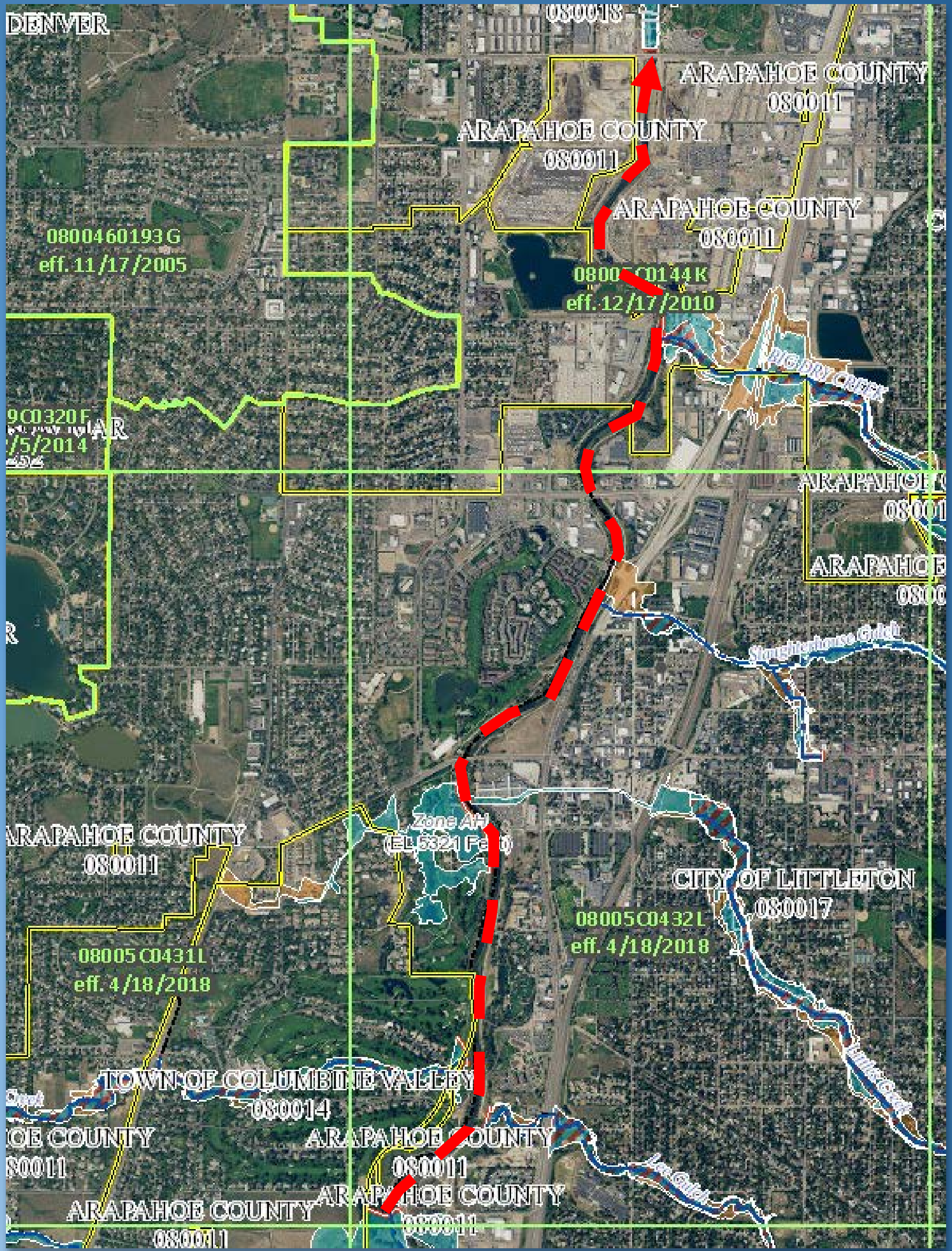
November 2013

Prepared By:
ICON Engineering, Inc.
8100 S. Akron St., Suite 300
Centennial, CO 80112

Contact: Mr. Craig Jacobson, P.E., CFM

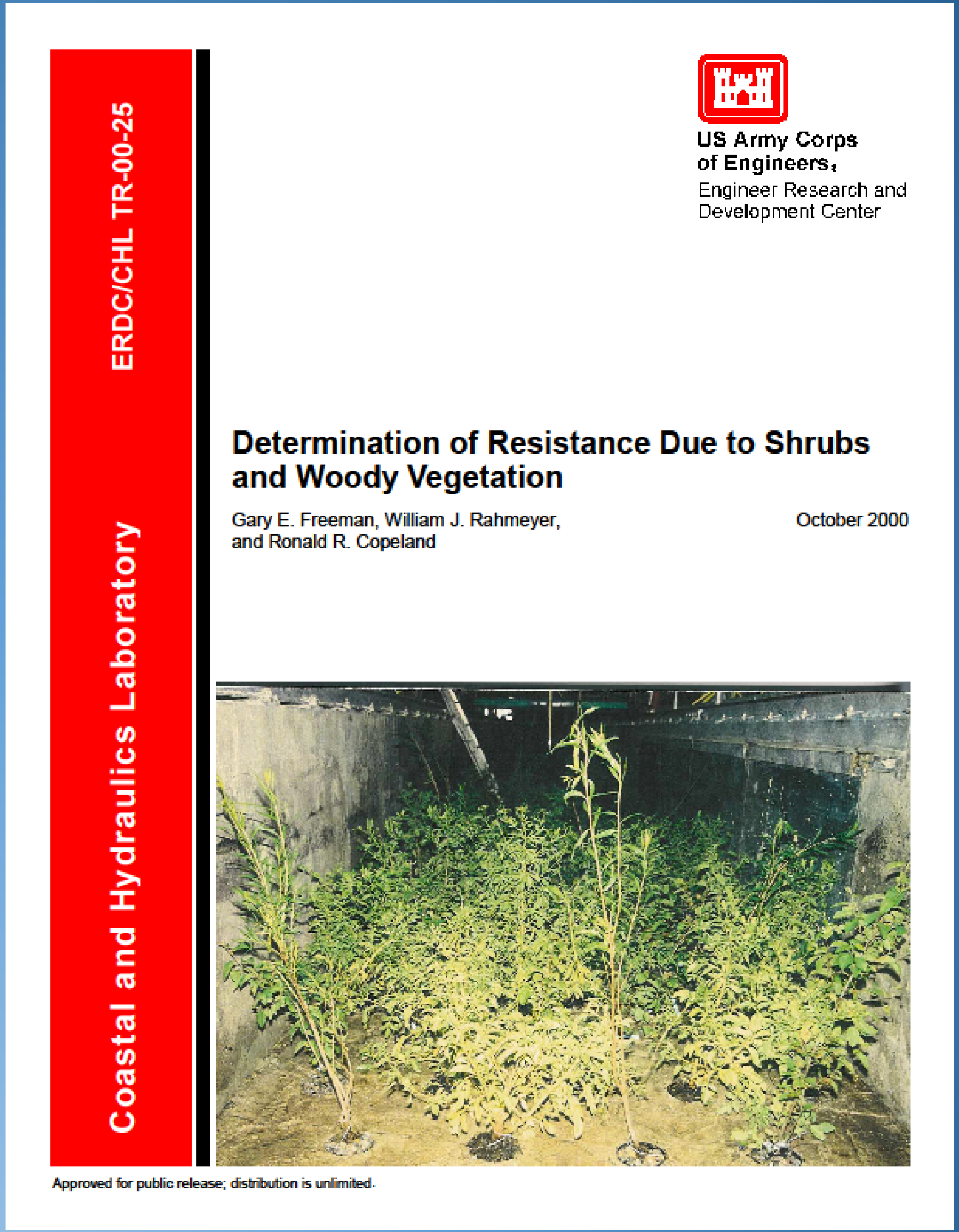
Project Approach

- **Document Review**
  - **COE Documentation**
  - **USGS Documentation**
- **Identification of Technical Approach**
- **Field Review**
  - **Characteristics of vegetation**
- **Relationship of Manning's n to:**
  - **Specific local vegetation communities,**
  - **Guidance for varying inundation depths**



COE TR-00-25 (2000)

- **Purpose:**
  - **Research roughness to use for woody vegetation, shrubs and other environmental or aesthetically desirable plants**
  - **Investigate the effects of flow resistance losses and drag – Utah Water Research Lab**
  - **Flume results from more than 220 experiments and 20 plant species**
  - **Established equations as a function of slope and depth**


ERDC/CHL TR-00-25

Coastal and Hydraulics Laboratory

US Army Corps of Engineers
Engineer Research and Development Center

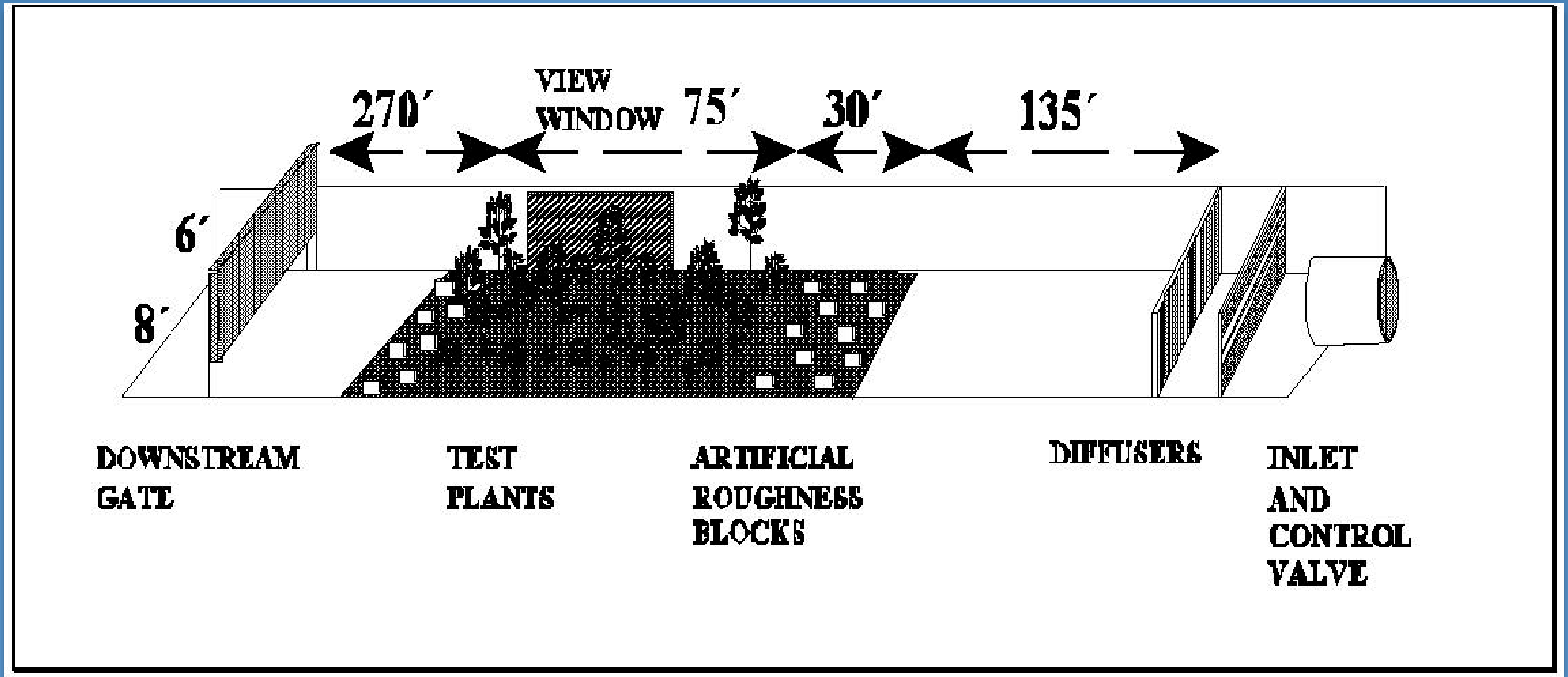
Determination of Resistance Due to Shrubs and Woody Vegetation

Gary E. Freeman, William J. Rahmeyer, and Ronald R. Copeland

October 2000

Approved for public release; distribution is unlimited.

COE TR-00-25 (2000)



COE TR-00-25 (2000)

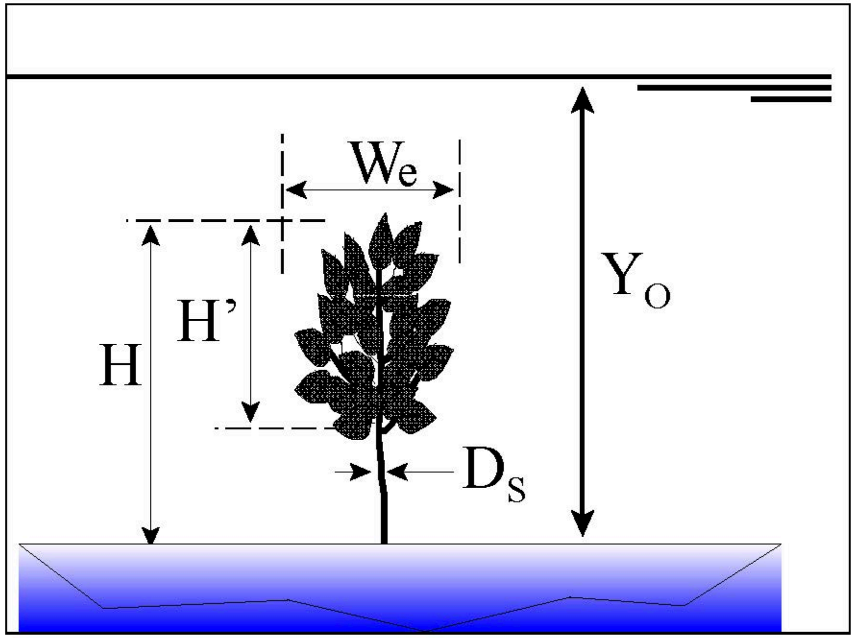


Figure 1. Plant dimension definitions for submerged plants

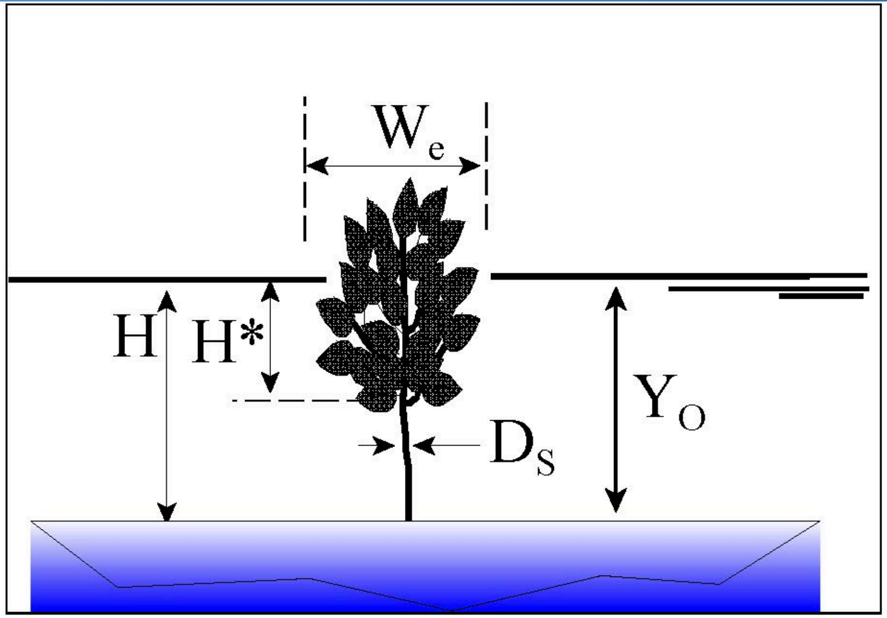


Figure 2. Plant dimension definitions for partially submerged plants

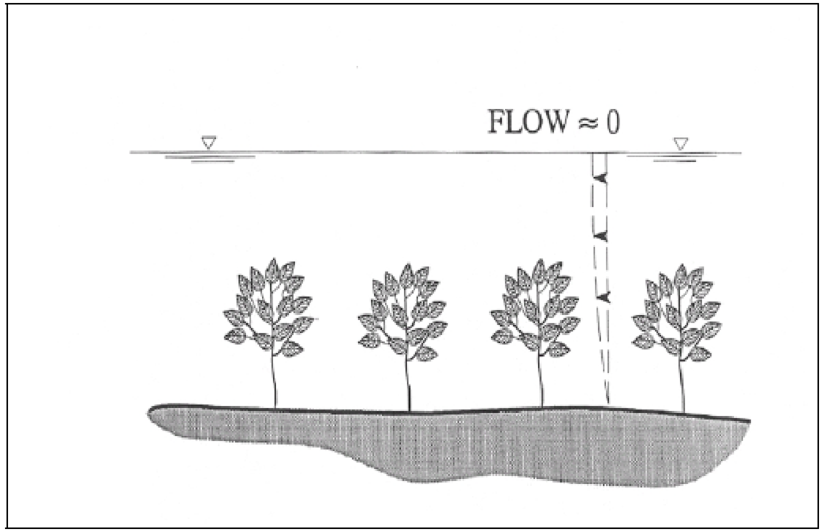


Figure 6. Plants at zero flow

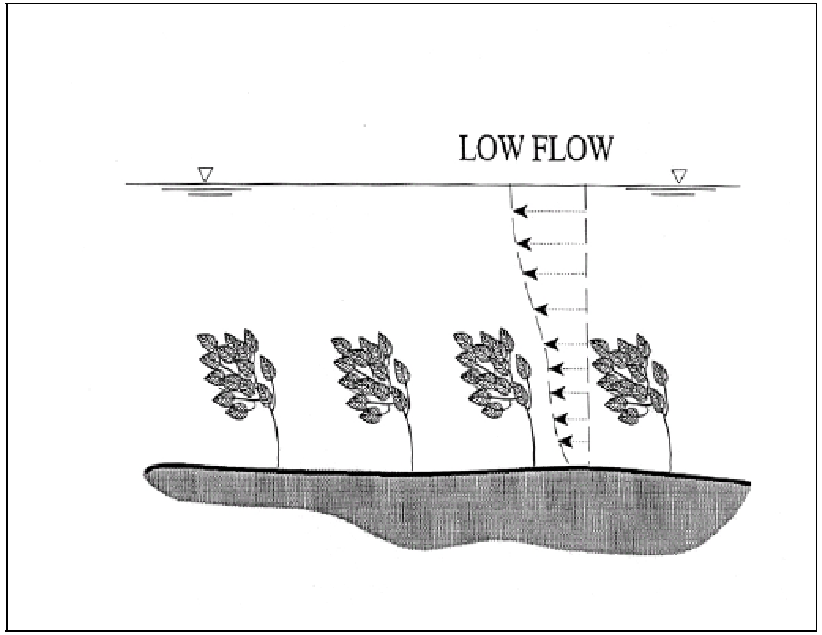


Figure 7. Plants at low flow

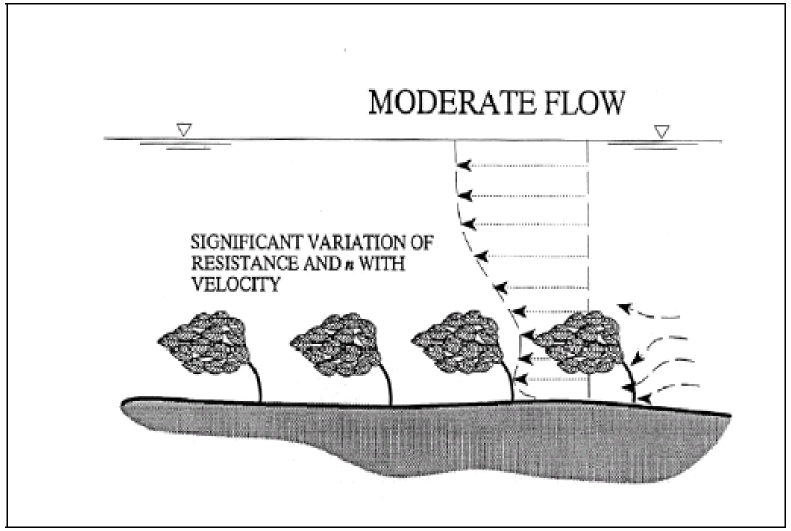


Figure 8. Plants at moderate flow

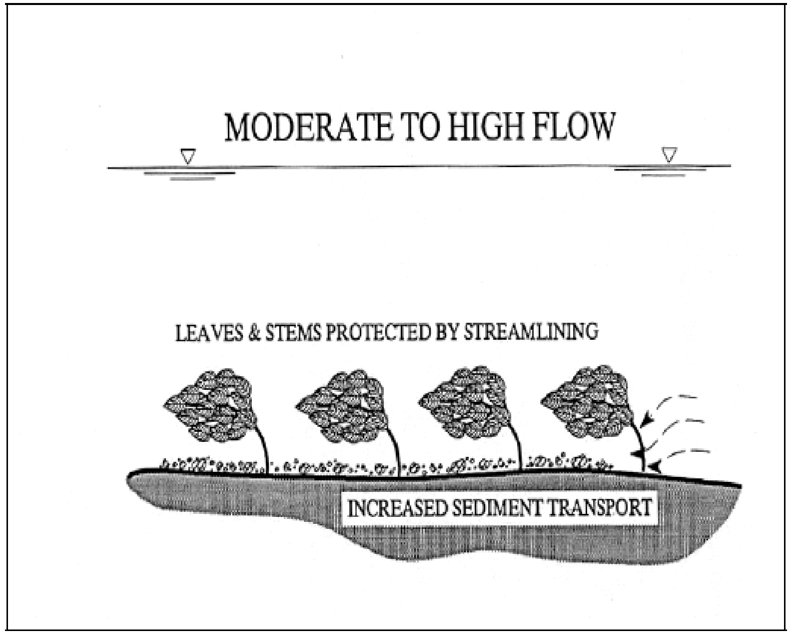


Figure 9. Plants with sediment transport

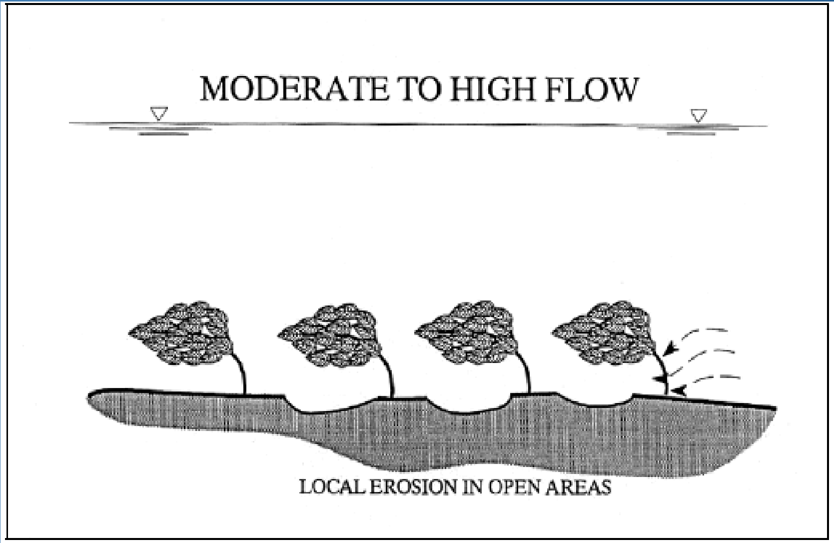


Figure 10. Plants with local erosion

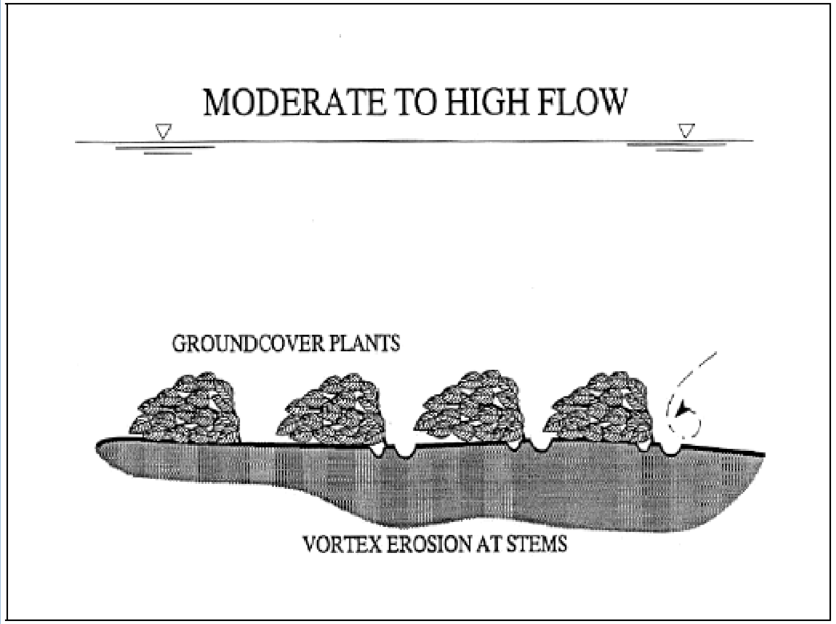


Figure 11. Plants with stem erosion

COE T

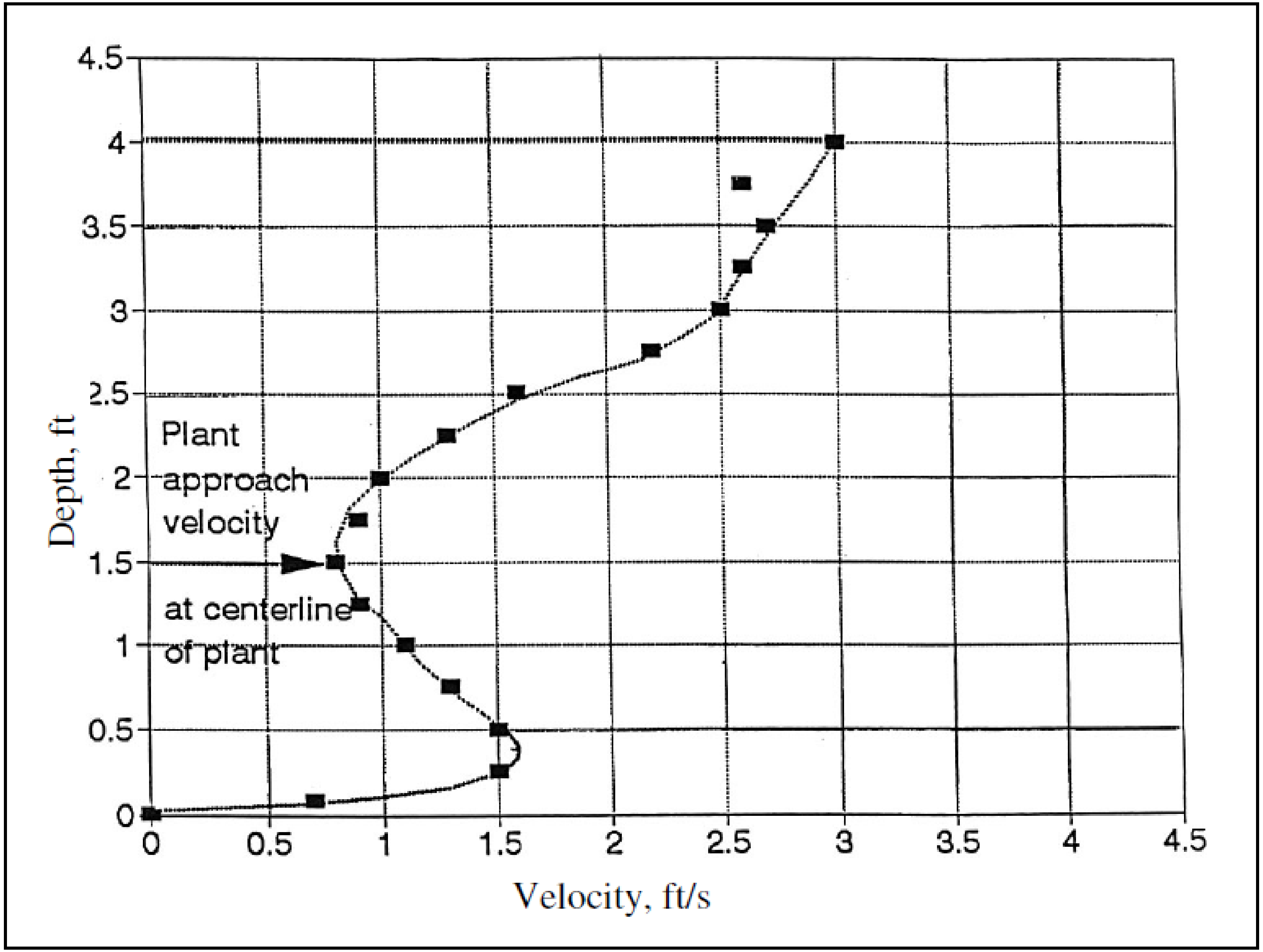


Figure 5. Example velocity profile for an experimental run with dogwoods (To convert feet to meters, multiply by 0.3048)

COE T

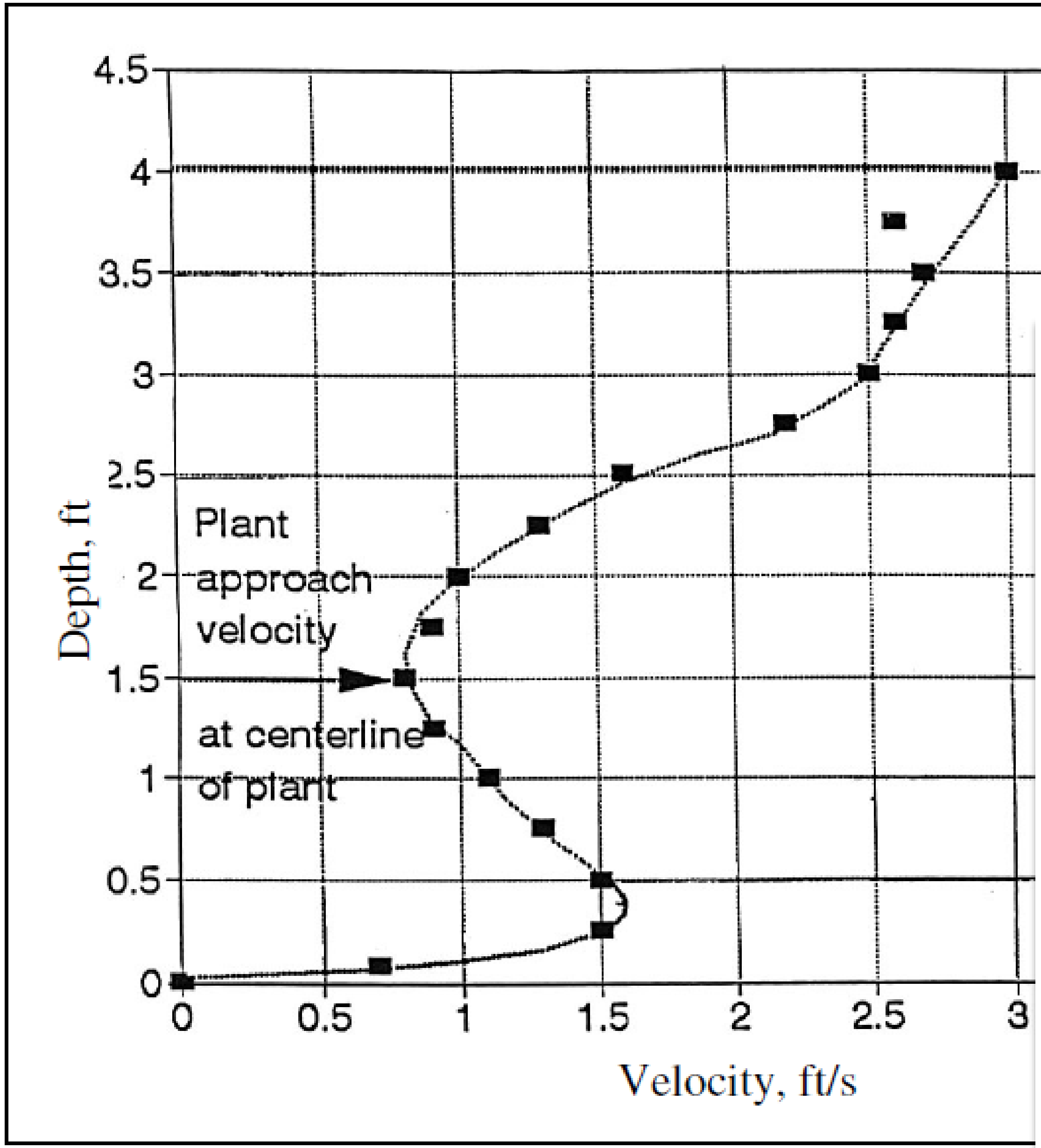


Figure 5. Example velocity profile for an experimental ru
convert feet to meters, multiply by 0.3048)

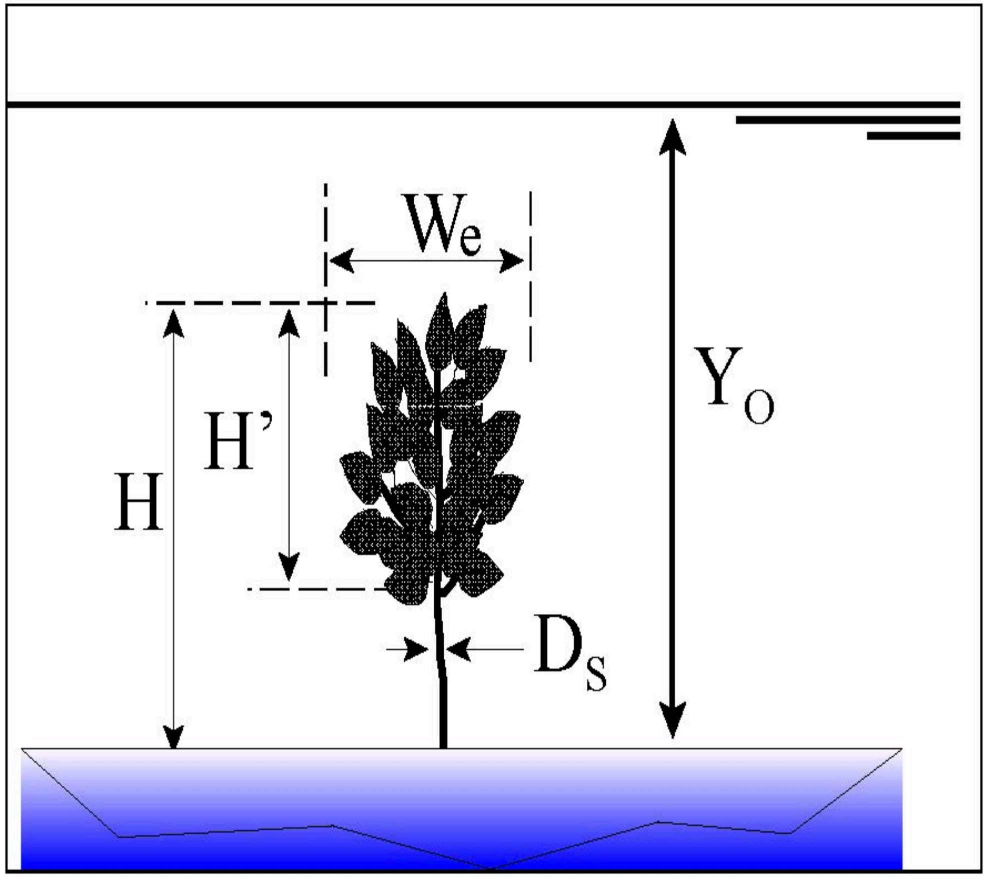


Figure 1. Plant dimension definitions for submerged plants

COE TR-00-25 (2000) – Regression Equations

- **Submerged Vegetation**

$$n = K_n \, 0.183 \left(\frac{E_s \, A_s}{\rho \, A_i \, V_*^2} \right)^{0.183} \left(\frac{H}{Y_O} \right)^{0.243} \left(M \, A_i \right)^{0.273} \left(\frac{\nu}{V_* R_h} \right)^{0.115} \left(\frac{1}{V^*} \right) \left(R_h \right)^{2/3} \left(S \right)^{1/2} \quad (22)$$

- **Partially Submerged Vegetation**

$$\mathrm{n} = K_n \, 3.487E-05 \left(\frac{E_s \, A_s}{\rho \, A_i^* \, V_*^2} \right)^{0.150} \left(M \, A_i^* \right)^{0.166} \left(\frac{V_* R_h}{\nu} \right)^{0.622} \left(\frac{R_h^{2/3} \, S^{1/2}}{V_*} \right) \quad (24)$$

COE TR-00-25 (2000) – Submerged Vegetation

Regression Results

$$\frac{V_*}{V} = \frac{\sqrt{g}}{C} = 0.183\left(\frac{E_s A_s}{\rho A_i V_*^2}\right)^{0.183}\left(\frac{H}{Y_O}\right)^{0.243}(M\ A_i)^{0.273}\left(\frac{v}{V_* R_h}\right)^{0.115} \quad (21)$$

MATH!

Manning's Equation

$$V = \frac{1.49\left(R^{2/3}S^{1/2}\right)}{n}$$

'n' Values

$$n = K_n\ 0.183\left(\frac{E_s\ A_s}{\rho\ A_i\ V_*^2}\right)^{0.183}\left(\frac{H}{Y_O}\right)^{0.243}(M\ A_i)^{0.273}\left(\frac{v}{V_* R_h}\right)^{0.115}\left(\frac{1}{V^*}\right)(R_h)^{2/3}(S)^{1/2} \quad (22)$$

COE TR-00-25 (2000) – Submerged Vegetation

E_s = Modulus of Plant Stiffness lbf/ft^2

A_s = Area of All Stems, ft^2

Kn = Manning's Unit Conversion

1.4861 ft1/3/s English

1.0 m1/3/s Metric

$$n = K_n\, 0.183 \left(\frac{E_s\, A_s}{\rho\, A_i\, V_*^2}\right)^{0.183} \left(\frac{H}{Y_O}\right)^{0.243} (M\, A_i)^{0.273} \left(\frac{\nu}{V_* R_h}\right)^{0.115} \left(\frac{1}{V^*}\right) (R_h)^{2/3} (S)^{1/2} \quad (22)$$

0.183 Calibration Constant for Submerged Flow

V_* = Shear Velocity, ft/s

A_i = Frontal Area of Plant blocking flow

ρ = fluid density

ICON ENGINEERING, INC.

COE TR-00-25 (2000) – Submerged Vegetation

H = Avg. Undeflected Plant Height

ν = Fluid dynamic viscosity, ft^2/s

$$n = K_n \, 0.183 \left(\frac{E_s \, A_s}{\rho \, A_i \, V_*^2} \right)^{0.183} \left(\frac{H}{Y_O} \right)^{0.243} \left(M \, A_i \right)^{0.273} \left(\frac{\nu}{V_* R_h} \right)^{0.115} \left(\frac{1}{V^*} \right) \left(R_h \right)^{2/3} \left(S \right)^{1/2} \quad (22)$$

Y_o = Flow depth

M = Relative plant density, number of plants per ft^2 or m^2

ICON ENGINEERING, INC.

COE TR-00-25 (2000) – Partially Submerged Vegetation

$$n = K_n \, 3.487E-05 \left(\frac{E_s \, A_s}{\rho \, A_i^* \, V_*^2} \right)^{0.150} \left(M \, A_i^* \right)^{0.166} \left(\frac{V_* R_h}{\nu} \right)^{0.622} \left(\frac{R_h^{2/3} \, S^{1/2}}{V_*} \right) \qquad (24)$$

Calibration Constant for Submerged Flow

COE TR-00-25 (2000) – Results

- **Key Variables for ‘n’:**
  - **Hydraulic Variables:**
    - **R_h = Hydraulic Radius**
    - **Y_o = Flow Depth**
    - **S = Slope**
    - **V_* = Shear Velocity = $(gR_hS)^{½}$**
  - **Vegetation Variables**
    - **E_s = Modulus of Plant Stiffness**
    - **A_s = Area of All Stems**
    - **A_i = Frontal Area of Plant blocking flow**
    - **M = Relative plant density, number of plants per ft^2**

COE TR-00-25 (2000) – Submerged Vegetation

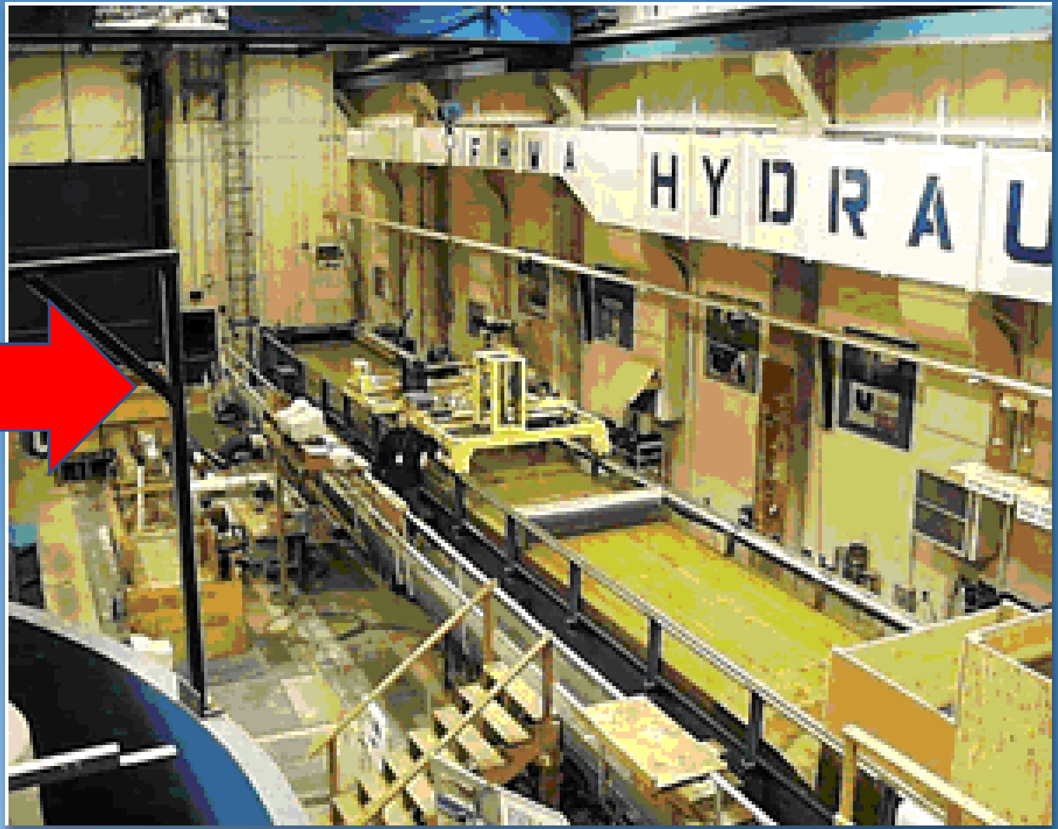
- **Key Variables for 'n':**
  - **Hydraulic Variables:**
    - **R_h = Hydraulic Radius**
    - **Y_o = Flow Depth**
    - **S = Slope**
    - **V_* = Shear Velocity = $(gR_hS)^{1/2}$**
  - **Vegetation Variables**
    - **E_s = Modulus of Plant Stiffness**
    - **A_s = Area of All Stems**
    - **A_i = Frontal Area of Plant blocking flow**
    - **M = Relative plant density, number of plants per ft^2**

COE TR-00-25 (2000) – Submerged Vegetation

- **Key Variables for 'n':**
  - **Hydraulic Variables:**
    - **R_h = Hydraulic Radius**
    - **Y_o = Flow Depth**
    - **S = Slope**
    - **V_* = Shear Velocity = $(gR_hS)^{½}$**
  - **Vegetation Variables**
    - **E_s = Modulus of Plant Stiffness**
    - **A_s = Area of All Stems**
    - **A_i = Frontal Area of Plant blocking flow**
    - **M = Relative plant density, number of plants per ft^2**

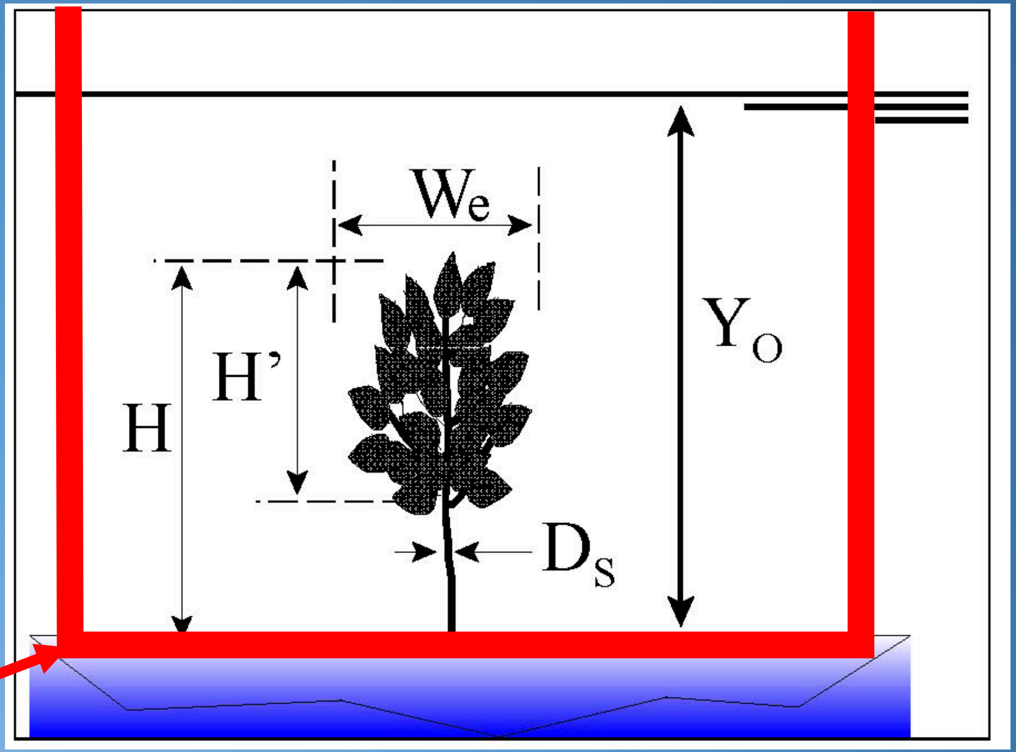
COE TR-00-25 (2000) – Submerged Vegetation

- **Key Variables for 'n':**
  - **Hydraulic Variables:**
    - R_h = Hydraulic Radius
    - Y_o = Flow Depth
    - S = Slope
    - V_* = Shear Velocity = $(gR_hS)^{1/2}$
  - **Vegetation Variables**
    - E_s = Modulus of Plant Stiffness
    - A_s = Area of All Stems
    - A_i = Frontal Area of Plant blocking flow
    - M = Relative plant density, number of plants per ft^2



Theoretical Flume

- Assumptions (?)
  - Hydraulic Variables:
    - Y_o = Flow Depth
    - W = Width
    - R_h = Hydraulic Radius = A/P
    - S = Slope
    - V_* = Shear Velocity = $(gR_hS)^{½}$



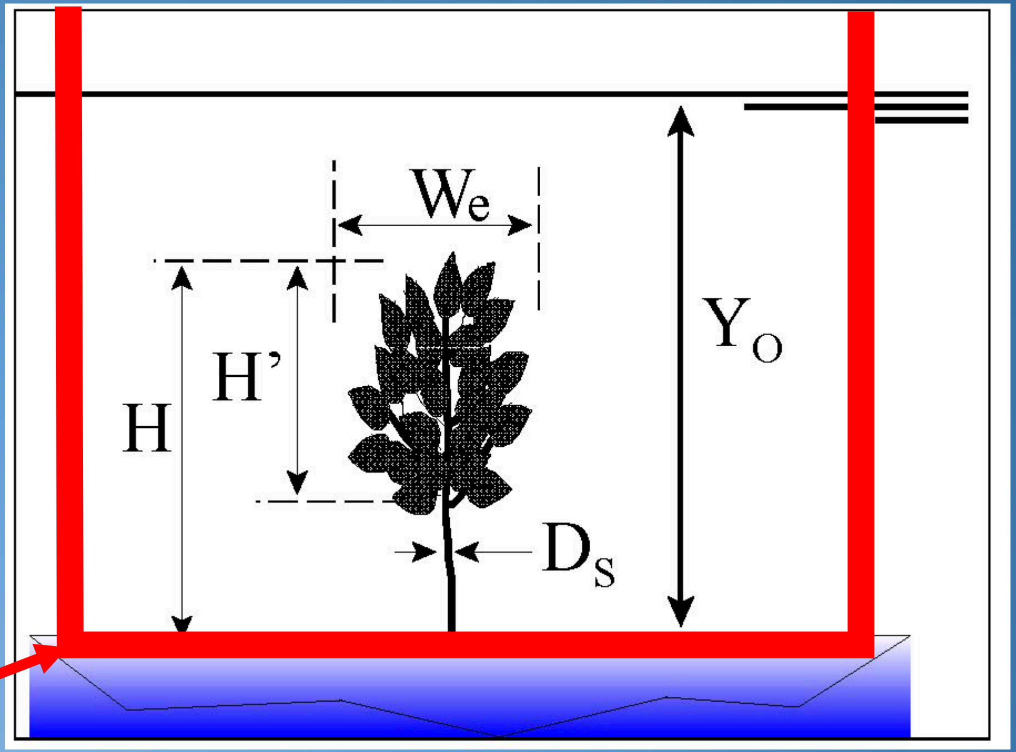
- Y_o, W, A, P, Rh

Theoretical Flume

- **Assumptions (?)**
  - **Hydraulic Variables:**
    - Y_o = Flow Depth
    - W = Width
    - R_h = Hydraulic Radius = A/P
    - S = Slope
    - V_* = Shear Velocity = $(gR_hS)^{½}$

Variable!

- Y_o, W, A, P, Rh



Theoretical Flume

- **Vegetation Variables**
  - E_s = Modulus of Plant Stiffness
  - A_s = Area of All Stems
  - A_i = Frontal Area of Plant blocking flow
  - M = Relative plant density

Table 2
Dimensions and Characteristics of Plants (Non-SI Units)

Common Name	Scientific Name	Plant Height *H*, ft	Plant Width *We*, ft	Effective Height, *H'*, ft	Blockage Area *A* Ft^2	Stem Diameter *Ds*, ft	Stem Number	Elasticity *Es*, lbf/ft^2
Large Flume								
Yellow Twig Dogwood	Cornus Stolonifera Flaviramea	1.67	0.750	1.08	0.818	0.0313	1	6.706
Berried Elderberry	Sambucus Racemosa	2.33	1.167	1.67	1.948	0.0313	1	1.099
Purpleleaf Euonymus	Euonymus Fortunei Colorata	0.67	0.833	0.67	0.560	0.0208	2	8.648
Red Twig Dogwood	Cornus Sericea	3.18	1.583	2.50	3.958	0.0833	2	21.308
Service Berry	Amelanchier	2.33	0.583	1.67	0.969	0.0208	6	99.436
Yellow Twig Dogwood	Cornus Stolonifera Flaviramea	2.33	0.833	2.00	1.666	0.0313	2	62.461
Mulefat	Baccharis Glutinosa	3.18	0.250	1.67	0.420	0.0420	1	12.430
Alder	Alnus Incana	2.50	0.500	2.33	1.150	0.0260	1	35.513
Valley Elderberry	Sambucus Mexicana	3.18	2.500	3.00	7.503	0.0879	1	34.469
Salt Cedar	Tamarix spp.	5.00	2.000	4.50	9.001	0.1040	1	27.366
Black Willow	Salix Nigra	4.00	1.000	4.00	4.005	0.0630	1	3.134
Red Willow	Salix spp.	2.00	0.500	2.00	1.001	0.0310	1	9.401
Mountain Willow	Salix Monticola	5.00	3.000	4.00	12.003	0.0840	4	7.123
Small Flume								
Yellow Twig Dogwood	Cornus Stolonifera Flaviramea	1.67	0.750	1.08	0.818	0.0313	1	6.706
Purpleleaf Eunonyus	Euonymus Fortunei Colorata	0.67	0.833	0.67	0.560	0.0208	2	8.648
Artic Blue Willow	Salix Purpurea Nana	1.84	1.000	1.67	1.669	0.0417	1	2.486
Norway Maple	Acer Platenoides	2.33	1.000	1.00	1.001	0.0417	1	39.900
Common Privet	Ligustrum Vulgare	2.67	0.833	2.25	1.873	0.0417	1	8.231
Blue Elderberry	Sambucus Canadensis	1.75	1.500	1.33	1.997	0.0833	1	0.549
French Pink Pussywillow	Salix Caprea Pendula	3.00	0.833	0.83	0.700	0.0625	1	2.319
Sycamore	Platenus Acer Ifolia	3.00	0.667	2.75	1.831	0.0333	1	57.448
Western Sand Cherry	Prunis Besseyi	2.43	0.500	1.67	0.829	0.0278	1	60.163
Staghorn Sumac	Rhus Typhina	2.50	0.833	1.00	0.829	0.0417	1	10.612
Sand Bar Willow	Salix exigua	7.15		5.91	7.09	0.0492	1	180
Pacific Willow	Salix lasiandra	7.84		6.56	21.31	0.0558	1	207
Lemon's Willow	Salix lemonii	7.0		5.58	4.09	0.0427	1	180
Wild Rose Bush	Rosa spp.	3.87		0.354	11.30	0.0230	1	272

Theoretical Flume?

- Vegetation Variables
  - E_s = Modulus of Plant Stiffness
  - A_s = Area of All Stems
  - A_i = Frontal Area of Plant blocking flow
  - M = Relative plant density,

Theoretical Flume?

- Vegetation Variables
  - E_s = Modulus of Plant Stiffness
  - A_s = Area of All Stems
  - A_i = Frontal Area of Plant blocking flow
  - M = Relative plant density,

Application: South Platte River Basin

- **Inventory of native/adapted plant species**
  - **Visual/pictorial survey (not destructive)**
  - **Minimum of ¼ mile roundtrip**
  - **Excluding undesirable non-natives**
- **3 sampling locations along the channel**
  - **1 Established: South Platte Park**
  - **1 Recently restored: Lee Gulch**
  - **1 Disturbed/non-natives: Union Ave.**
- **Grasses (14), forbs (17), shrubs (16), trees (6)**

Grasses (Sample)	**Mean Height**	**Growth Habit**	**Flexibility**	**Density**
Agropyron cristatum, crested wheatgrass*	18-36 inches	bunch grass	rigid	dense foliage
Bouteloua gracilis, blue grama*	6-24 inches	spreading	rigid	dense foliage
Bouteloua curtipendula, sideoats grama*	12-24 inches	spreading	flexible	dense foliage
Bromus inermis, smooth brome*	6-36 inches	spreading	flexible	dense foliage
Buchloe dactyloides, buffalograss*	3-8 inches	spreading	rigid	dense foliage

Forbs (Sample)	**Mean Height**	**Mean Width**	**Flexibility**	**Density**
Apocynum cannabinum, Indian hemp	12-36 inches	12-24 inches	very flexible	sparse foliage
Artemisia frigida, fringed sage*	6-18 inches	18-24 inches	very flexible	dense foliage
Artemisia ludoviciana, mountain sage	24-36 inches	36-48 inches	very flexible	sparse foliage
Asclepias incarnata, swamp milkweed*	24-36 inches	24-26 inches	flexible	sparse foliage

*= recommended species for revegetation efforts.






Relationship to values in the COE document

- **Mean height x width at maturity of grasses and forbs**
  - **Wide range of sizes due to climate, water availability and competition**
- **Shrubs and trees can take decades to reach maturity**
- **Growth habit (branching/suckering) + flexibility = parallel species**
- **Plant species list was cross-referenced with recommendations from:**
  - ***Native Plant Revegetation Guide for Colorado***
  - ***Woody Plants of South Platte Park***

ICON ENGINEERING, INC.

COE TR-00-25 Table 9

Table 9
Modulus of Plant Stiffness for Evaluated Plants

Plant name		$E_S/(H/D_S)^{1.5}$ N/m²	$E_S/(H/D_S)^{1.5}$ lbf/ft²
Alder	*Alnus incana*	1.804e+06	3.768e+04
Arctic Blue Willow	*Salix purpurea nana*	4.091e+05	8.544e+03
Black Willow	*Salix nigra*	2.930e+05	6.119e+03
Blue Elderberry	*Sambucus Canadensis*	2.733e+05	5.708e+03
Common Privet	*Ligustrum vulgare*	7.7040e+05	1.609e+04
Yellow Twig Dogwood	*Cornus stolonifera flaviramea*	2.550e+06	5.326e+04
Red-osier Dogwood	*Cornus Sericea*	4.342e+06	9.069e+04
Berried Elderberry	*Sambucus racemosa*	8.168e+04	1.706e+03
Purpleleaf Euonymus	*Euonymus fortunei colorata*	2.278e+06	4.758e+04
Mountain Black Willow	*Salix monticola*	7.430e+05	1.552e+04
Mulefat	*Baccharis glutinosa*	8.992e+05	1.878e+04
Norway Maple	*Acer platenoides*	4.569e+06	9.542e+04
French Pink Pussywillow	*Salix caprea pendula*	3.345e+05	6.986e+03
Red Willow	*Salix spp.*	8.810e+05	1.840e+04
Salt Cedar	*Tamarix spp.*	3.930e+06	8.207e+04
Service Berry	*Amelanchier*	4.003e+06	8.360e+04
Staghorn Sumac	*Rhus typhina*	1.095e+06	2.288e+04
Sycamore	*Platenus acer ifolia*	3.244e+06	6.774e+04
Valley Elderberry	*Sambucus mexicana*	7.672e+06	1.602e+05
Western Sand Cherry	*Prunis besseyi*	3.567e+06	7.449e+04
Sand Bar Willow	*Salix exigua*	4.990e+06	1.040e+05
Pacific Willow	*Salix lasiandra*	5.300e+06	1.120e+05
Lemon's Willow	Salix lemonii	4.090e+06	8.530e+04
Wild Rose Bush	Rosa spp.	6.070e+06	1.250e+05

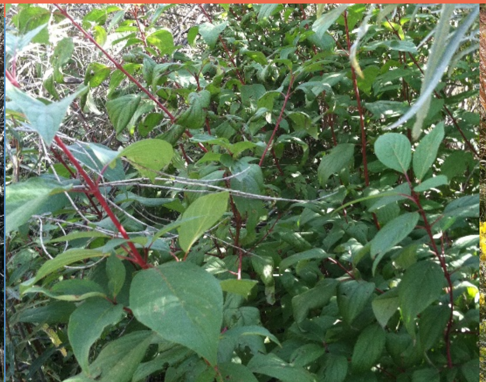
South Platte River Shrub and Tree Species — Notes on Parallel Species from Table 9 in COE

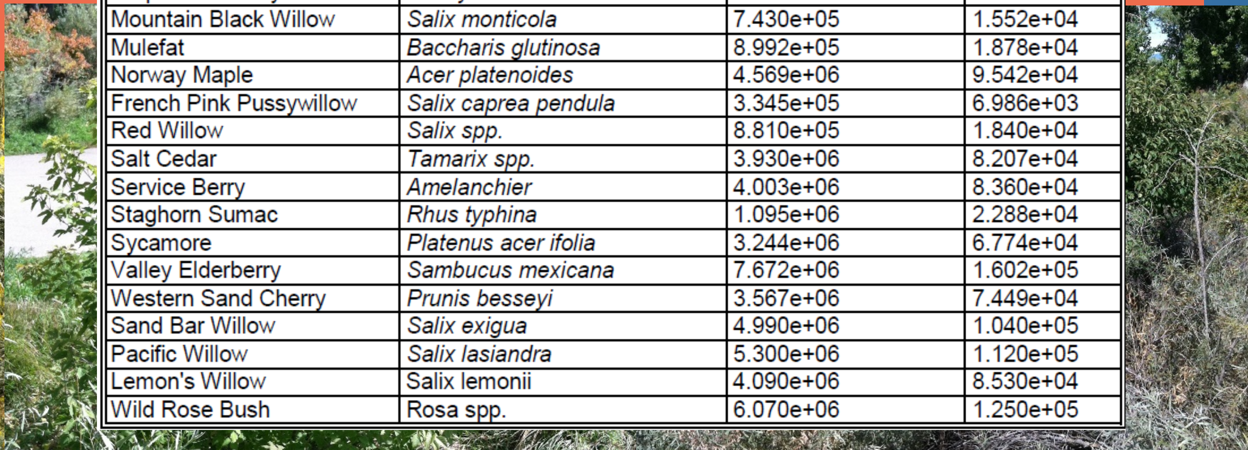
South Platte River Shrub and Tree Species	Notes on Parallel Species from Table 9 in COE
Shrubs (Sample)	
Acer glabrum, Rocky Mountain maple	between serviceberry and blue elderberry
Atriplex canescens, four wing saltbush	no parallel in table – upland species anyway
Cornus sericea, red osier dogwood*	same species – red osier (a.k.a redtwig) dogwood
Ericameria nauseosa, rubber rabbitbrush	no parallel in table – upland species anyway
Prunus americana, American plum*	western sand cherry
Trees (Sample)	
Acer ginnala, amur maple	between
Acer negundo, box-elder	between
Celtis reticulata, netleaf hackberry	sycamor
Populus angustifolia, narrowleaf cottonwood	between

*= recommended species for revegetation efforts.

Table 9
Modulus of Plant Stiffness for Evaluated Plants

Plant name		$E_S/(H/D_S)^{1.5}$ N/m²	$E_S/(H/D_S)^{1.5}$ lbf/ft²
Alder	*Alnus incana*	1.804e+06	3.768e+04
Arctic Blue Willow	*Salix purpurea nana*	4.091e+05	8.544e+03
Black Willow	*Salix nigra*	2.930e+05	6.119e+03
Blue Elderberry	*Sambucus Canadensis*	2.733e+05	5.708e+03
Common Privet	*Ligustrum vulgare*	7.7040e+05	1.609e+04
Yellow Twig Dogwood	*Cornus stolonifera flaviramea*	2.550e+06	5.326e+04
Red-osier Dogwood	*Cornus Sericea*	4.342e+06	9.069e+04
Berried Elderberry	*Sambucus racemosa*	8.168e+04	1.706e+03
Purpleleaf Euonymus	*Euonymus fortunei colorata*	2.278e+06	4.758e+04
Mountain Black Willow	*Salix monticola*	7.430e+05	1.552e+04
Mulefat	*Baccharis glutinosa*	8.992e+05	1.878e+04
Norway Maple	*Acer platenoides*	4.569e+06	9.542e+04
French Pink Pussywillow	*Salix caprea pendula*	3.345e+05	6.986e+03
Red Willow	*Salix spp.*	8.810e+05	1.840e+04
Salt Cedar	*Tamarix spp.*	3.930e+06	8.207e+04
Service Berry	*Amelanchier*	4.003e+06	8.360e+04
Staghorn Sumac	*Rhus typhina*	1.095e+06	2.288e+04
Sycamore	*Platenus acer ifolia*	3.244e+06	6.774e+04
Valley Elderberry	*Sambucus mexicana*	7.672e+06	1.602e+05
Western Sand Cherry	*Prunis besseyi*	3.567e+06	7.449e+04
Sand Bar Willow	*Salix exigua*	4.990e+06	1.040e+05
Pacific Willow	*Salix lasiandra*	5.300e+06	1.120e+05
Lemon's Willow	Salix lemonii	4.090e+06	8.530e+04
Wild Rose Bush	Rosa spp.	6.070e+06	1.250e+05



	Woody Plants - Flexable (Es(H/Ds)^1.5) = 8.544E^3 lbf/ft^2)								
	Low Density (4' Canopy, 10% Foliage Cover, 1:125)			Mid Density (4' Canopy, 25% Foliage Cover, 1:50)			High Density (4' Canopy, 80% Foliage Cover, 1:16)		
	1' to 3'	3' to 6'	6' & greater	1' to 3'	3' to 6'	6' & greater	1' to 3'	3' to 6'	6' & greater
PLANT FEATURES									
Plant Height (ft)	5	5	5	5	5	5	5	5	5
Undeflected Height of Leaf Mass (H', ft)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Equivalent Ave Plant Width (We, ft)	4	4	4	4	4	4	4	4	4
Frontal Area of Plants (Ai, ft^2)	18	18	18	18	18	18	18	18	18
Number of Stems per Plant (#)	4	4	4	4	4	4	4	4	4
Diameter of Stem (Ds, in)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Area of Stem/plant (As, sqft)	0.005454154	0.005454154	0.005454154	0.005454154	0.005454154	0.005454154	0.005454154	0.005454154	0.005454154
Number of Plants per sqft (M, #)	0.008	0.008	0.008	0.02	0.02	0.02	0.0625	0.0625	0.0625
H/Ds	120	120	120	120	120	120	120	120	120
Modulus of Plant Stiffness Table 9	8.54E+03	8.54E+03	8.54E+03	8.54E+03	8.54E+03	8.54E+03	8.54E+03	8.54E+03	8.54E+03
Modulus of Plant Stiffness (Es, lbf/ft^2) (Table 9 multiplied by (H/Ds)^1.5)	1.12E+07	1.12E+07	1.12E+07	1.12E+07	1.12E+07	1.12E+07	1.12E+07	1.12E+07	1.12E+07
HYRAULIC FEATURES									
Depth of Flow (Yo, ft)	2.21	5.92	8.7	2.21	5.92	8.7	2.21	5.92	8.7
Yo/H	0.442	1.184	1.74	0.442	1.184	1.74	0.442	1.184	1.74
Submerged	NO	YES	YES	NO	YES	YES	NO	YES	YES
Frontal Area of Plants (Ai, ft^2)	18	18	18	18	18	18	18	18	18
Wetted Perimiter of Sub-area (P, ft)	47.02	54.44	60	47.02	54.44	60	47.02	54.44	60
Slope (S, ft/ft)	0.0016	0.0022	0.004	0.0016	0.0022	0.004	0.0016	0.0022	0.004
Flow Area (Qa, ft^2)	94	252	370	94	252	370	94	252	370
Hydrulic Radius (Rh, ft)	1.999149298	4.628949302	6.166666667	1.999149298	4.628949302	6.166666667	1.999149298	4.628949302	6.166666667
Shear Velocity (V*, ft/sec)	0.320930167	0.572638427	0.891216397	0.320930167	0.572638427	0.891216397	0.320930167	0.572638427	0.891216397
Fluid Deisity (ρ, slugs/ft^3)	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94
EsAs/(ρAiV*^2)	17031.98162	5349.648977	2208.614537	17031.98162	5349.648977	2208.614537	17031.98162	5349.648977	2208.614537
Frontal Area of Plants Unsubmerged (Ai*, ft^2)	8.84	23.68	34.8	8.84	23.68	34.8	8.84	23.68	34.8
EsAs/(ρAi*V*^2)	34680.50557	4066.456148	1142.386829	34680.50557	4066.456148	1142.386829	34680.50557	4066.456148	1142.386829
M*Ai	0.144	0.144	0.144	0.36	0.36	0.36	1.125	1.125	1.125
M*Ai*	0.07072	0.18944	0.2784	0.1768	0.4736	0.696	0.5525	1.48	2.175
Dynamic Viscosity (v, ft^2/sec)	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05
V**Rh/v	45827.66552	189336.7321	392559.6035	45827.66552	189336.7321	392559.6035	45827.66552	189336.7321	392559.6035
Mannings n	0.025117198	0.041619316	0.031095716	0.029243492	0.053448136	0.039933574	0.035332498	0.072950222	0.054504485

	Woody Plants - Rigid (Es(H/Ds)^1.5) = 4.758E^4 lbf/ft^2)								
	Low Density (4' Canopy, 10% Foliage Cover, 1:125)			Mid Density (4' Canopy, 25% Foliage Cover, 1:50)			High Density (4' Canopy, 80% Foliage Cover, 1:16)		
	1' to 3'	3' to 6'	6' & greater	1' to 3'	3' to 6'	6' & greater	1' to 3'	3' to 6'	6' & greater
PLANT FEATURES									
Plant Height (ft)	5	5	5	5	5	5	5	5	5
Undeflected Height of Leaf Mass (H', ft)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Equivalent Ave Plant Width (We, ft)	4	4	4	4	4	4	4	4	4
Frontal Area of Plants (Ai, ft^2)	18	18	18	18	18	18	18	18	18
Number of Stems per Plant (#)	4	4	4	4	4	4	4	4	4
Diameter of Stem (Ds, in)	1	1	1	1	1	1	1	1	1
Area of Stem/plant (As, sqft)	0.021816616	0.021816616	0.021816616	0.021816616	0.021816616	0.021816616	0.021816616	0.021816616	0.021816616
Number of Plants per sqft (M, #)	0.008	0.008	0.008	0.02	0.02	0.02	0.0625	0.0625	0.0625
H/Ds	60	60	60	60	60	60	60	60	60
Modulus of Plant Stiffness Table 9	4.76E+04	4.76E+04	4.76E+04	4.76E+04	4.76E+04	4.76E+04	4.76E+04	4.76E+04	4.76E+04
Modulus of Plant Stiffness (Es, lbf/ft^2) (Table 9 multiplied by (H/Ds)^1.5)	2.21E+07	2.21E+07	2.21E+07	2.21E+07	2.21E+07	2.21E+07	2.21E+07	2.21E+07	2.21E+07
HYRAULIC FEATURES									
Depth of Flow (Yo, ft)	2.21	5.92	8.7	2.21	5.92	8.7	2.21	5.92	8.7
Yo/H	0.442	1.184	1.74	0.442	1.184	1.74	0.442	1.184	1.74
Submerged	NO	YES	YES	NO	YES	YES	NO	YES	YES
Frontal Area of Plants (Ai, ft^2)	18	18	18	18	18	18	18	18	18
Wetted Perimiter of Sub-area (P, ft)	47.02	54.44	60	47.02	54.44	60	47.02	54.44	60
Slope (S, ft/ft)	0.0016	0.0022	0.004	0.0016	0.0022	0.004	0.0016	0.0022	0.004
Flow Area (Qa, ft^2)	94	252	370	94	252	370	94	252	370
Hydrulic Radius (Rh, ft)	1.999149298	4.628949302	6.166666667	1.999149298	4.628949302	6.166666667	1.999149298	4.628949302	6.166666667
Shear Velocity (V*, ft/sec)	0.320930167	0.572638427	0.891216397	0.320930167	0.572638427	0.891216397	0.320930167	0.572638427	0.891216397
Fluid Deisity (ρ, slugs/ft^3)	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94
EsAs/(ρAiV*^2)	134135.3898	42131.16634	17393.94619	134135.3898	42131.16634	17393.94619	134135.3898	42131.16634	17393.94619
Frontal Area of Plants Unsubmerged (Ai*, ft^2)	8.84	23.68	34.8	8.84	23.68	34.8	8.84	23.68	34.8
EsAs/(ρAi*V*^2)	273126.3593	32025.37982	8996.868718	273126.3593	32025.37982	8996.868718	273126.3593	32025.37982	8996.868718
M*Ai	0.144	0.144	0.144	0.36	0.36	0.36	1.125	1.125	1.125
M*Ai*	0.07072	0.18944	0.2784	0.1768	0.4736	0.696	0.5525	1.48	2.175
Dynamic Viscosity (v, ft^2/sec)	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05
V**Rh/v	45827.66552	189336.7321	392559.6035	45827.66552	189336.7321	392559.6035	45827.66552	189336.7321	392559.6035
Mannings n	0.034230475	0.060717495	0.045364849	0.039853913	0.077974298	0.058258204	0.048152193	0.106425458	0.079515382

	Woody Plants - Very Rigid (Es(H/Ds)^1.5) = 1.25E^5 lbf/ft^2)								
	Low Density (4' Canopy, 10% Foliage Cover, 1:125)			Mid Density (4' Canopy, 25% Foliage Cover, 1:50)			High Density (4' Canopy, 80% Foliage Cover, 1:16)		
	1' to 3'	3' to 6'	6' & greater	1' to 3'	3' to 6'	6' & greater	1' to 3'	3' to 6'	6' & greater
PLANT FEATURES									
Plant Height (ft)	5	5	5	5	5	5	5	5	5
Undeflected Height of Leaf Mass (H', ft)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Equivalent Ave Plant Width (We, ft)	4	4	4	4	4	4	4	4	4
Frontal Area of Plants (Ai, ft^2)	18	18	18	18	18	18	18	18	18
Number of Stems per Plant (#)	2	2	2	2	2	2	2	2	2
Diameter of Stem (Ds, in)	2	2	2	2	2	2	2	2	2
Area of Stem/plant (As, sqft)	0.043633231	0.043633231	0.043633231	0.043633231	0.043633231	0.043633231	0.043633231	0.043633231	0.043633231
Number of Plants per sqft (M, #)	0.008	0.008	0.008	0.02	0.02	0.02	0.0625	0.0625	0.0625
H/Ds	30	30	30	30	30	30	30	30	30
Modulus of Plant Stiffness Table 9	1.25E+05	1.25E+05	1.25E+05	1.25E+05	1.25E+05	1.25E+05	1.25E+05	1.25E+05	1.25E+05
Modulus of Plant Stiffness (Es, lbf/ft^2) (Table 9 multiplied by (H/Ds)^1.5)	2.05E+07	2.05E+07	2.05E+07	2.05E+07	2.05E+07	2.05E+07	2.05E+07	2.05E+07	2.05E+07
HYRAULIC FEATURES									
Depth of Flow (Yo, ft)	2.21	5.92	8.7	2.21	5.92	8.7	2.21	5.92	8.7
Yo/H	0.442	1.184	1.74	0.442	1.184	1.74	0.442	1.184	1.74
Submerged	NO	YES	YES	NO	YES	YES	NO	YES	YES
Frontal Area of Plants (Ai, ft^2)	18	18	18	18	18	18	18	18	18
Wetted Perimiter of Sub-area (P, ft)	47.02	54.44	60	47.02	54.44	60	47.02	54.44	60
Slope (S, ft/ft)	0.0016	0.0022	0.004	0.0016	0.0022	0.004	0.0016	0.0022	0.004
Flow Area (Qa, ft^2)	94	252	370	94	252	370	94	252	370
Hydrulic Radius (Rh, ft)	1.999149298	4.628949302	6.166666667	1.999149298	4.628949302	6.166666667	1.999149298	4.628949302	6.166666667
Shear Velocity (V*, ft/sec)	0.320930167	0.572638427	0.891216397	0.320930167	0.572638427	0.891216397	0.320930167	0.572638427	0.891216397
Fluid Deisity (ρ, slugs/ft^3)	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94
EsAs/(ρAiV*^2)	249180.4427	78266.16597	32312.36155	249180.4427	78266.16597	32312.36155	249180.4427	78266.16597	32312.36155
Frontal Area of Plants Unsubmerged (Ai*, ft^2)	8.84	23.68	34.8	8.84	23.68	34.8	8.84	23.68	34.8
EsAs/(ρAi*V*^2)	507380.992	59492.86265	16713.29046	507380.992	59492.86265	16713.29046	507380.992	59492.86265	16713.29046
M*Ai	0.144	0.144	0.144	0.36	0.36	0.36	1.125	1.125	1.125
M*Ai*	0.07072	0.18944	0.2784	0.1768	0.4736	0.696	0.5525	1.48	2.175
Dynamic Viscosity (v, ft^2/sec)	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05
V**Rh/v	45827.66552	189336.7321	392559.6035	45827.66552	189336.7321	392559.6035	45827.66552	189336.7321	392559.6035
Mannings n	0.037562848	0.068004157	0.050809051	0.043733733	0.087331936	0.065249729	0.05283986	0.119197499	0.089057965

	Forbes Plants - Flexable (Es(H/Ds)^1.5) = 8.544E^3 lbf/ft^2)								
	Low Density (2' Canopy, 10% Foliage Cover, 1:31)			Mid Density (2' Canopy, 25% Foliage Cover, 1:13)			High Density (2' Canopy, 80% Foliage Cover, 1:4)		
	1' to 3'	3' to 6'	6' & greater	1' to 3'	3' to 6'	6' & greater	1' to 3'	3' to 6'	6' & greater
PLANT FEATURES									
Plant Height (ft)	3	3	3	3	3	3	3	3	3
Undeflected Height of Leaf Mass (H', ft)	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
Equivalent Ave Plant Width (We, ft)	2	2	2	2	2	2	2	2	2
Frontal Area of Plants (Ai, ft^2)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Number of Stems per Plant (#)	4	4	4	4	4	4	2	2	2
Diameter of Stem (Ds, in)	0.25	0.25	0.25	0.5	0.5	0.5	1	1	1
Area of Stem/plant (As, sqft)	0.001363538	0.001363538	0.001363538	0.005454154	0.005454154	0.005454154	0.010908308	0.010908308	0.010908308
Number of Plants per sqft (M, #)	0.032258065	0.032258065	0.032258065	0.076923077	0.076923077	0.076923077	0.25	0.25	0.25
H/Ds	144	144	144	72	72	72	36	36	36
Modulus of Plant Stiffness Table 9	8.54E+03	8.54E+03	8.54E+03	8.54E+03	8.54E+03	8.54E+03	8.54E+03	8.54E+03	8.54E+03
Modulus of Plant Stiffness (Es, lbf/ft^2) (Table 9 multiplied by (H/Ds)^1.5)	1.48E+07	1.48E+07	1.48E+07	5.22E+06	5.22E+06	5.22E+06	1.85E+06	1.85E+06	1.85E+06
HYRAULIC FEATURES									
Depth of Flow (Yo, ft)	2.21	5.92	8.7	2.21	5.92	8.7	2.21	5.92	8.7
Yo/H	0.736666667	1.973333333	2.9	0.736666667	1.973333333	2.9	0.736666667	1.973333333	2.9
Submerged	NO	YES	YES	NO	YES	YES	NO	YES	YES
Frontal Area of Plants (Ai, ft^2)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Wetted Perimiter of Sub-area (P, ft)	47.02	54.44	60	47.02	54.44	60	47.02	54.44	60
Slope (S, ft/ft)	0.0016	0.0022	0.004	0.0016	0.0022	0.004	0.0016	0.0022	0.004
Flow Area (Qa, ft^2)	94	252	370	94	252	370	94	252	370
Hydrulic Radius (Rh, ft)	1.999149298	4.628949302	6.166666667	1.999149298	4.628949302	6.166666667	1.999149298	4.628949302	6.166666667
Shear Velocity (V*, ft/sec)	0.320930167	0.572638427	0.891216397	0.320930167	0.572638427	0.891216397	0.320930167	0.572638427	0.891216397
Fluid Deisity (ρ, slugs/ft^3)	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94
EsAs/(ρAiV*^2)	22389.12128	7032.296206	2903.299206	31662.99897	9945.168669	4105.885113	22389.12128	7032.296206	2903.299206
Frontal Area of Plants Unsubmerged (Ai*, ft^2)	4.42	11.84	17.4	4.42	11.84	17.4	4.42	11.84	17.4
EsAs/(ρAi*V*^2)	22794.35425	2672.747713	750.853243	32236.08492	3779.836065	1061.86684	22794.35425	2672.747713	750.853243
M*Ai	0.14516129	0.14516129	0.14516129	0.346153846	0.346153846	0.346153846	1.125	1.125	1.125
M*Ai*	0.142580645	0.381935484	0.561290323	0.34	0.910769231	1.338461538	1.105	2.96	4.35
Dynamic Viscosity (v, ft^2/sec)	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05
V**Rh/v	45827.66552	189336.7321	392559.6035	45827.66552	189336.7321	392559.6035	45827.66552	189336.7321	392559.6035
Mannings n	0.026496134	0.038732297	0.028938691	0.032241201	0.05231819	0.03908934	0.037222591	0.067741159	0.050612553

	Forbes Plants - Rigid (Es(H/Ds)^1.5) = 4.758E^4 lbf/ft^2)								
	Low Density (2' Canopy, 10% Foliage Cover, 1:31)			Mid Density (2' Canopy, 25% Foliage Cover, 1:13)			High Density (2' Canopy, 80% Foliage Cover, 1:4)		
	1' to 3'	3' to 6'	6' & greater	1' to 3'	3' to 6'	6' & greater	1' to 3'	3' to 6'	6' & greater
PLANT FEATURES									
Plant Height (ft)	3	3	3	3	3	3	3	3	3
Undeflected Height of Leaf Mass (H', ft)	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
Equivalent Ave Plant Width (We, ft)	2	2	2	2	2	2	2	2	2
Frontal Area of Plants (Ai, ft^2)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Number of Stems per Plant (#)	4	4	4	4	4	4	2	2	2
Diameter of Stem (Ds, in)	0.25	0.25	0.25	0.5	0.5	0.5	1	1	1
Area of Stem/plant (As, sqft)	0.001363538	0.001363538	0.001363538	0.005454154	0.005454154	0.005454154	0.010908308	0.010908308	0.010908308
Number of Plants per sqft (M, #)	0.032258065	0.032258065	0.032258065	0.076923077	0.076923077	0.076923077	0.25	0.25	0.25
H/Ds	144	144	144	72	72	72	36	36	36
Modulus of Plant Stiffness Table 9	4.76E+04	4.76E+04	4.76E+04	4.76E+04	4.76E+04	4.76E+04	4.76E+04	4.76E+04	4.76E+04
Modulus of Plant Stiffness (Es, lbf/ft^2) (Table 9 multiplied by (H/Ds)^1.5)	8.22E+07	8.22E+07	8.22E+07	2.91E+07	2.91E+07	2.91E+07	1.03E+07	1.03E+07	1.03E+07
HYRAULIC FEATURES									
Depth of Flow (Yo, ft)	2.21	5.92	8.7	2.21	5.92	8.7	2.21	5.92	8.7
Yo/H	0.736666667	1.973333333	2.9	0.736666667	1.973333333	2.9	0.736666667	1.973333333	2.9
Submerged	NO	YES	YES	NO	YES	YES	NO	YES	YES
Frontal Area of Plants (Ai, ft^2)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Wetted Perimiter of Sub-area (P, ft)	47.02	54.44	60	47.02	54.44	60	47.02	54.44	60
Slope (S, ft/ft)	0.0016	0.0022	0.004	0.0016	0.0022	0.004	0.0016	0.0022	0.004
Flow Area (Qa, ft^2)	94	252	370	94	252	370	94	252	370
Hydrulic Radius (Rh, ft)	1.999149298	4.628949302	6.166666667	1.999149298	4.628949302	6.166666667	1.999149298	4.628949302	6.166666667
Shear Velocity (V*, ft/sec)	0.320930167	0.572638427	0.891216397	0.320930167	0.572638427	0.891216397	0.320930167	0.572638427	0.891216397
Fluid Deisity (ρ, slugs/ft^3)	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94
EsAs/(ρAiV*^2)	124680.9914	39161.59334	16167.95134	176325.549	55382.85642	22864.93606	124680.9914	39161.59334	16167.95134
Frontal Area of Plants Unsubmerged (Ai*, ft^2)	4.42	11.84	17.4	4.42	11.84	17.4	4.42	11.84	17.4
EsAs/(ρAi*V*^2)	126937.6609	14884.05152	4181.366725	179516.9617	21049.22753	5913.345532	126937.6609	14884.05152	4181.366725
M*Ai	0.14516129	0.14516129	0.14516129	0.346153846	0.346153846	0.346153846	1.125	1.125	1.125
M*Ai*	0.142580645	0.381935484	0.561290323	0.34	0.910769231	1.338461538	1.105	2.96	4.35
Dynamic Viscosity (v, ft^2/sec)	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05
V**Rh/v	45827.66552	189336.7321	392559.6035	45827.66552	189336.7321	392559.6035	45827.66552	189336.7321	392559.6035
Mannings n	0.034280488	0.053033211	0.039623565	0.04171341	0.071635348	0.053522082	0.048158292	0.092752855	0.069299948

	Forbes Plants - Very Rigid (Es(H/Ds)^1.5) = 1.25E^5 lbf/ft^2)								
	Low Density (2' Canopy, 10% Foliage Cover, 1:31)			Mid Density (2' Canopy, 25% Foliage Cover, 1:13)			High Density (2' Canopy, 80% Foliage Cover, 1:4)		
	1' to 3'	3' to 6'	6' & greater	1' to 3'	3' to 6'	6' & greater	1' to 3'	3' to 6'	6' & greater
PLANT FEATURES									
Plant Height (ft)	3	3	3	3	3	3	3	3	3
Undeflected Height of Leaf Mass (H', ft)	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
Equivalent Ave Plant Width (We, ft)	2	2	2	2	2	2	2	2	2
Frontal Area of Plants (Ai, ft^2)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Number of Stems per Plant (#)	4	4	4	4	4	4	2	2	2
Diameter of Stem (Ds, in)	0.25	0.25	0.25	0.5	0.5	0.5	1	1	1
Area of Stem/plant (As, sqft)	0.001363538	0.001363538	0.001363538	0.005454154	0.005454154	0.005454154	0.010908308	0.010908308	0.010908308
Number of Plants per sqft (M, #)	0.032258065	0.032258065	0.032258065	0.076923077	0.076923077	0.076923077	0.25	0.25	0.25
H/Ds	144	144	144	72	72	72	36	36	36
Modulus of Plant Stiffness Table 9	1.25E+05	1.25E+05	1.25E+05	1.25E+05	1.25E+05	1.25E+05	1.25E+05	1.25E+05	1.25E+05
Modulus of Plant Stiffness (Es, lbf/ft^2) (Table 9 multiplied by (H/Ds)^1.5)	2.16E+08	2.16E+08	2.16E+08	7.64E+07	7.64E+07	7.64E+07	2.70E+07	2.70E+07	2.70E+07
HYRAULIC FEATURES									
Depth of Flow (Yo, ft)	2.21	5.92	8.7	2.21	5.92	8.7	2.21	5.92	8.7
Yo/H	0.736666667	1.973333333	2.9	0.736666667	1.973333333	2.9	0.736666667	1.973333333	2.9
Submerged	NO	YES	YES	NO	YES	YES	NO	YES	YES
Frontal Area of Plants (Ai, ft^2)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Wetted Perimiter of Sub-area (P, ft)	47.02	54.44	60	47.02	54.44	60	47.02	54.44	60
Slope (S, ft/ft)	0.0016	0.0022	0.004	0.0016	0.0022	0.004	0.0016	0.0022	0.004
Flow Area (Qa, ft^2)	94	252	370	94	252	370	94	252	370
Hydrulic Radius (Rh, ft)	1.999149298	4.628949302	6.166666667	1.999149298	4.628949302	6.166666667	1.999149298	4.628949302	6.166666667
Shear Velocity (V*, ft/sec)	0.320930167	0.572638427	0.891216397	0.320930167	0.572638427	0.891216397	0.320930167	0.572638427	0.891216397
Fluid Deisity (ρ, slugs/ft^3)	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94
EsAs/(ρAiV*^2)	327556.1985	102883.547	42475.70234	463234.4184	145499.3075	60069.71432	327556.1985	102883.547	42475.70234
Frontal Area of Plants Unsubmerged (Ai*, ft^2)	4.42	11.84	17.4	4.42	11.84	17.4	4.42	11.84	17.4
EsAs/(ρAi*V*^2)	333484.8175	39102.69946	10985.09543	471618.7517	55299.5679	15535.27094	333484.8175	39102.69946	10985.09543
M*Ai	0.14516129	0.14516129	0.14516129	0.346153846	0.346153846	0.346153846	1.125	1.125	1.125
M*Ai*	0.142580645	0.381935484	0.561290323	0.34	0.910769231	1.338461538	1.105	2.96	4.35
Dynamic Viscosity (v, ft^2/sec)	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05	1.40E-05
V**Rh/v	45827.66552	189336.7321	392559.6035	45827.66552	189336.7321	392559.6035	45827.66552	189336.7321	392559.6035
Mannings n	0.039625051	0.063286894	0.047284566	0.048216816	0.085485653	0.063870286	0.0556665	0.110686116	0.082698717

Manning's 'n' Value per Inundation Depth Above Plant Base			
Inundation Depth	Shallow (1' to 3')	Medium (3' to 6')	Deep (> 6')
Trees (up to 6" trunk diameter)			
Low Density (1:1250 sf)	--	0.035	--
Medium Density (1:314 sf)	--	0.051	--
High Density (1:78 sf)	--	0.074	--
Woody Vegetation (up to 60" tall x 48" wide)			
Stiffness - Flexible			
Low Density (1:125 sf)	0.025	0.042	0.031
Medium Density (1:50 sf)	0.029	0.053	0.040
High Density (1:16 sf)	0.035	0.073	0.055
Stiffness - Rigid			
Low Density (1:125 sf)	0.034	0.061	0.045
Medium Density (1:50 sf)	0.040	0.078	0.058
High Density (1:16 sf)	0.048	0.106	0.080
Stiffness - Very Rigid			
Low Density (1:125 sf)	0.038	0.068	0.051
Medium Density (1:50 sf)	0.044	0.087	0.065
High Density (1:16 sf)	0.053	0.119	0.089
Forbes / Non-woody Vegetation (up to 36" tall x 24" wide)			
Stiffness - Flexible			
Low Density (1:125 sf)	0.026	0.039	0.029
Medium Density (1:50 sf)	0.032	0.052	0.039
High Density (1:16 sf)	0.037	0.068	0.051
Stiffness - Rigid			
Low Density (1:125 sf)	0.034	0.053	0.040
Medium Density (1:50 sf)	0.042	0.072	0.054
High Density (1:16 sf)	0.048	0.093	0.069
Stiffness - Very Rigid			
Low Density (1:125 sf)	0.040	0.063	0.047
Medium Density (1:50 sf)	0.048	0.085	0.064
High Density (1:16 sf)	0.056	0.111	0.083
Upland & Wetland Grasses			
Inundation Depth	Shallow (< 1x Height of Grass)	Medium (1x to 2x Ht. of Grass)	Deep (>2x Height of Grass)
Short Turf Grasses	0.060	0.035	0.010
Field Grasses (Up to 24" Height)	0.080	0.040	0.020
Field Grasses (Greater than 24" Height)	0.100	0.050	0.025

ICON ENGINEERING, INC.

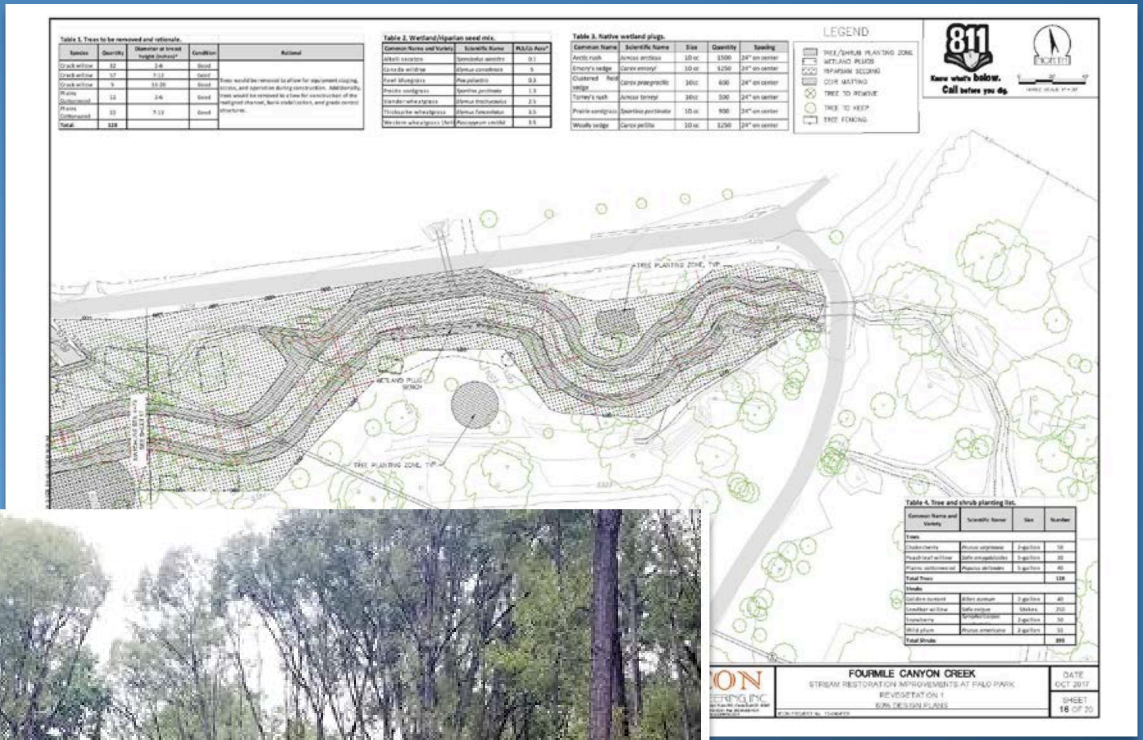
	Manning's 'n' Value per Inundation Depth Above Plant Base		
Inundation Depth	Shallow (1' to 3')	Medium (3' to 6')	Deep (> 6')
Trees (up to 6" trunk diameter)			
Low Density (1:1250 sf)	--	0.035	--
Medium Density (1:314 sf)	--	0.051	--
High Density (1:78 sf)	--	0.074	--
Woody Vegetation (up to 60" tall x 48" wide)			
Stiffness - Flexible			
Low Density (1:125 sf)	0.025	0.042	0.031
Medium Density (1:50 sf)	0.029	0.053	0.040
High Density (1:16 sf)	0.035	0.073	0.055
Stiffness - Rigid			
Low Density (1:125 sf)	0.034	0.061	0.045
Medium Density (1:50 sf)	0.040	0.078	0.058
High Density (1:16 sf)	0.048	0.106	0.080
Stiffness - Very Rigid			
Low Density (1:125 sf)	0.038	0.068	0.051
Medium Density (1:50 sf)	0.044	0.087	0.065
High Density (1:16 sf)	0.053	0.119	0.089
Forbes / Non-woody Vegetation (up to 36" tall x 24" wide)			
Stiffness - Flexible			
Low Density (1:125 sf)	0.026	0.039	0.029
Medium Density (1:50 sf)	0.032	0.052	0.039
High Density (1:16 sf)	0.037	0.068	0.051
Stiffness - Rigid			
Low Density (1:125 sf)	0.034	0.053	0.040
Medium Density (1:50 sf)	0.042	0.072	0.054
High Density (1:16 sf)	0.048	0.093	0.069
Stiffness - Very Rigid			
Low Density (1:125 sf)	0.040	0.063	0.047
Medium Density (1:50 sf)	0.048	0.085	0.064
High Density (1:16 sf)	0.056	0.111	0.083
Upland & Wetland Grasses			
Inundation Depth	Shallow (< 1x Height of Grass)	Medium (1x to 2x Ht. of Grass)	Deep (>2x Height of Grass)
Short Turf Grasses	0.060	0.035	0.010
Field Grasses (Up to 24" Height)	0.080	0.040	0.020
Field Grasses (Greater than 24" Height)	0.100	0.050	0.025

TR-OO-25 Computation

USGS, Water-supply Paper 2339

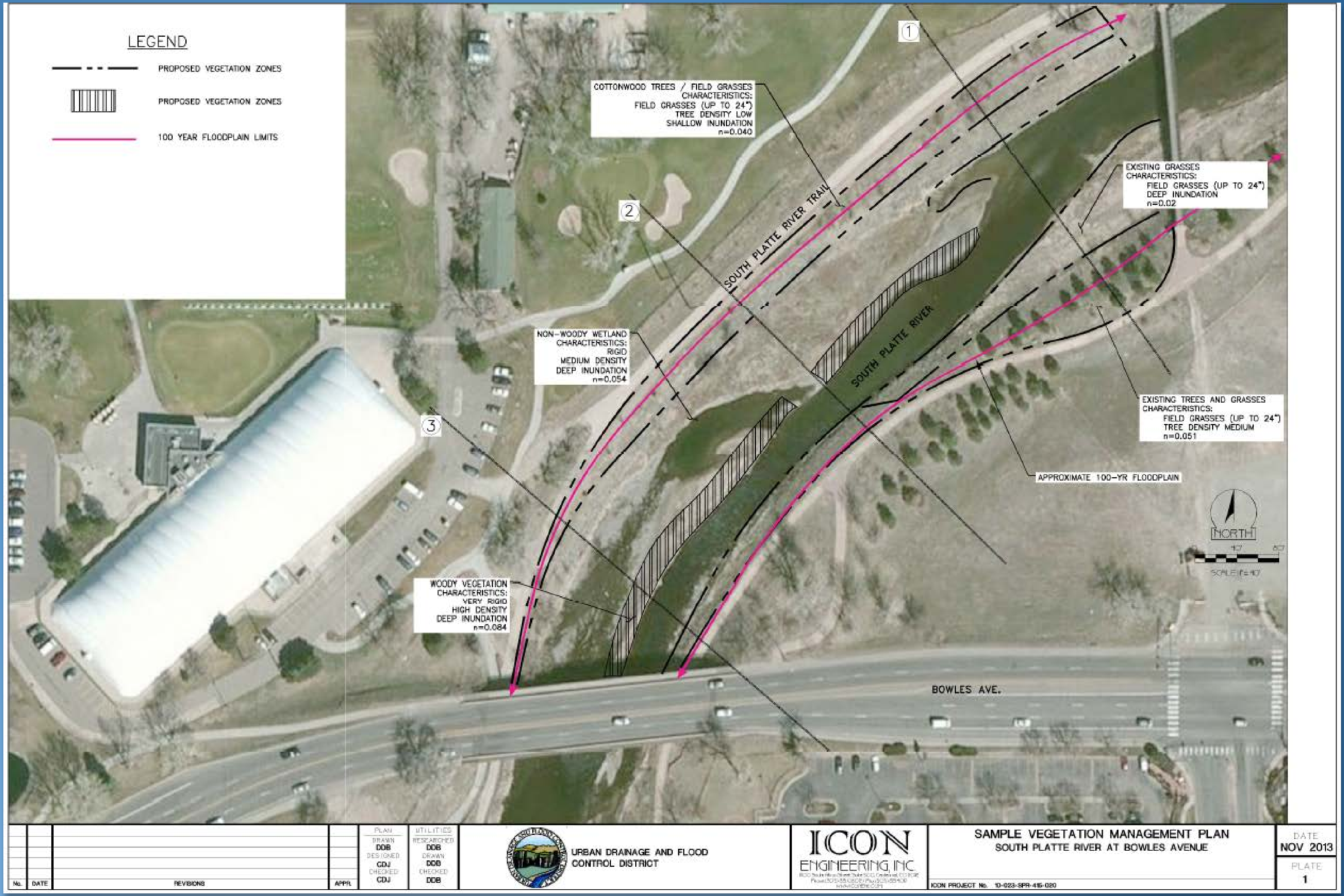
ICON ENGINEERING, INC.

Application



ICON ENGINEERING, INC.

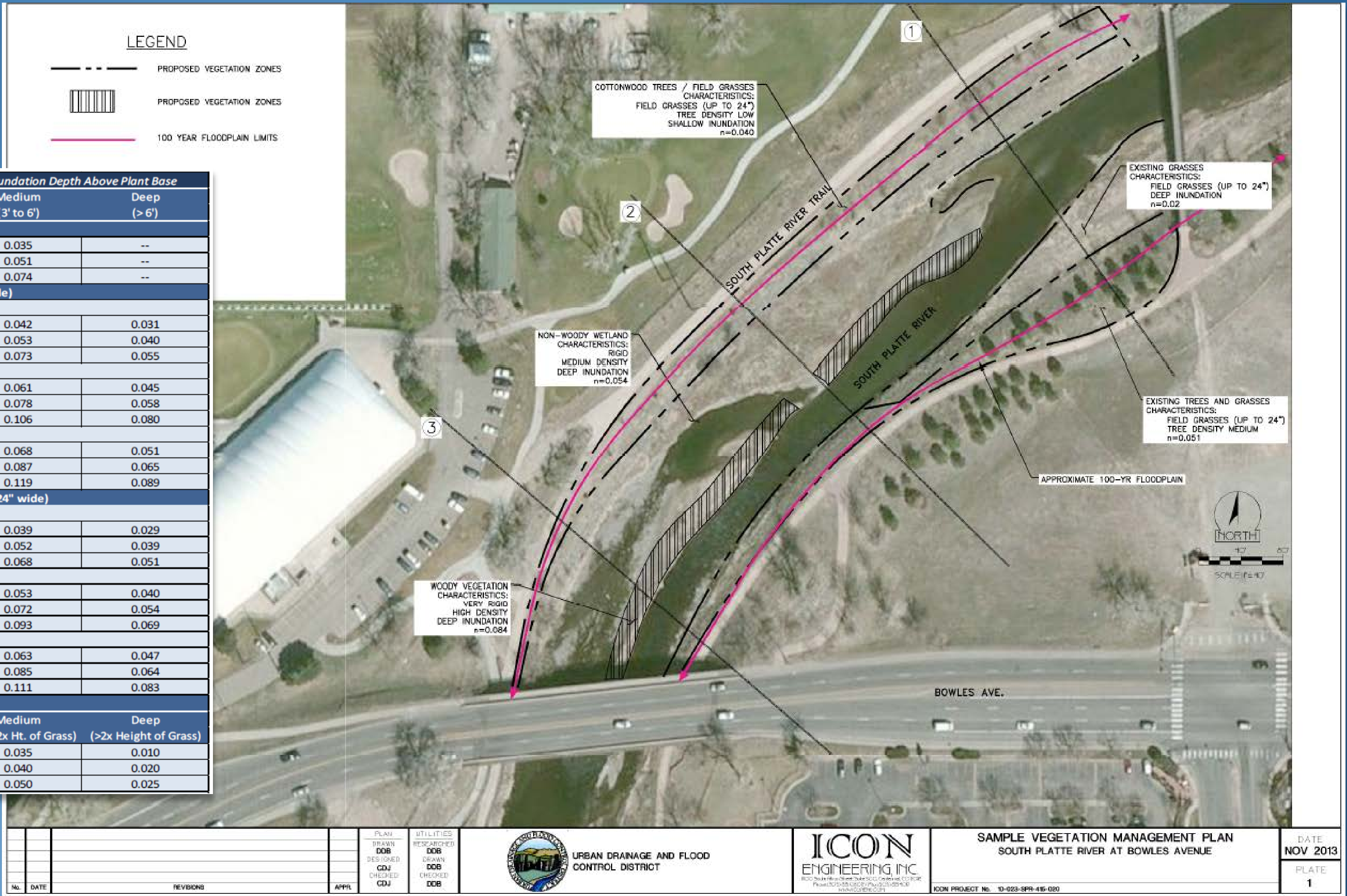
Application



ICON ENGINEERING, INC.

Application

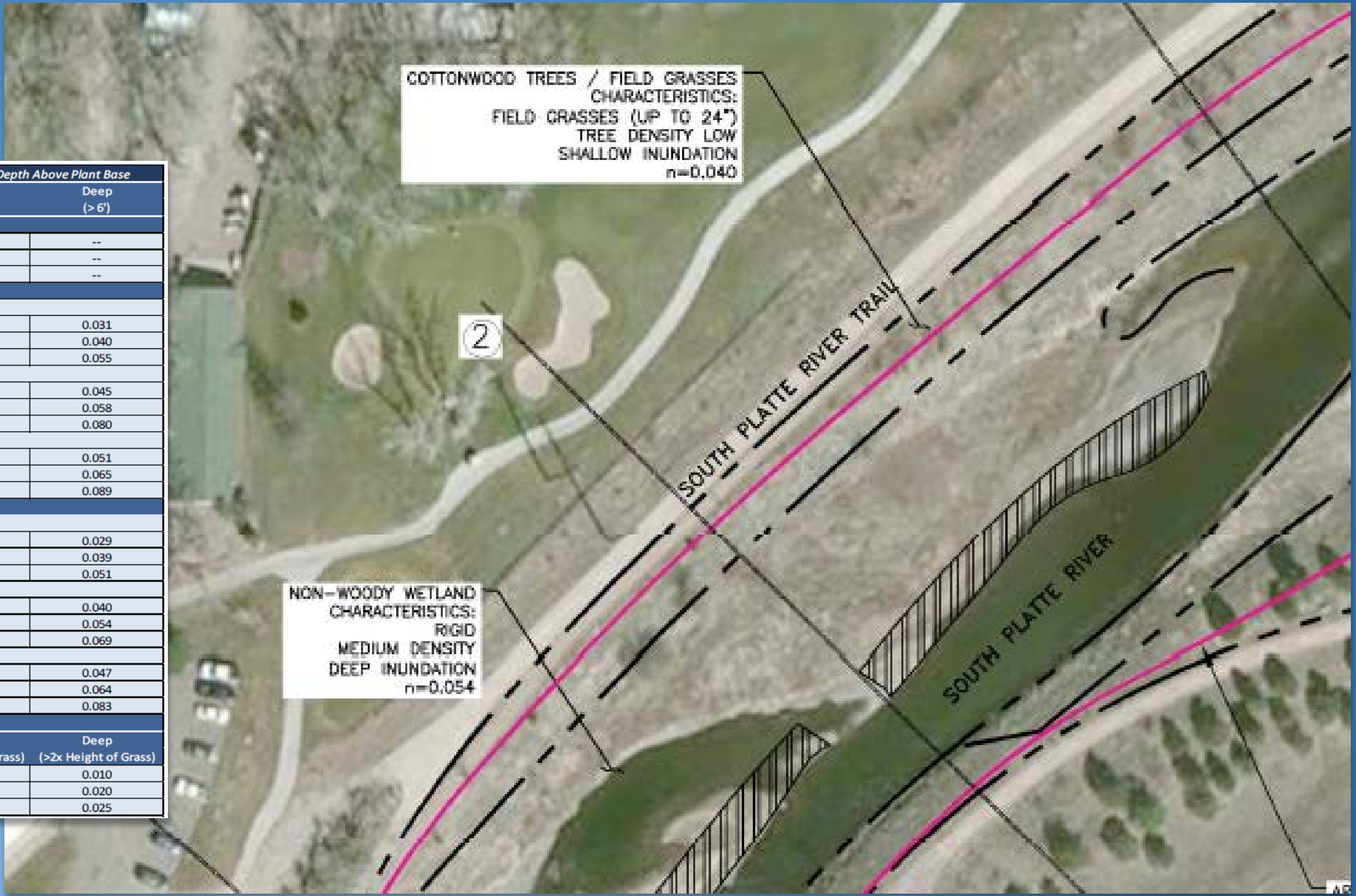
Manning's 'n' Value per Inundation Depth Above Plant Base			
Inundation Depth	Shallow (1' to 3')	Medium (3' to 6')	Deep (> 6')
Trees (up to 6" trunk diameter)			
Low Density (1:1250 sf)	--	0.035	--
Medium Density (1:314 sf)	--	0.051	--
High Density (1:78 sf)	--	0.074	--
Woody Vegetation (up to 60" tall x 48" wide)			
Stiffness - Flexible			
Low Density (1:125 sf)	0.025	0.042	0.031
Medium Density (1:50 sf)	0.029	0.053	0.040
High Density (1:16 sf)	0.035	0.073	0.055
Stiffness - Rigid			
Low Density (1:125 sf)	0.034	0.061	0.045
Medium Density (1:50 sf)	0.040	0.078	0.058
High Density (1:16 sf)	0.048	0.106	0.080
Stiffness - Very Rigid			
Low Density (1:125 sf)	0.038	0.068	0.051
Medium Density (1:50 sf)	0.044	0.087	0.065
High Density (1:16 sf)	0.053	0.119	0.089
Forbes / Non-woody Vegetation (up to 36" tall x 24" wide)			
Stiffness - Flexible			
Low Density (1:125 sf)	0.026	0.039	0.029
Medium Density (1:50 sf)	0.032	0.052	0.039
High Density (1:16 sf)	0.037	0.068	0.051
Stiffness - Rigid			
Low Density (1:125 sf)	0.034	0.053	0.040
Medium Density (1:50 sf)	0.042	0.072	0.054
High Density (1:16 sf)	0.048	0.093	0.069
Stiffness - Very Rigid			
Low Density (1:125 sf)	0.040	0.063	0.047
Medium Density (1:50 sf)	0.048	0.085	0.064
High Density (1:16 sf)	0.056	0.111	0.083
Upland & Wetland Grasses			
Inundation Depth	Shallow (< 1x Height of Grass)	Medium (1x to 2x Ht. of Grass)	Deep (>2x Height of Grass)
Short Turf Grasses	0.060	0.035	0.010
Field Grasses (Up to 24" Height)	0.080	0.040	0.020
Field Grasses (Greater than 24" Height)	0.100	0.050	0.025



ICON ENGINEERING, INC.

Application

Manning's 'n' Value per Inundation Depth Above Plant Base			
Inundation Depth	Shallow (1' to 3')	Medium (3' to 6')	Deep (> 6')
Trees (up to 6" trunk diameter)			
Low Density (1:1250 sf)	--	0.035	--
Medium Density (1:314 sf)	--	0.051	--
High Density (1:78 sf)	--	0.074	--
Woody Vegetation (up to 60" tall x 48" wide)			
Stiffness - Flexible			
Low Density (1:125 sf)	0.025	0.042	0.031
Medium Density (1:50 sf)	0.029	0.053	0.040
High Density (1:16 sf)	0.035	0.073	0.055
Stiffness - Rigid			
Low Density (1:125 sf)	0.034	0.061	0.045
Medium Density (1:50 sf)	0.040	0.078	0.058
High Density (1:16 sf)	0.048	0.106	0.080
Stiffness - Very Rigid			
Low Density (1:125 sf)	0.038	0.068	0.051
Medium Density (1:50 sf)	0.044	0.087	0.065
High Density (1:16 sf)	0.053	0.119	0.089
Forbes / Non-woody Vegetation (up to 36" tall x 24" wide)			
Stiffness - Flexible			
Low Density (1:125 sf)	0.026	0.039	0.029
Medium Density (1:50 sf)	0.032	0.052	0.039
High Density (1:16 sf)	0.037	0.068	0.051
Stiffness - Rigid			
Low Density (1:125 sf)	0.034	0.053	0.040
Medium Density (1:50 sf)	0.042	0.072	0.054
High Density (1:16 sf)	0.048	0.093	0.069
Stiffness - Very Rigid			
Low Density (1:125 sf)	0.040	0.063	0.047
Medium Density (1:50 sf)	0.048	0.085	0.064
High Density (1:16 sf)	0.056	0.111	0.083
Upland & Wetland Grasses			
Inundation Depth	Shallow (< 1x Height of Grass)	Medium (1x to 2x Ht. of Grass)	Deep (>2x Height of Grass)
Short Turf Grasses	0.060	0.035	0.010
Field Grasses (Up to 24" Height)	0.080	0.040	0.020
Field Grasses (Greater than 24" Height)	0.100	0.050	0.025



Conclusions

- **Interesting or Applicability?**
- **Helpful or Uneasy?**
- **Next Steps.....**
  - **More data for forbes & non-woody species**
  - **Calibration and confirmation from high flow eve**
  - **Selection of plants for bioengineering structure/less flow resistance**
- **Do you need an Owl for Your garden?**

Evaluating and Improving Large-Scale 2D H&H Studies in Challenging Mountainous Regions

A Case Study from Garfield County, CO

Garrett Sprouse, EI, CFM
Eli Gruber, PE

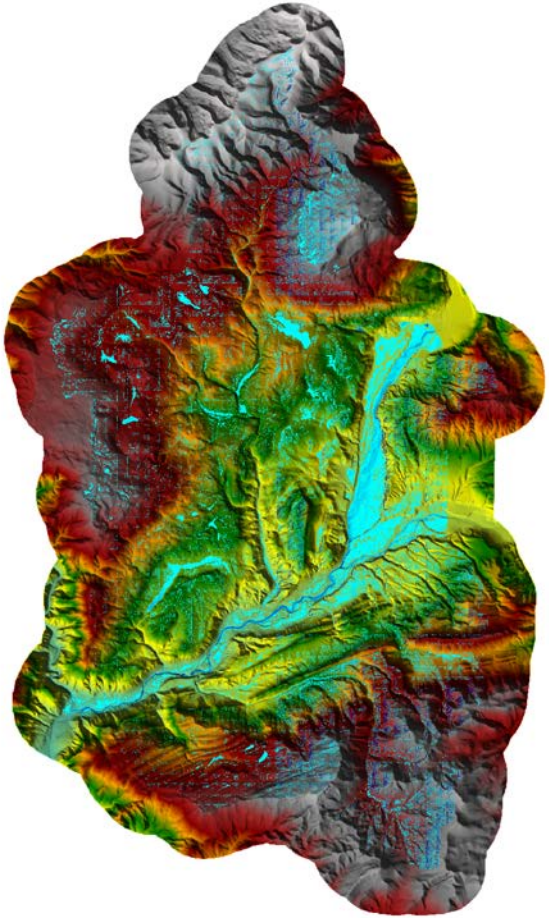
September 26, 2019

CDM Smith

WATER + ENVIRONMENT + TRANSPORTATION + ENERGY + FACILITIES

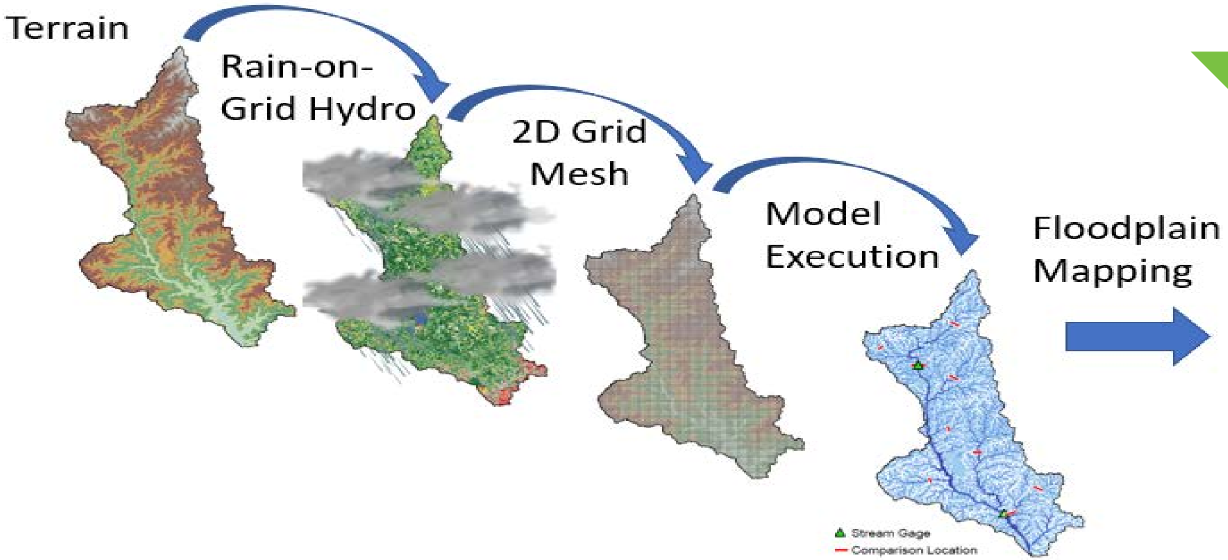
Overview

- Define 2D Base Level Engineering (BLE)
- Research and Development (R&D) project scope and background
- R&D methods and results
- Process improvements and decision support tools



2D Base Level Engineering (BLE)

- What is BLE?
  - Watershed-level hydraulic modeling and floodplain mapping



Accuracy & Efficiency

Cost & Time

CDM Smith

R&D Scope

- Investigate 2D BLE limitations
- Identify potential solutions
- Test viable solutions to provide proof-of-concept
  - Hydrologic considerations
  - Steep sloped streams
- Develop tools to improve 2D BLE

2D BLE Process Constraints

Hydrologic flexibility

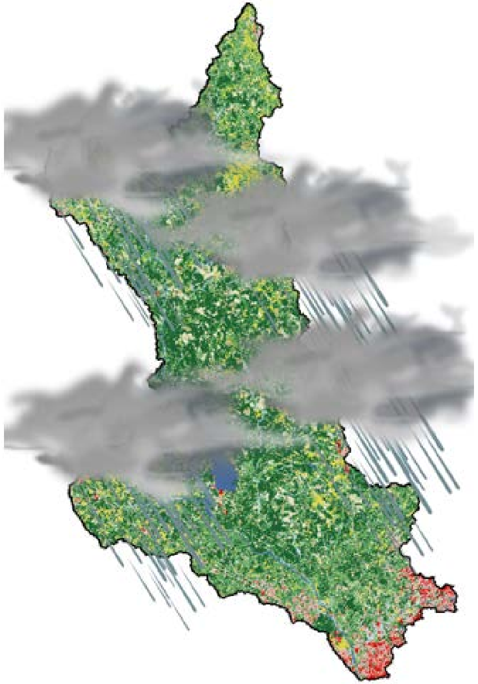
- No spatial variability for rain-on-grid inputs within model domain
- Limited knobs to turn for hydrologic calibration

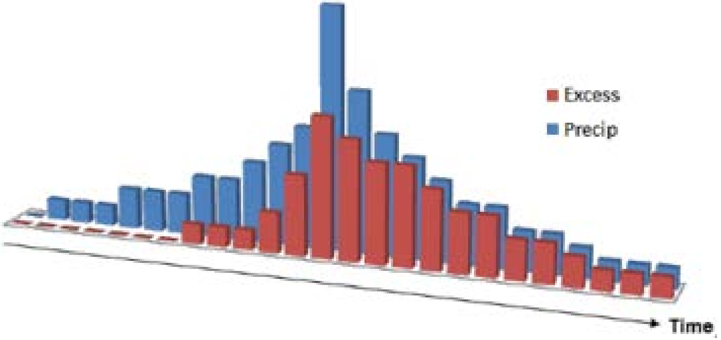
Modeling and mapping steep slopes

- RAS Mapper results export and interpolation limited
- Balancing accuracy versus efficiency
  - Cost in accuracy while maintaining BLE-level efficiency

Hydrologic Flexibility

- Excess hyetograph represents average CN and precip over entire watershed
- Will not represent 100-year runoff for all streams
  - Variable hydrologic drivers and storm distributions (snowmelt, rain on snow, cloudburst, etc.)
- Adjust hydrology to optimize model results





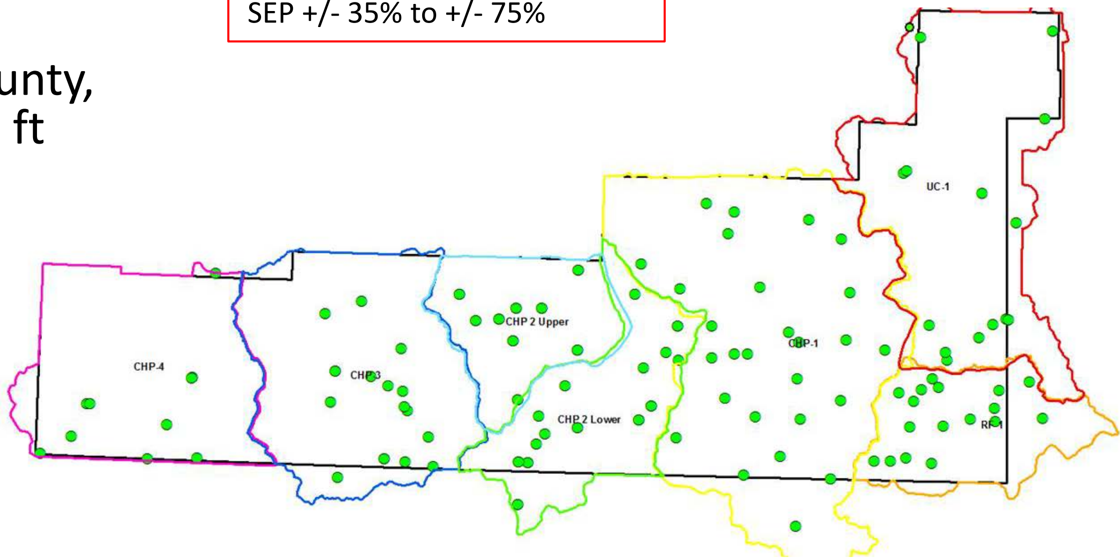
Garfield County Example

- Physical System*:
  - <8,000 ft -> cloudburst storms
  - >8,000 ft -> snowmelt and rain on snow
- Modeled: 24-hour SCS Type II Storm
- On average, each Garfield County, CO model domain has 6,000+ ft elevation difference

*Per Garfield County, CO FIS (080205V001A)

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%

SEP +/- 35% to +/- 75%



R&D Investigation

- Opportunities to improve results?
  - Averaging rain-on-grid parameters over different scales

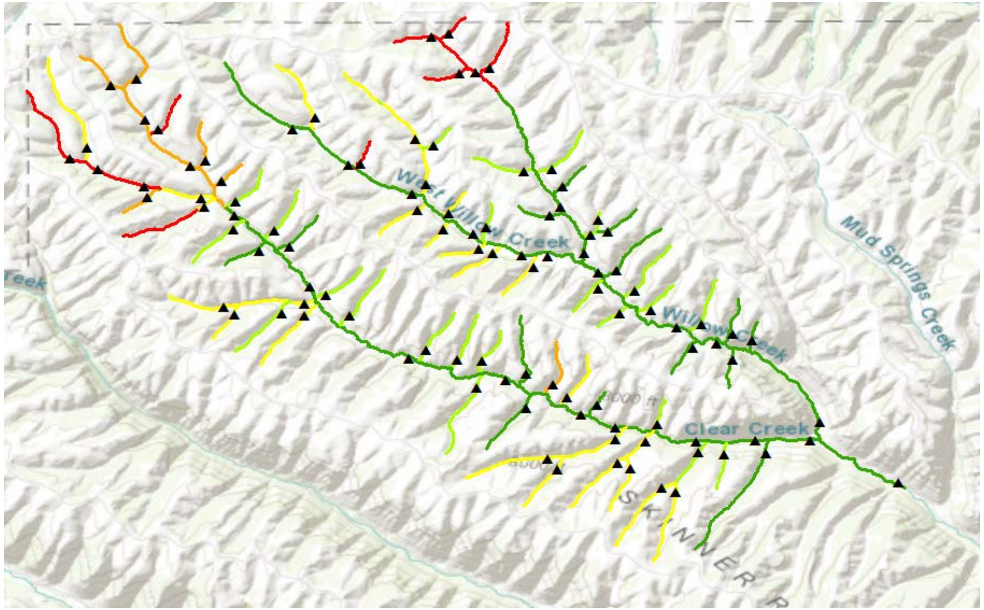
Scenario Test	CN	Excess Precip (in)	Discharge at Gage (cfs)			
			USGS 100yr	Scenario Test	Difference from USGS 100yr	% Difference from USGS 100yr
Original CN, BLE Precip	66.48	2.92	707	1,079	372	52.6%
Calibrated CN, BLE Precip	67.48	2.92	707	-	-	-
HUC8 CN, HUC8 Precip	69.72	2.72	707	634	-73	-10.3%
HUC10 CN, HUC10 Precip	64.43	2.94	707	370	-337	-47.7%
HUC12 CN, HUC12 Precip	57.38	3.06	707	61	-646	-91.4%
Local CN, Local Precip	57.44	3.16	707	73	-634	-89.7%

(orange)	Model Area Averaged Values
(yellow)	Calibrated BLE Values
(blue)	Variable CN, Variable Precip

** Generic rain on grid inputs aren't representative of the physical system

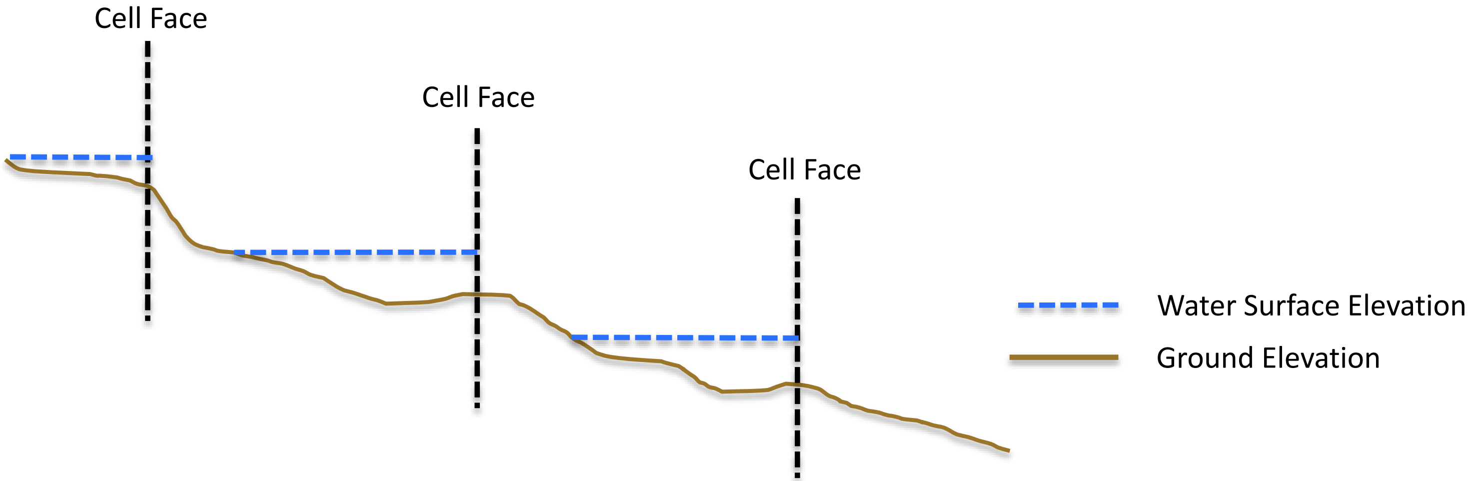
Findings

- A single stream within a watershed will require calibration
- Really need spatially variable parameters to accomplish more accurate hydrology across the watershed
- More data for optimization process (i.e., calculated 100-yr flows) = better watershed-wide representation

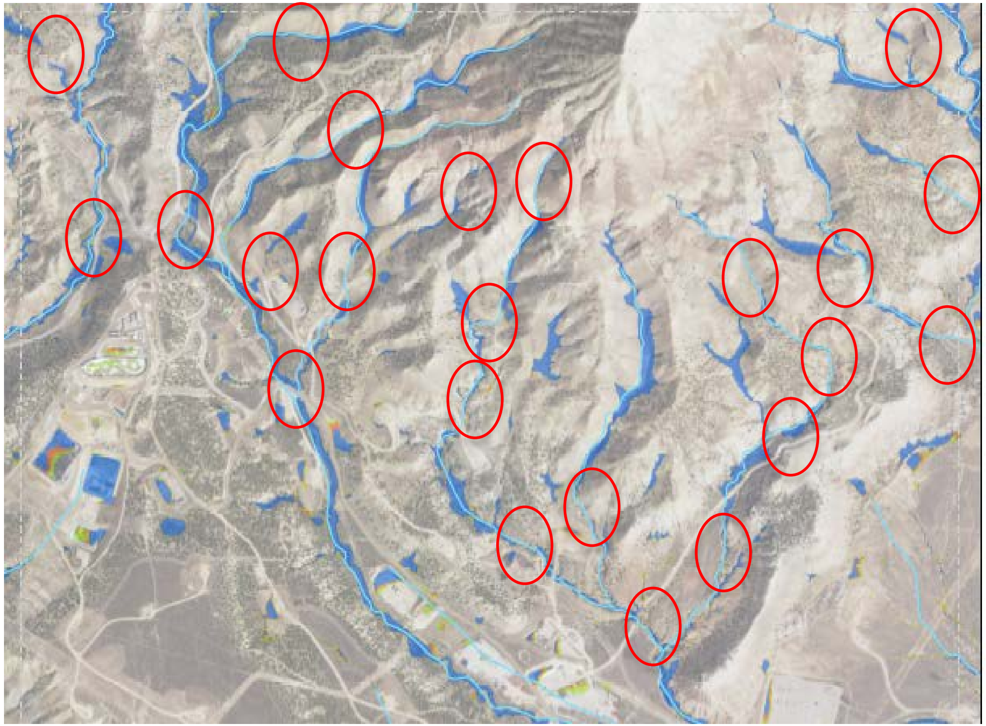


Floodplain Connectivity Issues

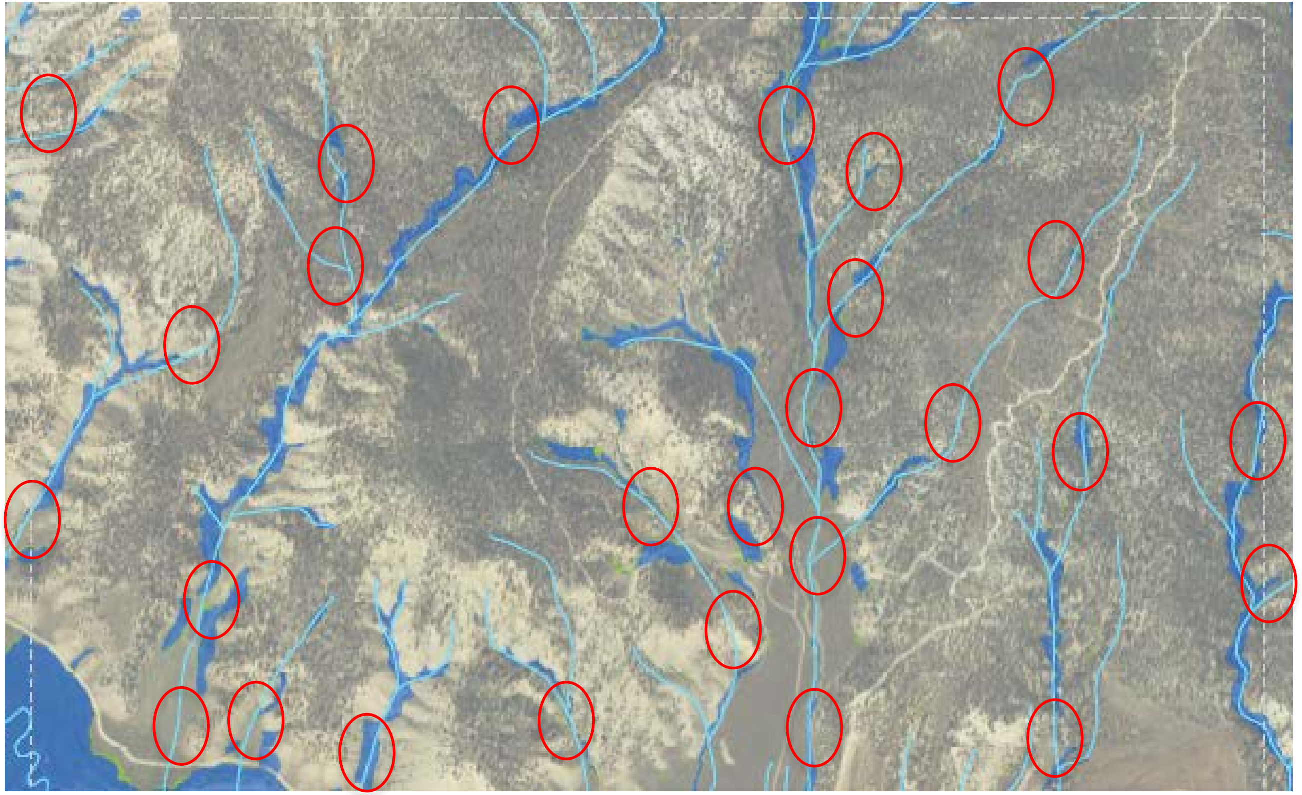
- Steep slopes cause “stairstep mapping”
- HEC-RAS fills lowest elevations of a cell first
- Reducing cell size improves connectivity – computational cost



Floodplain Connectivity Issues



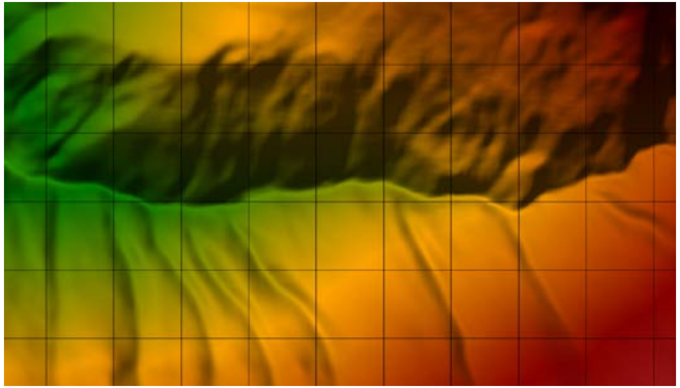
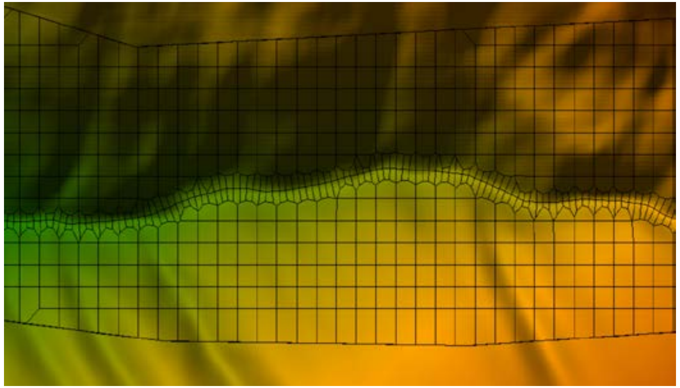
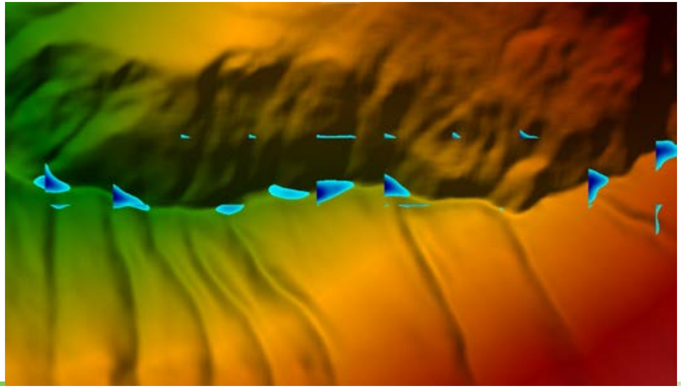
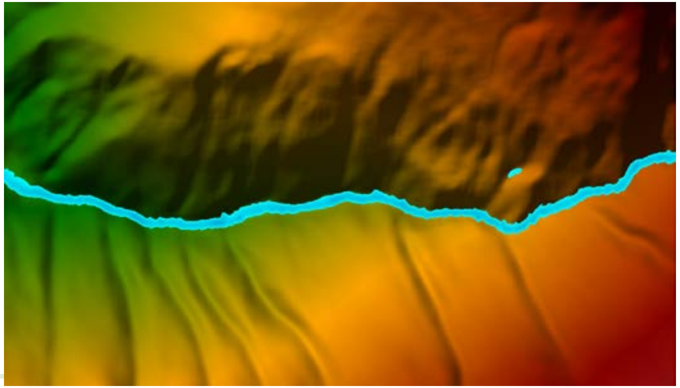
Floodplain Connectivity Issues



Solutions

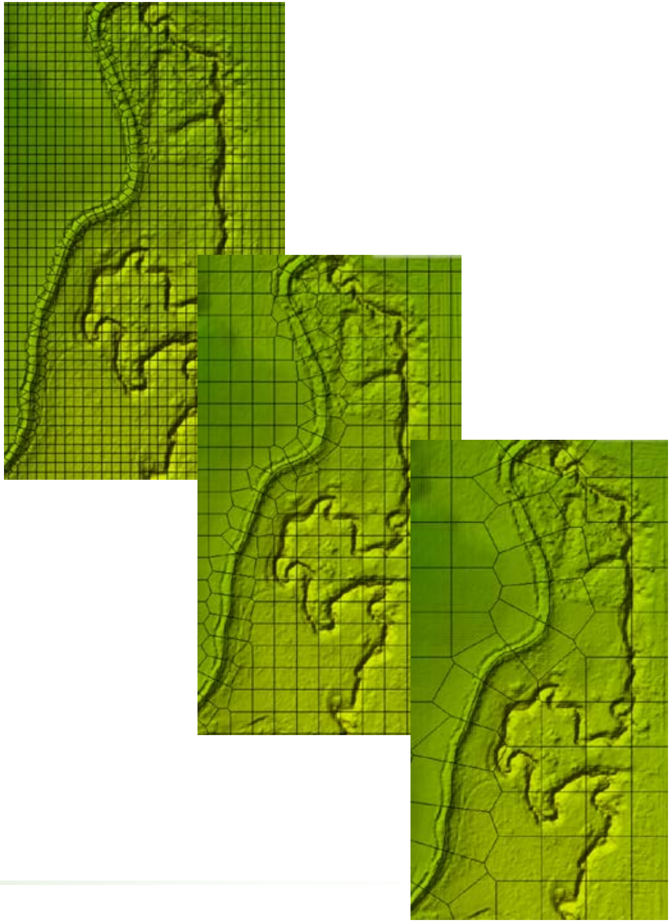
- Improve mapping interpolation methods
  - May overestimate floodplain
- Reduce grid cell size
  - Computational cost (cell size vs. run time)
  - Cell alignment

Effects of Cell Size Reduction/Alignment

Before	After
	
	

Methodology

- Can we determine what grid cell size produces mappable results
- Tested variable grid cell sizes, slopes, and discharges relationship to floodplain connectivity
  - Discharges (cfs): 10, 50, 100, 500, 1000, 5000
  - Grid Cell Sizes (ft): 10, 20, 50, 100, 200
  - Basins: 15 in total
  - Avg. Stream Slope: Ranging from 0.5 – 15.5 %



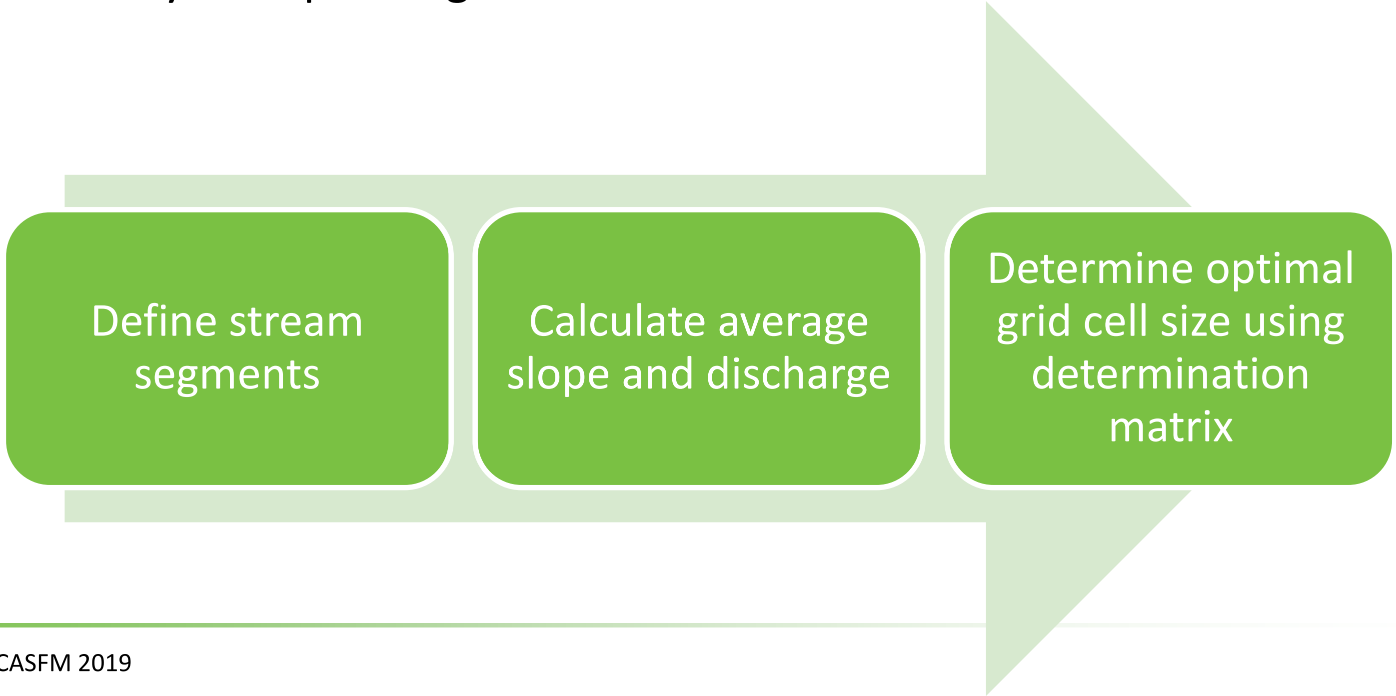
Slope and Discharge to Determine Grid Cell Size

Slope %	Grid Cell Size (ft)	Discharge (cfs)					
		10	50	100	500	1,000	5,000
0-2	10	Yes	Yes	Yes	Yes	Yes	Yes
	20	Yes	Yes	Yes	Yes	Yes	Yes
	50	No	Yes	Yes	Yes	Yes	Yes
	100	No	No	No	Yes	Yes	Yes
	200	No	No	No	No	Yes	Yes
6-8	10	No	Yes	Yes	Yes	Yes	Yes
	20	No	No	No	Yes	Yes	Yes
	50	No	No	No	No	Yes	Yes
	100	No	No	No	No	No	Yes
	200	No	No	No	No	No	No

Slope %	Grid Cell Size (ft)	Discharge (cfs)					
		10	50	100	500	1,000	5,000
10-12	10	No	Yes	Yes	Yes	Yes	Yes
	20	No	No	No	Yes	Yes	Yes
	50	No	No	No	No	No	Yes
	100	No	No	No	No	No	No
	200	No	No	No	No	No	No
14-16	10	No	No	No	Yes	Yes	Yes
	20	No	No	No	No	No	Yes
	50	No	No	No	No	No	No
	100	No	No	No	No	No	No
	200	No	No	No	No	No	No

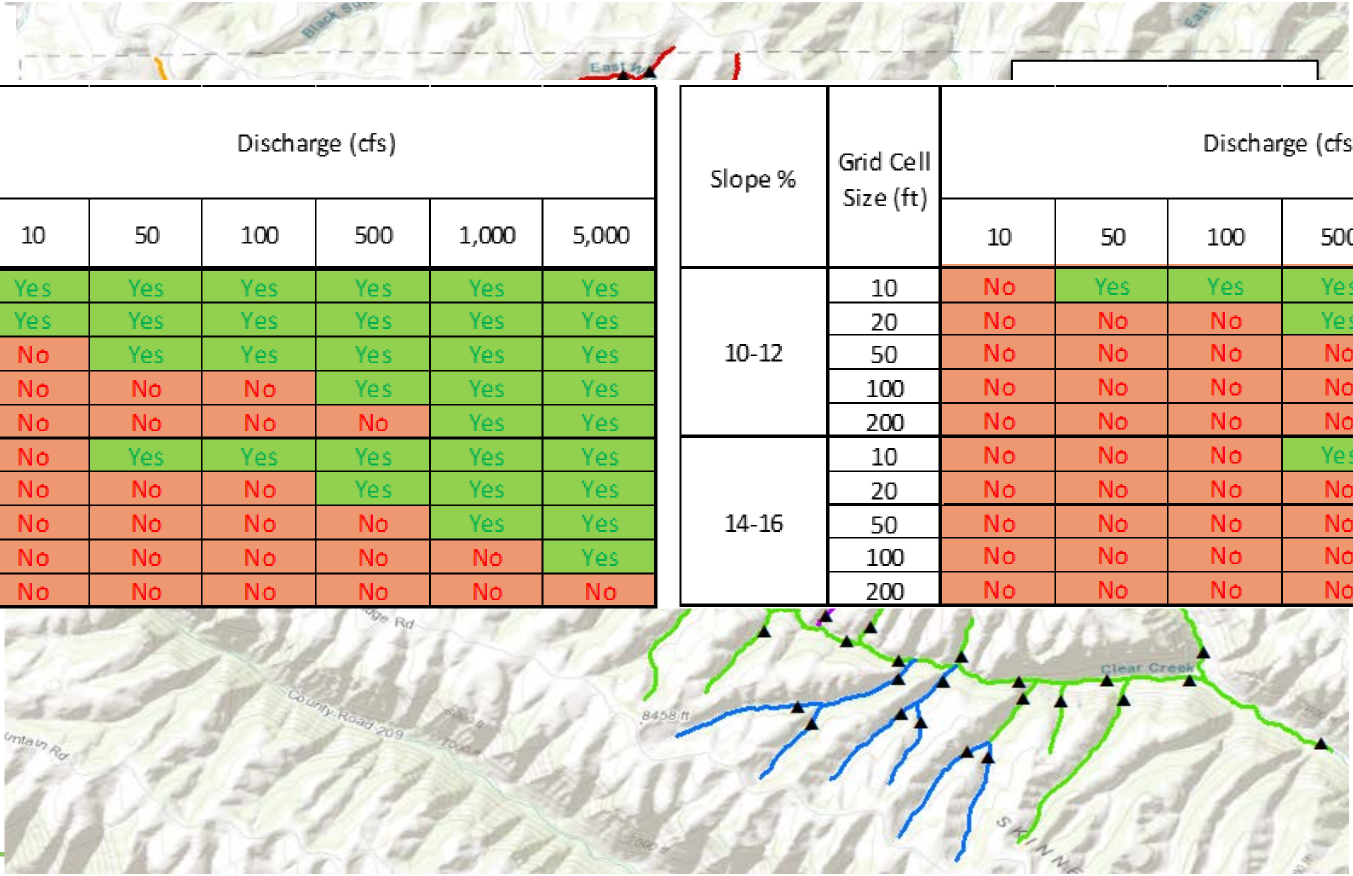
R&D Solution – 2D BLE Scoping Tool

- Create automated tool to:
  - Determine if 2D BLE appropriate for watershed
  - Identify the optimal grid cell size for all streams within a watershed:



Example Tool Process

Average Stream Slope (%)



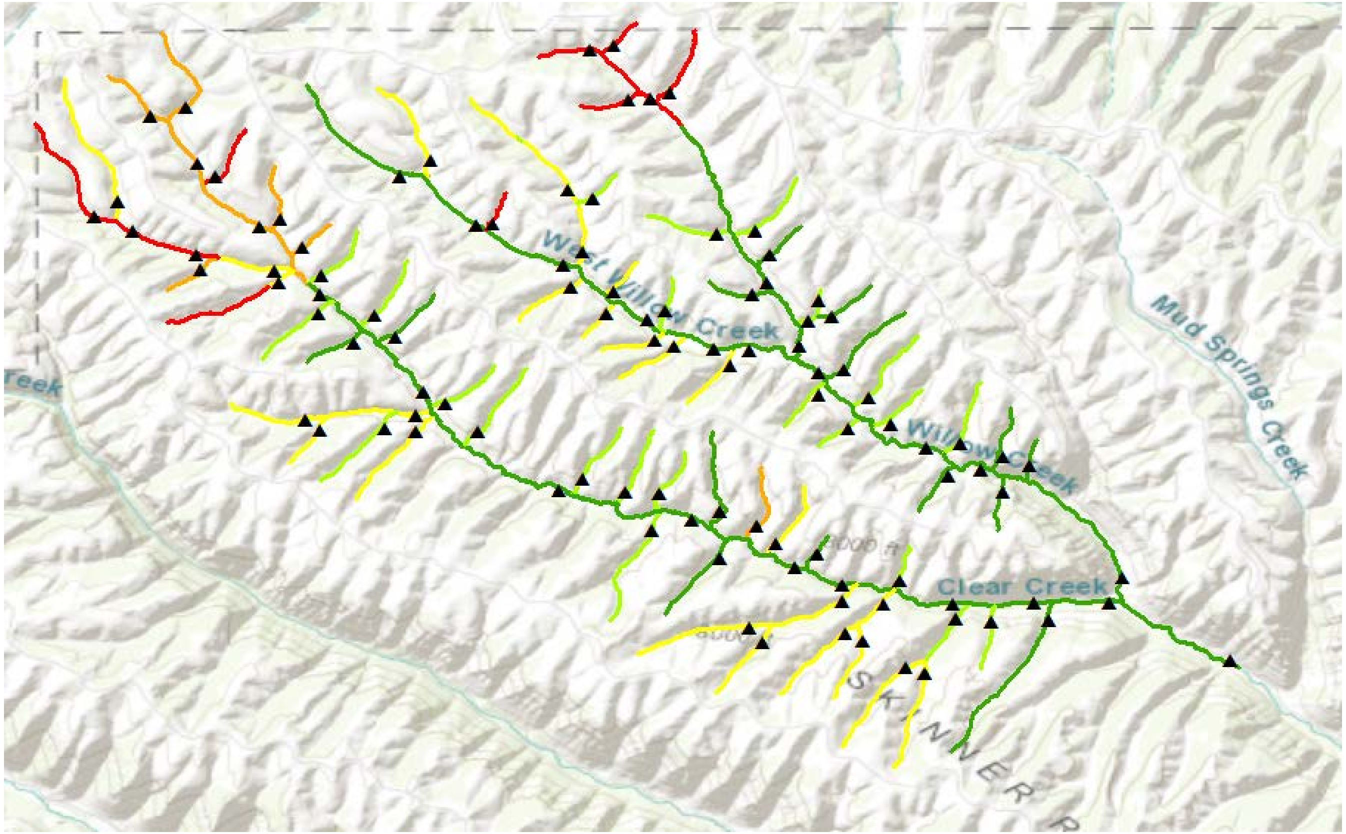
Slope %	Grid Cell Size (ft)	Discharge (cfs)					
		10	50	100	500	1,000	5,000
0-2	10	Yes	Yes	Yes	Yes	Yes	Yes
	20	Yes	Yes	Yes	Yes	Yes	Yes
	50	No	Yes	Yes	Yes	Yes	Yes
	100	No	No	No	Yes	Yes	Yes
	200	No	No	No	No	Yes	Yes
6-8	10	No	Yes	Yes	Yes	Yes	Yes
	20	No	No	No	Yes	Yes	Yes
	50	No	No	No	No	Yes	Yes
	100	No	No	No	No	No	Yes
	200	No	No	No	No	No	No

Slope %	Grid Cell Size (ft)	Discharge (cfs)					
		10	50	100	500	1,000	5,000
10-12	10	No	Yes	Yes	Yes	Yes	Yes
	20	No	No	No	Yes	Yes	Yes
	50	No	No	No	No	No	Yes
	100	No	No	No	No	No	No
	200	No	No	No	No	No	No
14-16	10	No	No	No	Yes	Yes	Yes
	20	No	No	No	No	No	Yes
	50	No	No	No	No	No	No
	100	No	No	No	No	No	No
	200	No	No	No	No	No	No

Grid Cell Requirements

Grid Cell Size Requirement (ft)

- 10
- 20
- 50
- 100
- 200



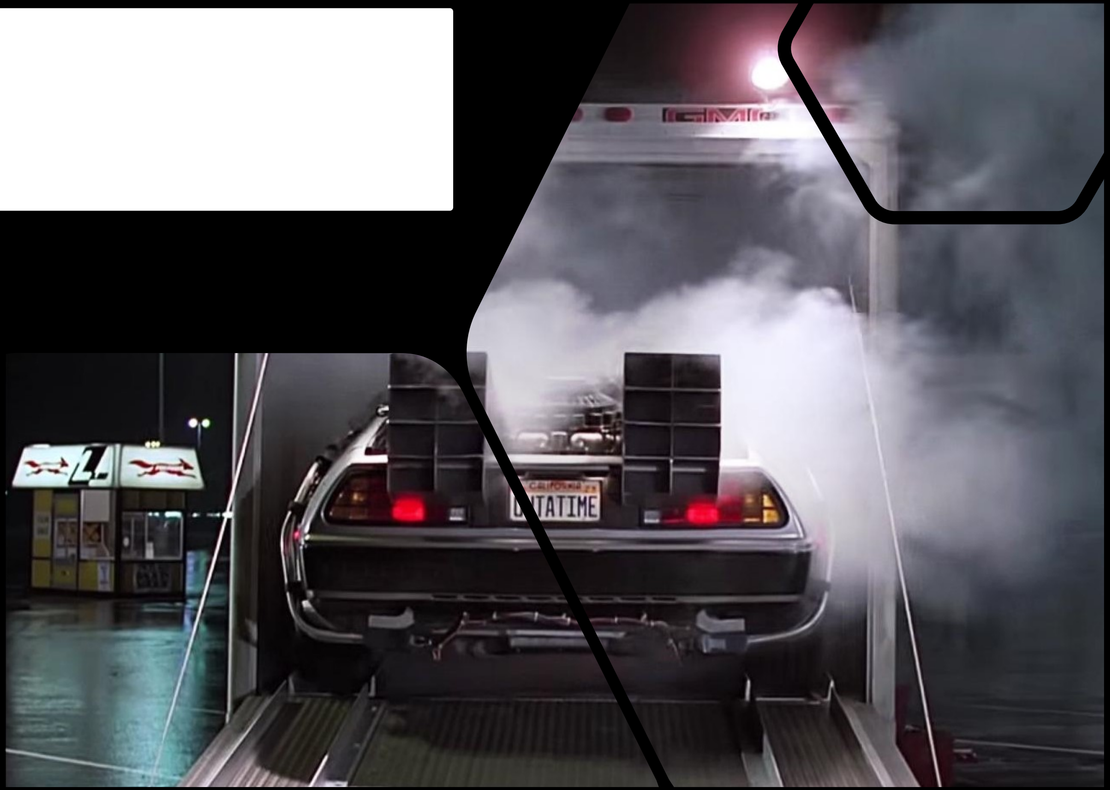
Future of 2D BLE

- Improved scoping and initial model development decisions
- Improved mapping decisions
- Better calibration decisions and model feedback
- HEC-RAS 5.1 capability will change the game

Questions?

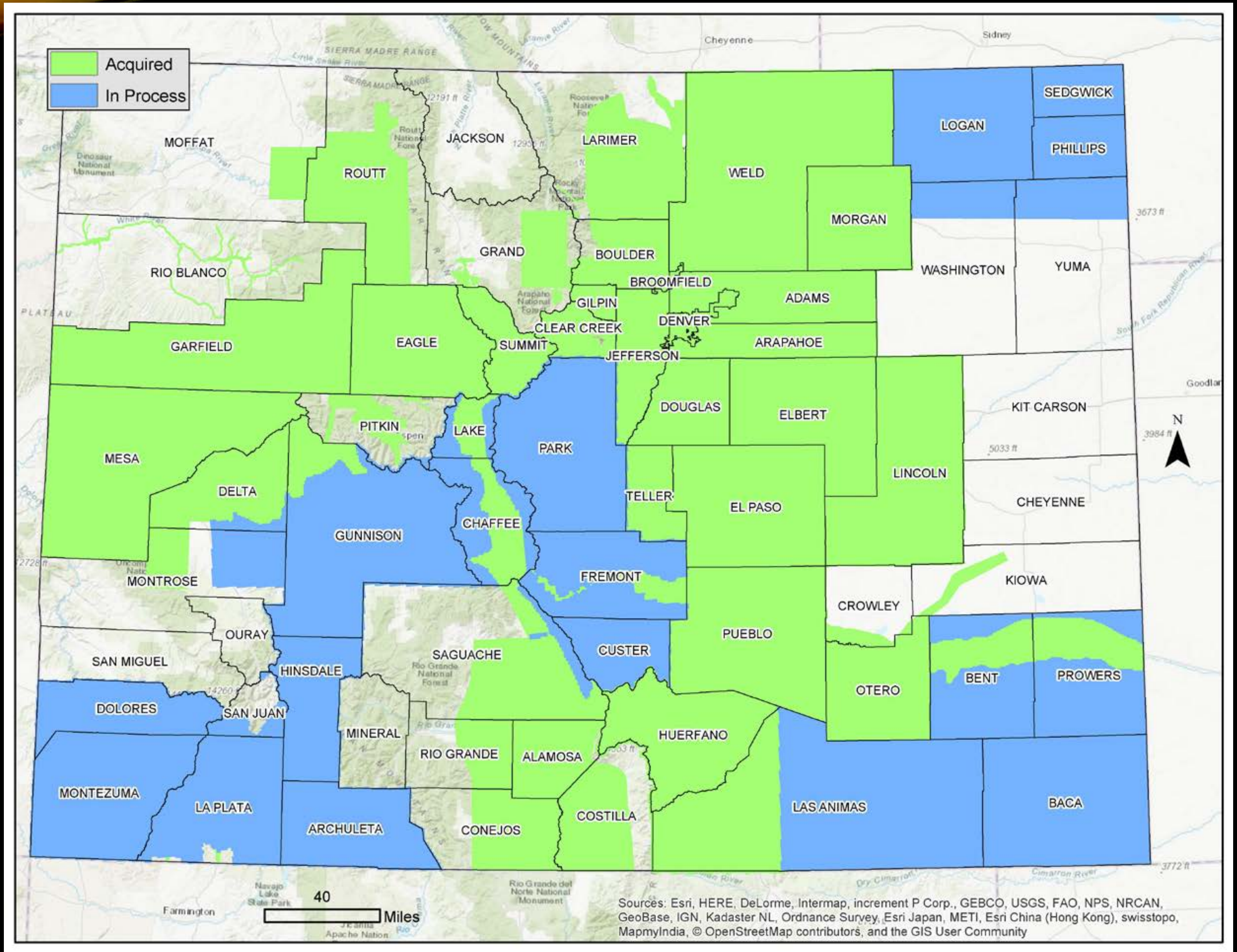

RISK MAP:
PAST, PRESENT,
FUTURE
Thuy Patton, CWCB
Rigel Rucker, AECOM

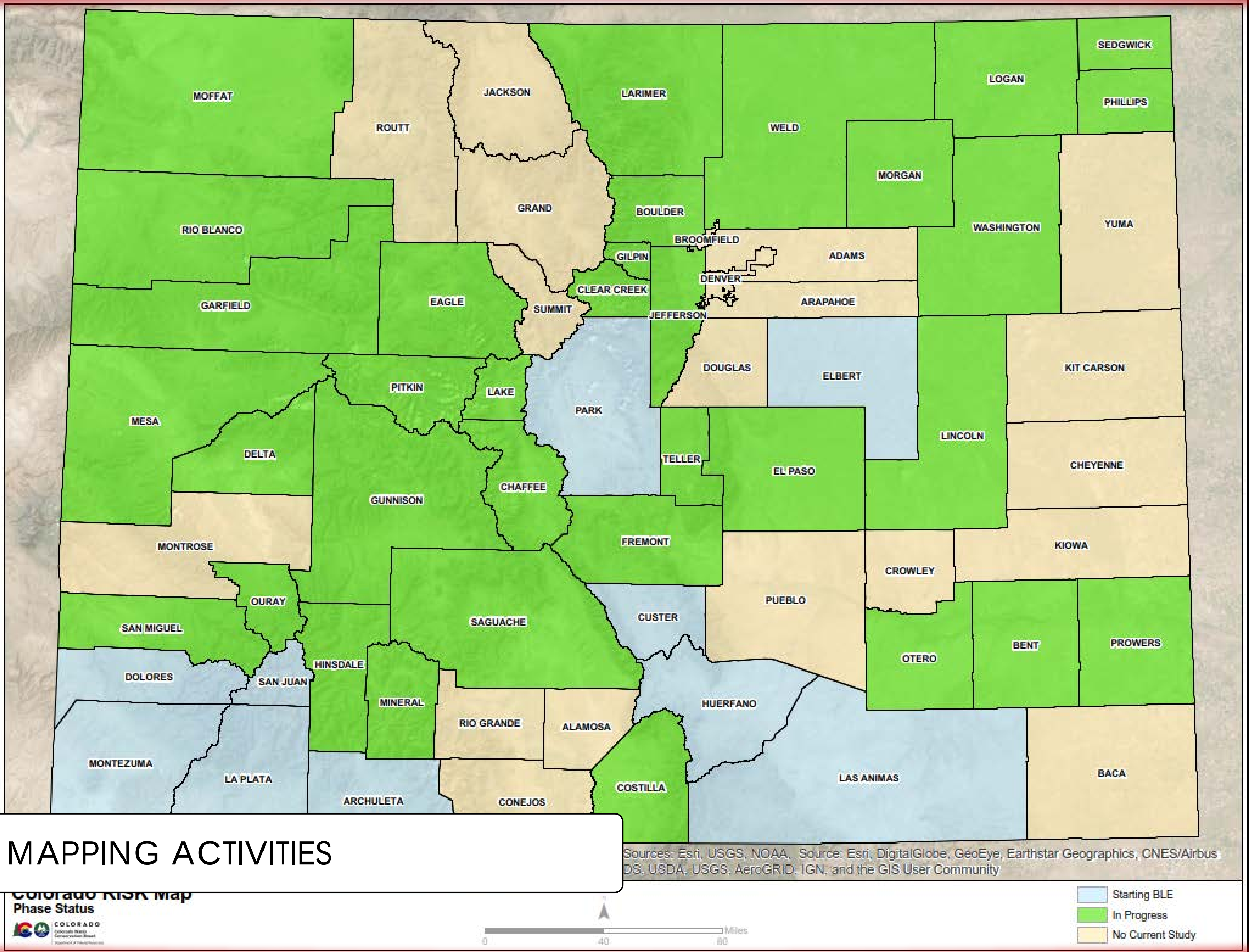
PRESENT



DISCLAIMER!
IF YOU ARE UNDER 30,
JUST IMAGINE RICK AND MORTY!


WOW! YOU MUST BE RICH!
quickmeme.com


Acquired
In Process
MOFFAT
ROUTT
JACKSON
LARIMER
WELD
LOGAN
SEDGWICK
PHILLIPS
MORGAN
RIO BLANCO
GRAND
BOULDER
BROOMFIELD
WASHINGTON
YUMA
GILPIN
ADAMS
CLEAR CREEK
DENVER
GARFIELD
EAGLE
SUMMIT
ARAPAHOE
JEFFERSON
PITKIN
LAKE
DOUGLAS
ELBERT
KIT CARSON
MESA
PARK
LINCOLN
DELTA
TELLER
CHEYENNE
GUNNISON
CHAFFEE
EL PASO
MONTROSE
FREMONT
KIOWA
CROWLEY
OURAY
SAN MIGUEL
SAGUACHE
CUSTER
PUEBLO
HINSDALE
OTERO
BENT
PROWERS
DOLORES
SAN JUAN
MINERAL
HUERFANO
RIO GRANDE
ALAMOSA
MONTEZUMA
LA PLATA
ARCHULETA
CONEJOS
COSTILLA
LAS ANIMAS
BACA
N
40
Miles
Cheyenne
Sidney
Farmington
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

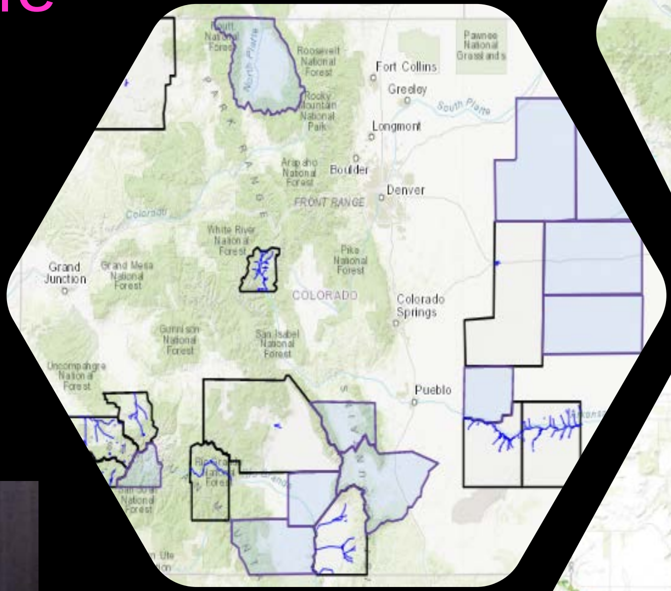


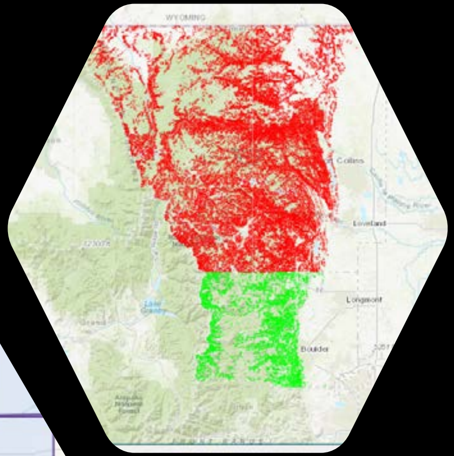
ONGOING MAPPING ACTIVITIES

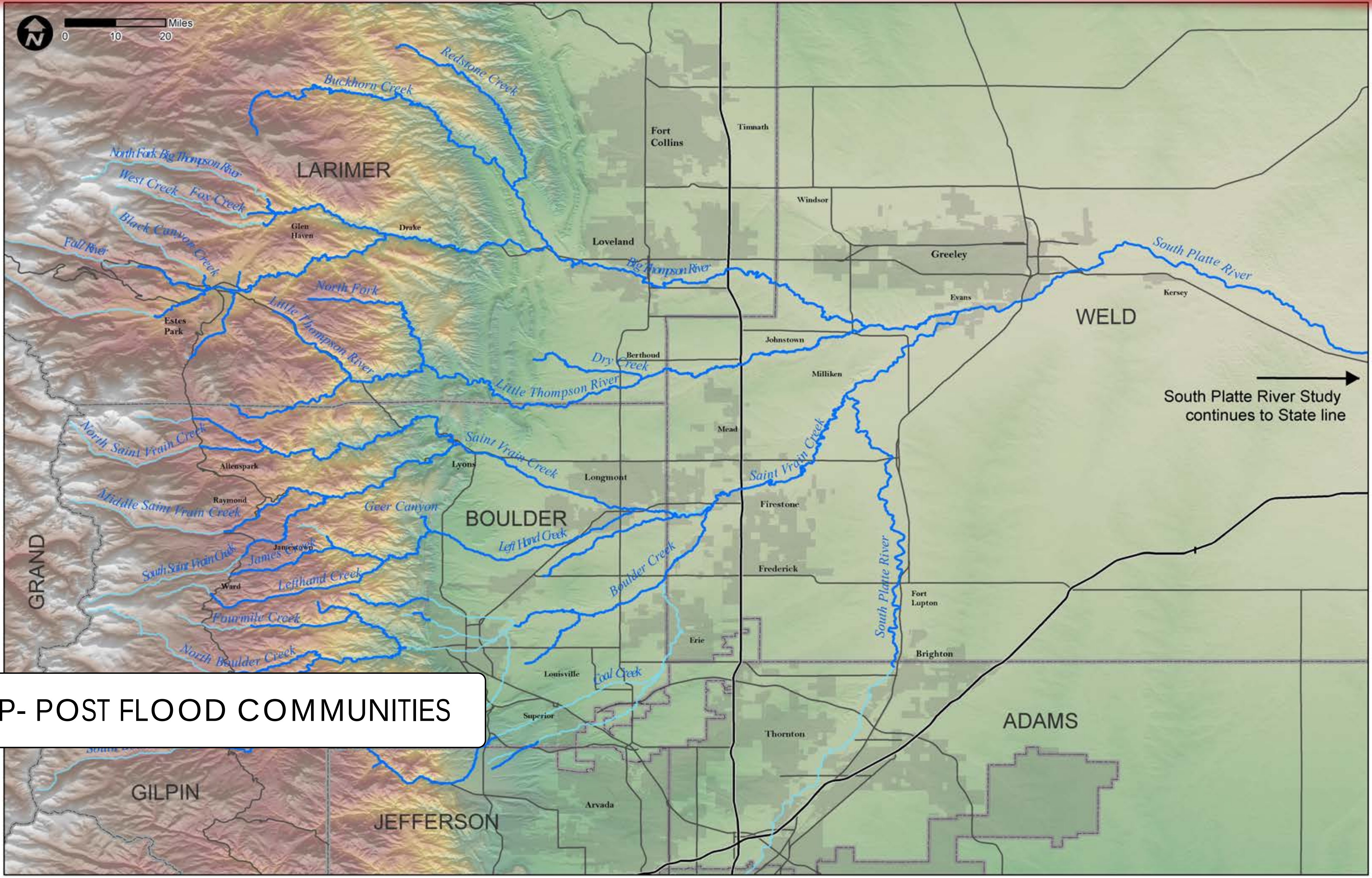
COLORADO HAZARD MAPPING PROGRAM

Resilient Colorado – Multiple Hazard Approach

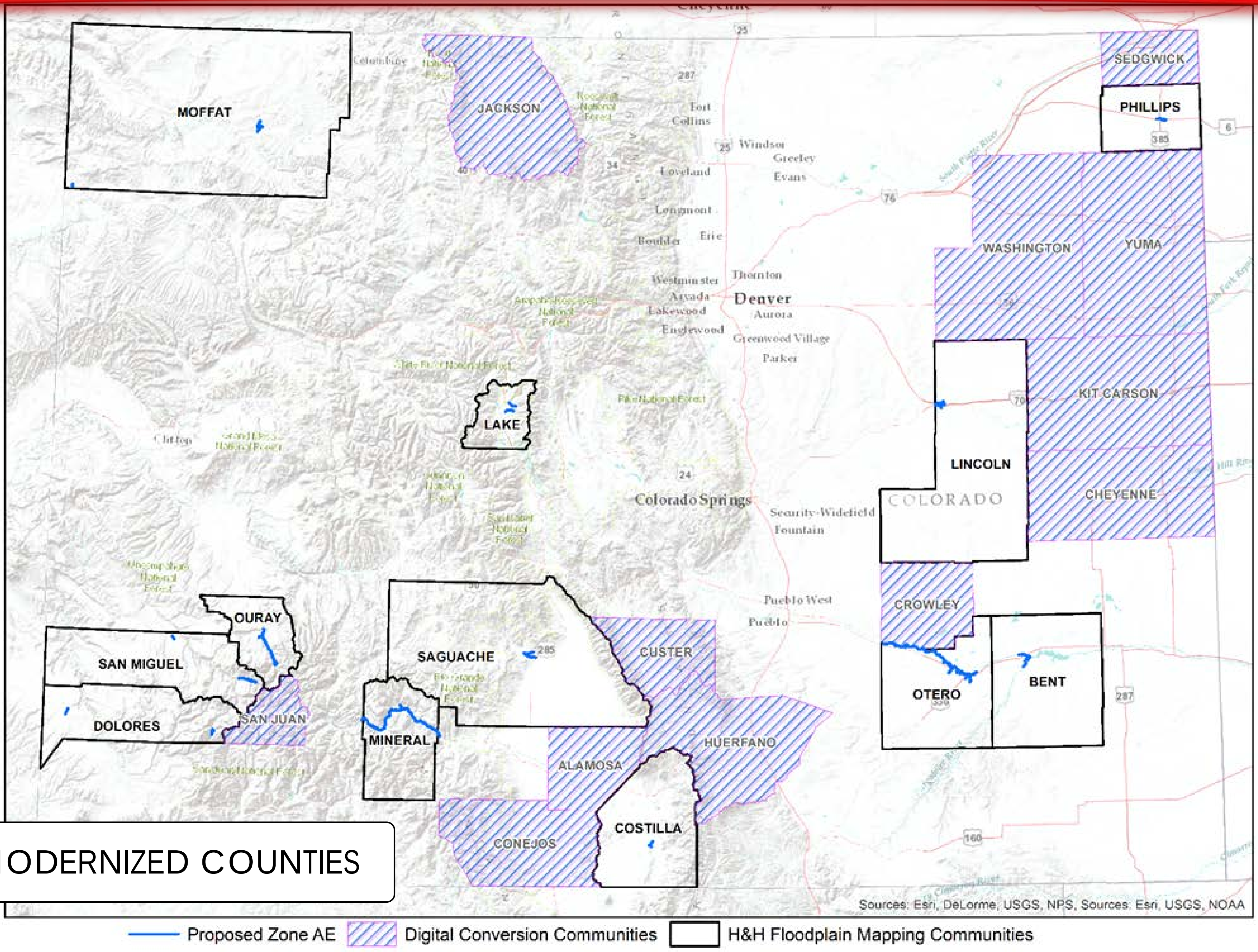
- Floodplain Mapping
- Paper Inventory
- Debris Flooding
- Erosion Hazard





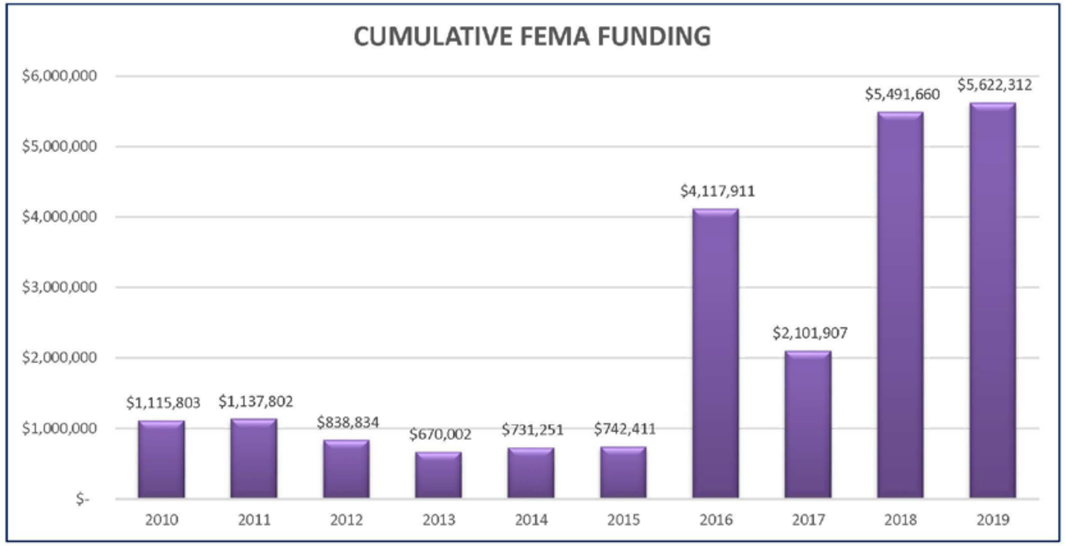


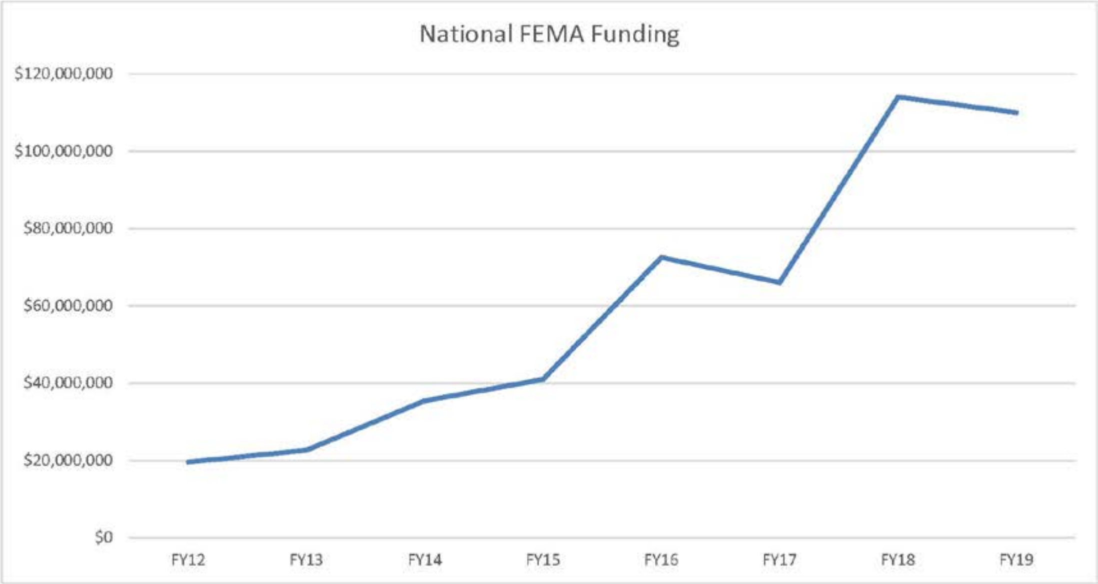
CHAMP- POST FLOOD COMMUNITIES



CHAMP – UNMODERNIZED COUNTIES

TRENDS AND FUNDING





2D

Colorado 2d Consortium (C2DC)

How to use new technology to our advantage

- Floodways
  - Unsteady flow
  - Multiple incoming streams
  - Large Models
- No-Rise
- Regulatory Product Use
- Web Based Determinations

NON-REGULATORY PRODUCTS/PILOT PROJECTS

Grids to Support Mitigation

- Depth Grids
- Hazard Grids
- Velocity Grids
- Others

Lidar LOMAs - GIS Instructions for new topo

- Teamed with Mile High Flood District
- Step by step
- Multiple successful pilots
- Additional info in Lidar LOMA presentation

Pilots to Support Local Needs

- Climate Change
- Snow Melt/Post Fire
- Tolerance and product testing
- Digital FIS

WEBSITE


Map
FAQ's
UMENTS
VIEW FREQUEN
Floodplain Mapping
Paper FIR
APPING
VISIT THE FLOODPLAIN MAPPING
VISIT THE PAP

CHALLENGES

LOCAL INTEREST AND UNDERSTANDING

Keeping Locals Informed/Engaged

- Risk MAP is not most local officials first job.
- Some see results as negative for community
- Turnover given lengthy process
- Differing levels of understanding of process
- Developed support documents
- Provide in-person support

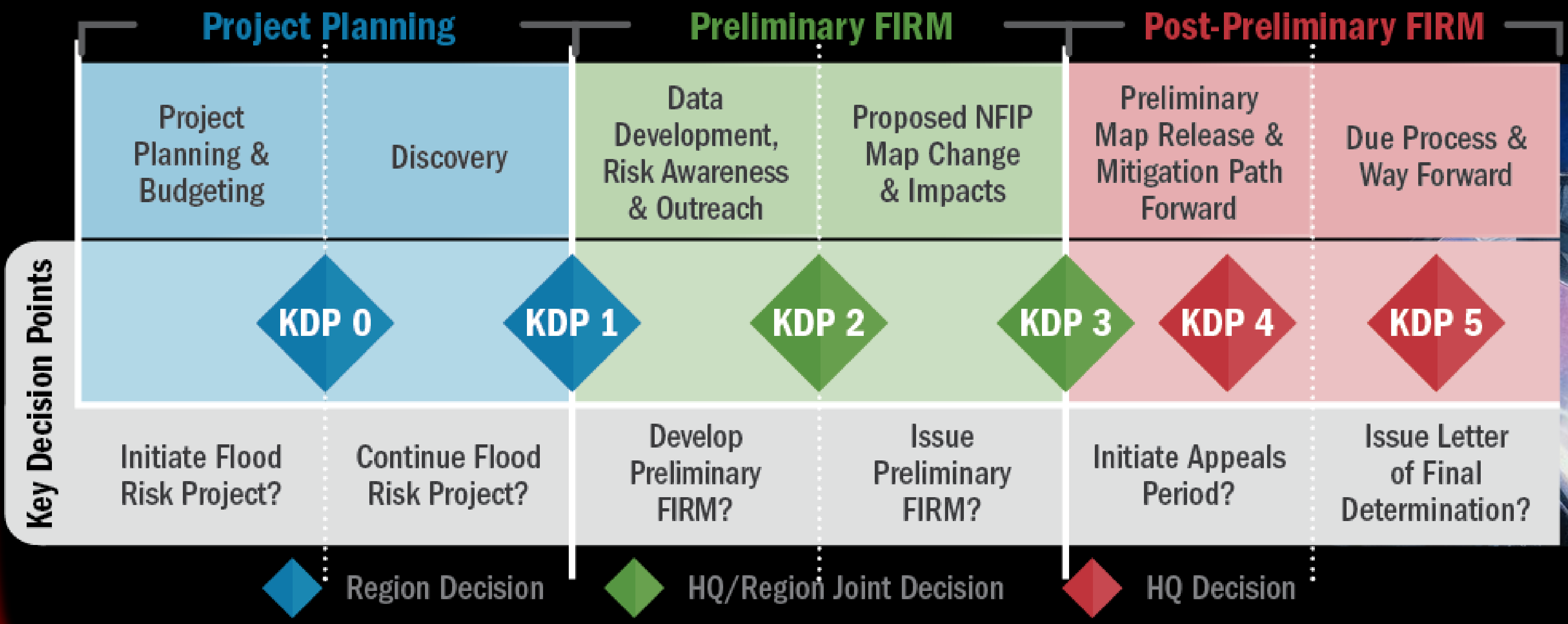
CNMS

FEMA's Inventory Could Expire every 5 Years

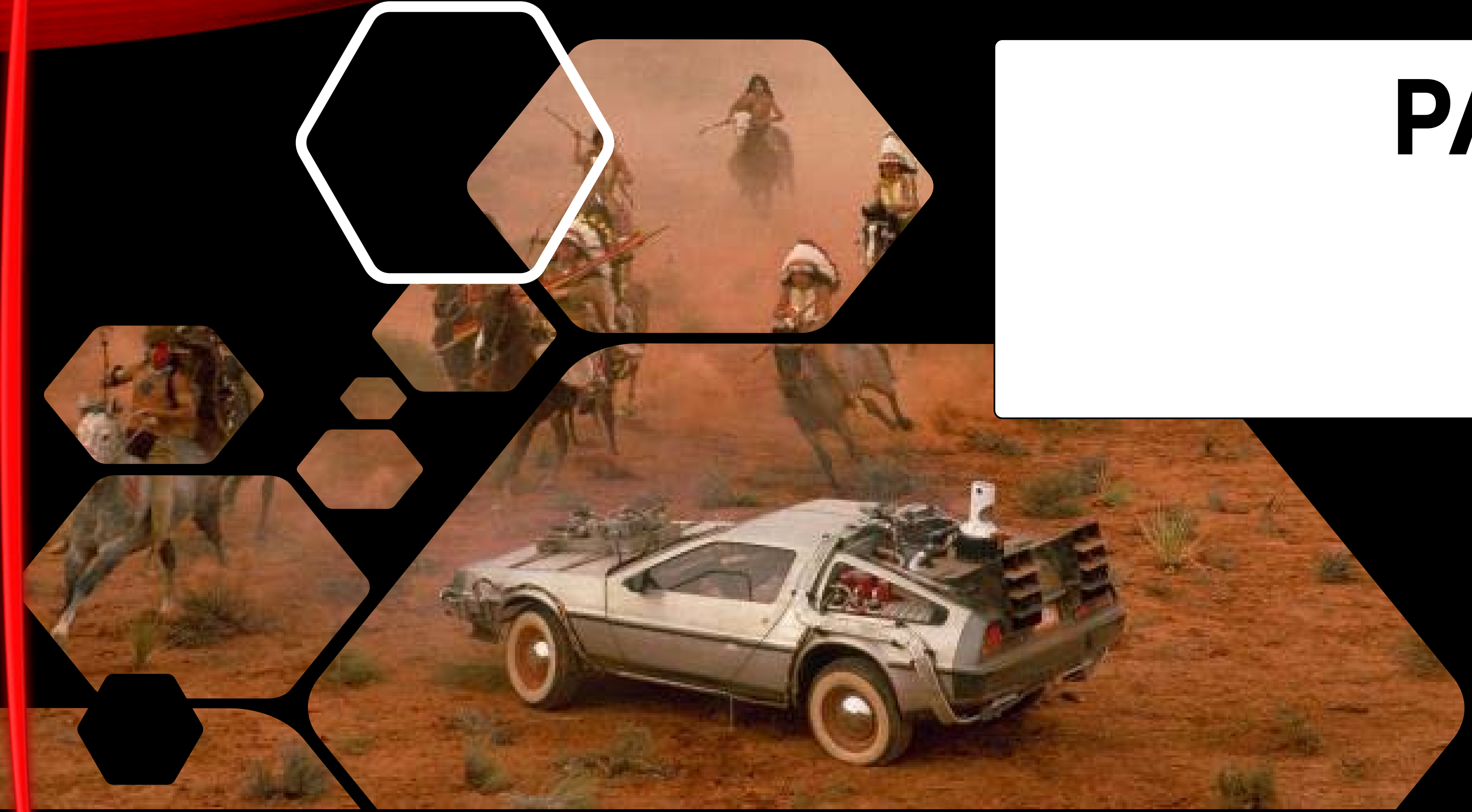
- FEMA works with CTPs to monitor New, Valid, Updated Engineering (NVUE)
- Has to be revisited every 5 years
- Things like new topo, new hydrology, and land use changes could trigger unverified streams.

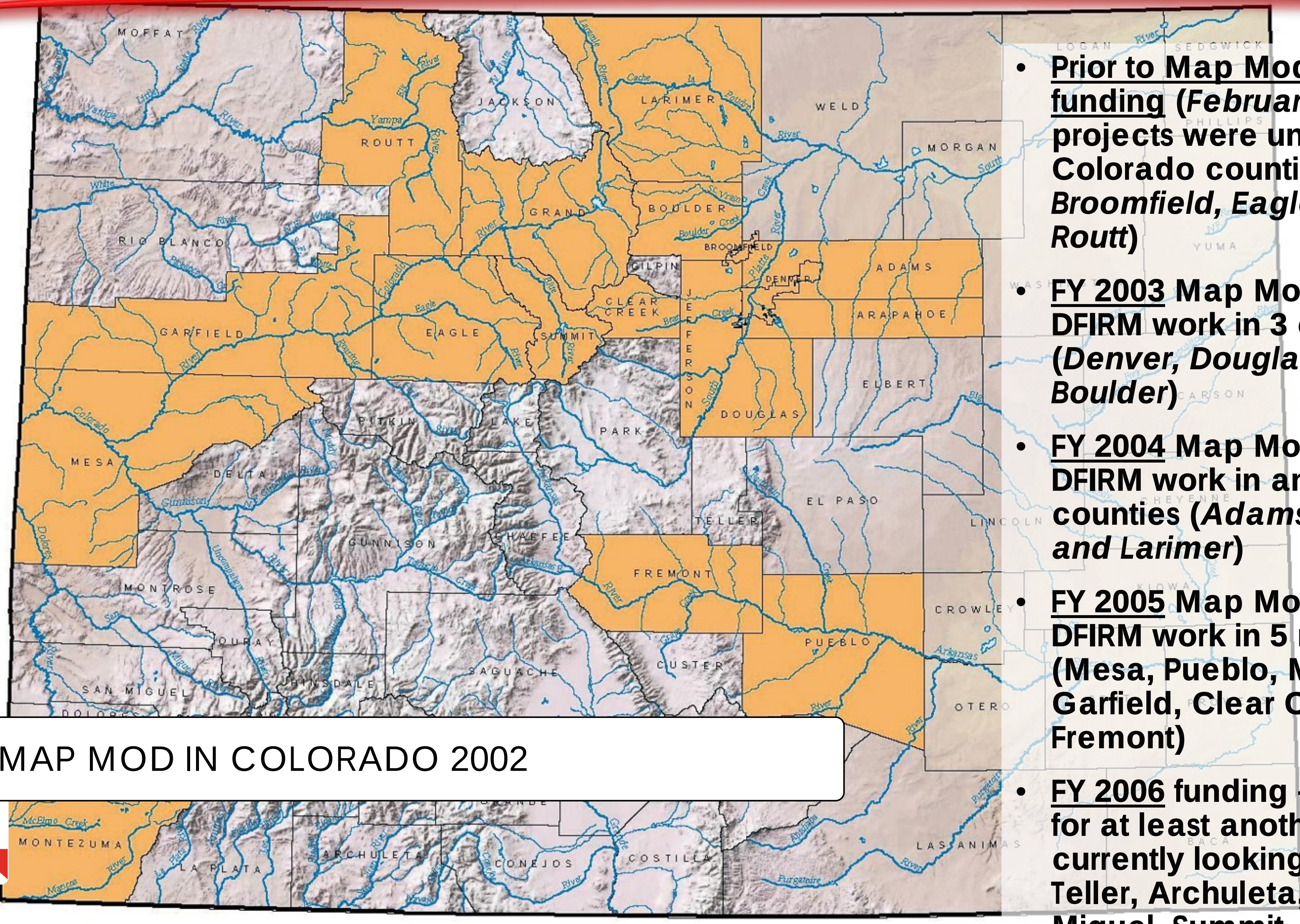
KEY DECISION POINTS: THE BASICS

- KDP Process Along with Review Process Takes Time
  - Intentional, coordinated, project management decision-making
  - Consistent management data collection for all flood risk projects



PAST





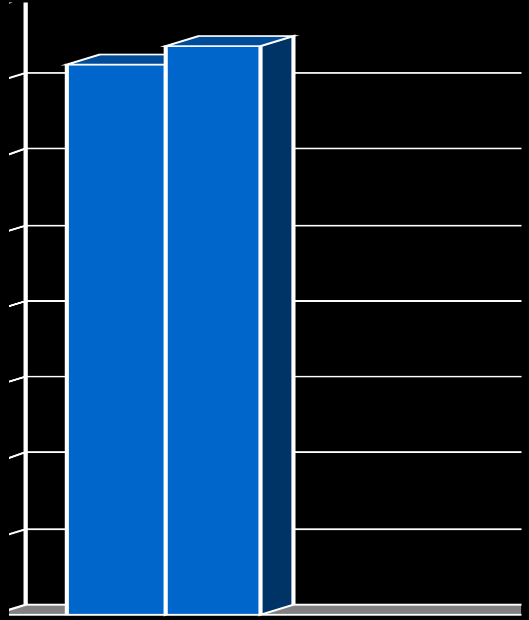
MAP MOD IN COLORADO 2002

Flood Map Modernization Counties (completed, ongoing, or current FY start)

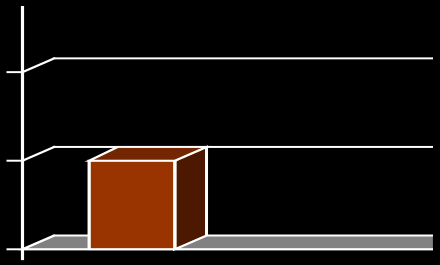
- <u>Prior to Map Modernization funding</u> (*February 2003*), DFIRM projects were underway in 5 Colorado counties (***Jefferson, Broomfield, Eagle, Grand, and Routt***)
- <u>FY 2003</u> Map Mod funds - new DFIRM work in 3 counties (***Denver, Douglas, and Boulder***)
- <u>FY 2004</u> Map Mod funds - new DFIRM work in an additional 3 counties (***Adams, Arapahoe, and Larimer***)
- <u>FY 2005</u> Map Mod funds – new DFIRM work in 5 more counties (Mesa, Pueblo, Montezuma, Garfield, Clear Creek, Fremont)
- <u>FY 2006</u> funding – anticipated for at least another 5 counties, currently looking at Weld, Teller, Archuleta, LaPlata, San Miguel, Summit, Mineral, Lake, and Park as possibilities

MAP MOD BUDGET

Map Mod
$100-150M / Year



Pre-Map Mod
< $25M / Year



Regional Study Budgets

Table 3-4. Planned Map Production Funding Distribution by Region, FY04-FY08

Region	Distribution to Region	FY04 Funding	FY05 Funding	FY06 Funding	FY07 Funding	FY08 Funding
1	3.7%	$4,440,000	$5,328,000	$5,661,000	$5,827,500	$5,827,500
2	7.9%	$9,480,000	$11,376,000	$12,087,000	$12,442,500	$12,442,500
3	8.4%	$10,080,000	$12,096,000	$12,852,000	$13,230,000	$13,230,000
4	24.9%	$29,880,000	$35,856,000	$38,097,000	$39,217,500	$39,217,500
5	11.9%	$14,280,000	$17,136,000	$18,207,000	$18,742,500	$18,742,500
6	17.5%	$21,000,000	$25,200,000	$26,775,000	$27,562,500	$27,562,500
7	7.0%	$8,400,000	$10,080,000	$10,710,000	$11,025,000	$11,025,000
8	4.7%	$5,640,000	$6,768,000	$7,191,000	$7,402,500	$7,402,500
9	10.1%	$12,120,000	$14,544,000	$15,453,000	$15,907,500	$15,907,500
10	3.9%	$4,680,000	$5,616,000	$5,967,000	$6,142,500	$6,142,500
Total	**100%**	**$120,000,000**	**$144,000,000**	**$153,000,000**	**$157,500,000**	**$157,500,000**

Table ES-4. Map Production Funding Distribution by Region, FY04-FY08

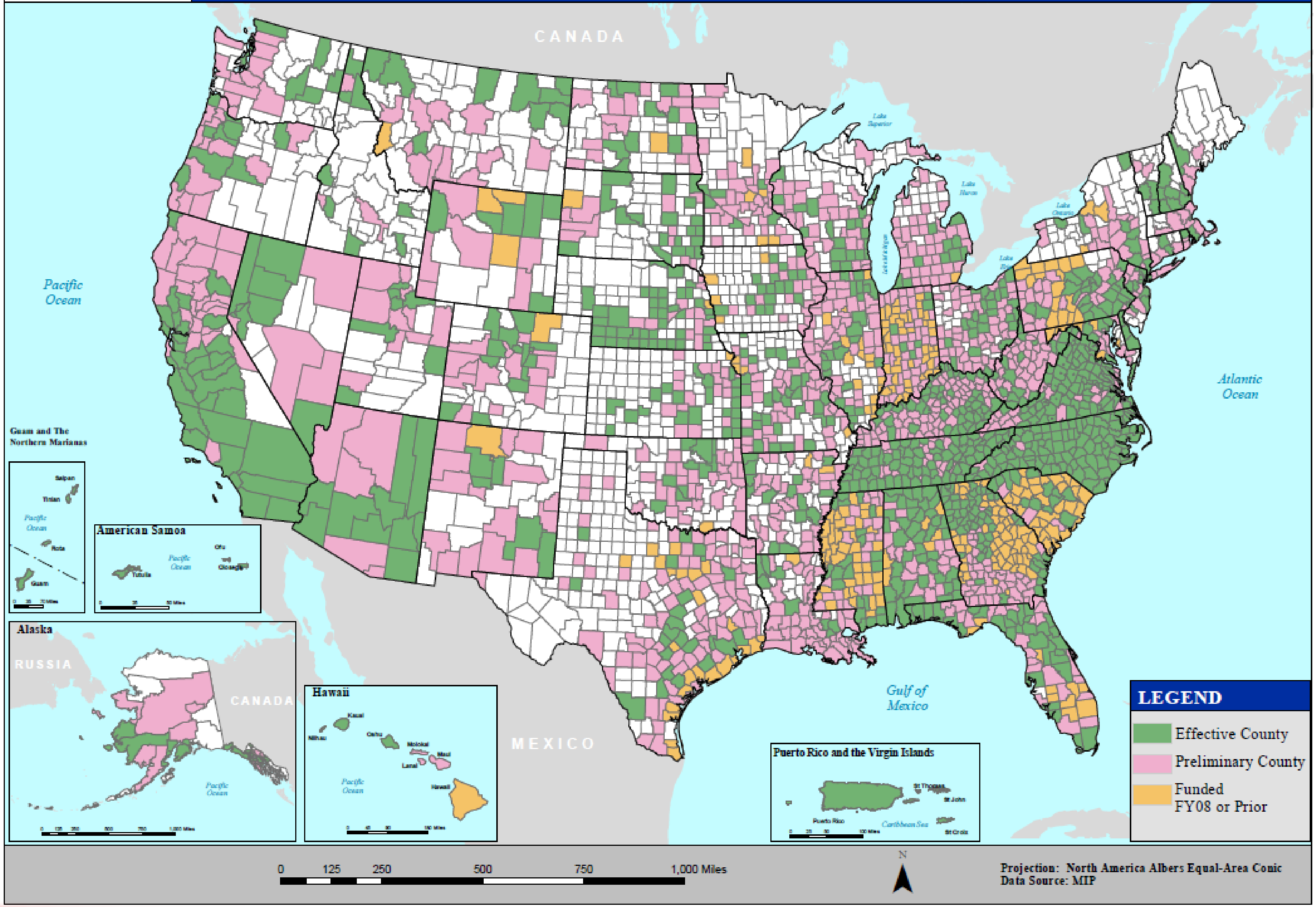
Region	FY04 Funding[1]	FY05 Funding[1]	FY06 Funding[1]	FY07 Funding[2]	FY08 Funding[2]
1	$4,222,000	$5,911,980	$6,240,000	$5,670,000	$5,670,000
2	$9,604,000	$11,675,013	$11,806,000	$13,070,000	$13,070,000
3	$10,235,000	$13,250,000	$14,172,000	$13,390,000	$13,390,000
4	$38,268,620	$39,638,112	$36,316,119	$39,530,000	$39,530,000
5	$14,446,417	$17,155,627	$16,880,022	$19,060,000	$19,060,000
6	$20,629,000	$27,047,947	$25,772,340	$25,360,000	$25,360,000
7	$8,575,000	$10,294,183	$10,343,077	$10,870,000	$10,870,000
8	$6,181,000	$8,959,254	$7,319,783	$8,190,000	$8,190,000
9	$13,228,750	$15,406,259	$14,140,000	$14,800,000	$14,800,000
10	$4,974,400	$6,418,200	$5,692,000	$7,560,000	$7,560,000
Total	**$130,364,687**	**$155,756,575**	**$148,681,341**	**$157,500,000**	**$157,500,000**

1 – Actual
2 – Proposed

FEMA

Map 7. Progress of Mapping Activities Through FY09

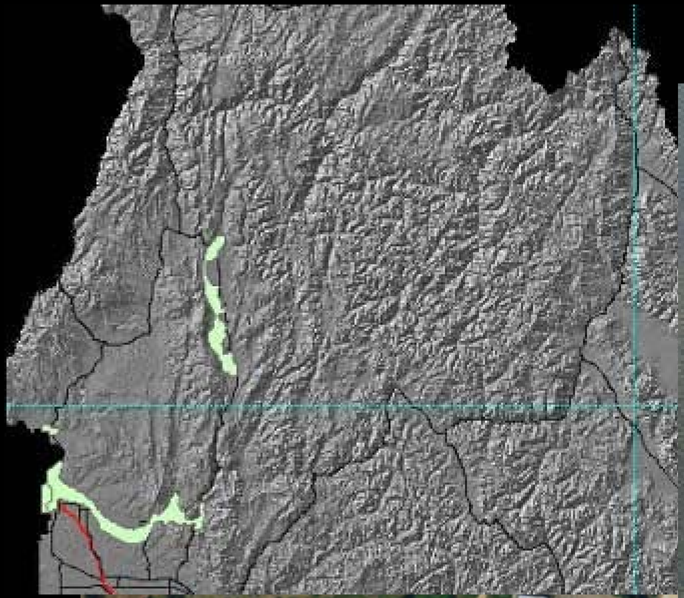
As of December 2008



MAP MOD CHALLENGES

Nothing goes as planned

- Mid Course Adjustment – Funding Issues
- Priority of Mapping changes
- Levees and non-levees
- Limited Topography



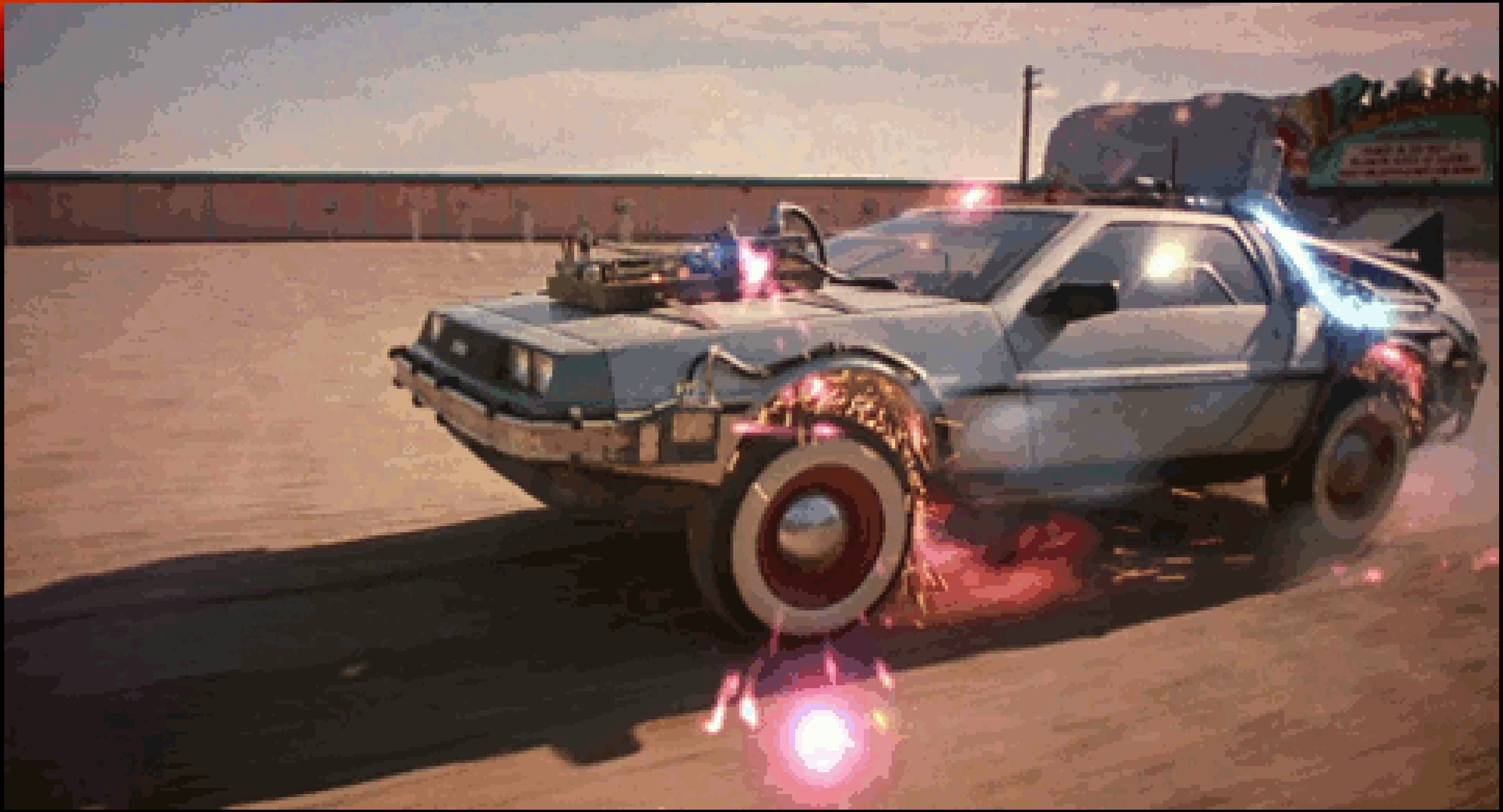
MAP MOD TRANSITION

Things are starting to change

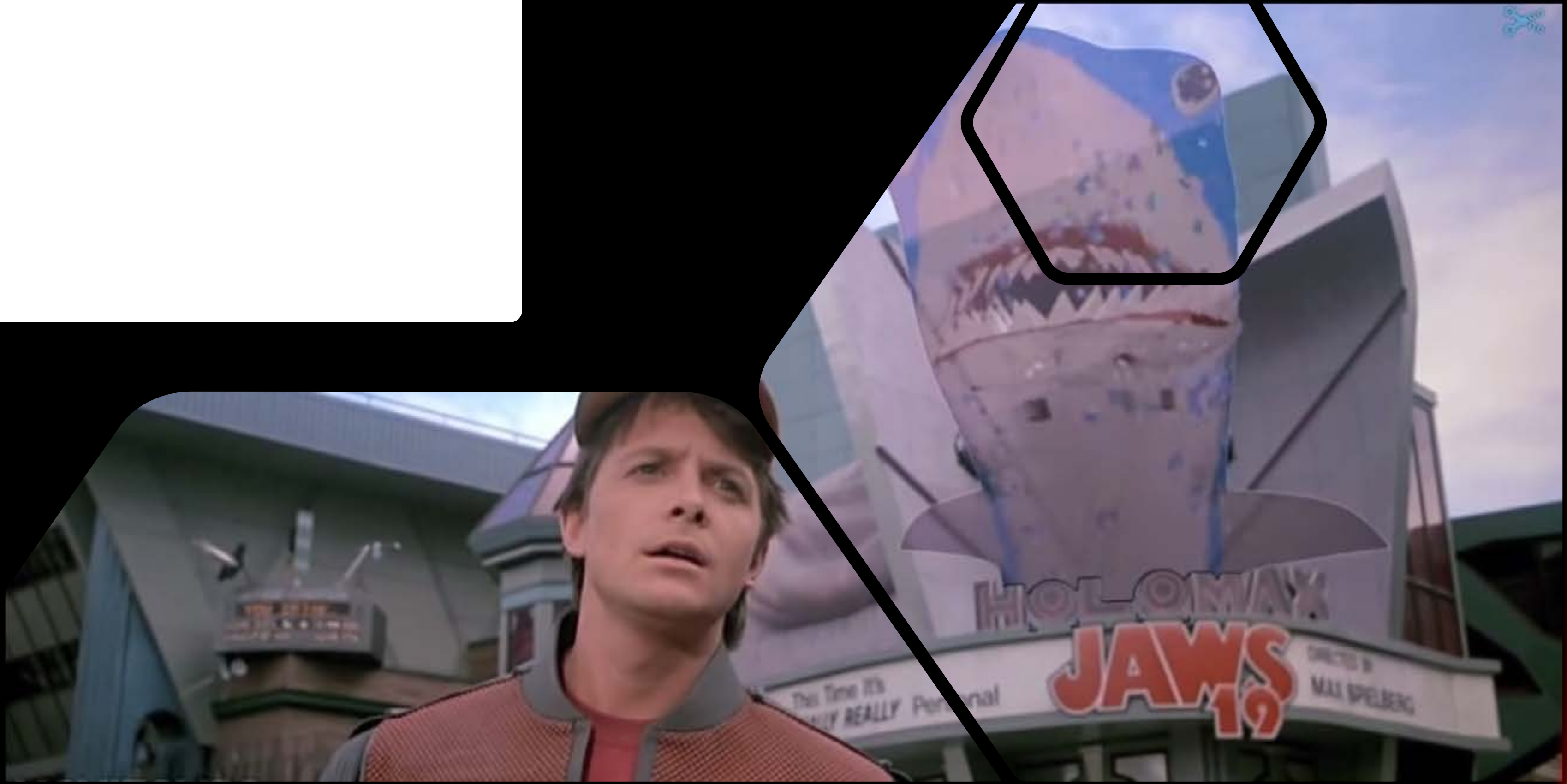
- Local Input needed
- More Budget for Detailed Studies
- Mapping Information Platform
- Multi-Year Flood Hazard Identification Plan
- Multi-Hazard Focus

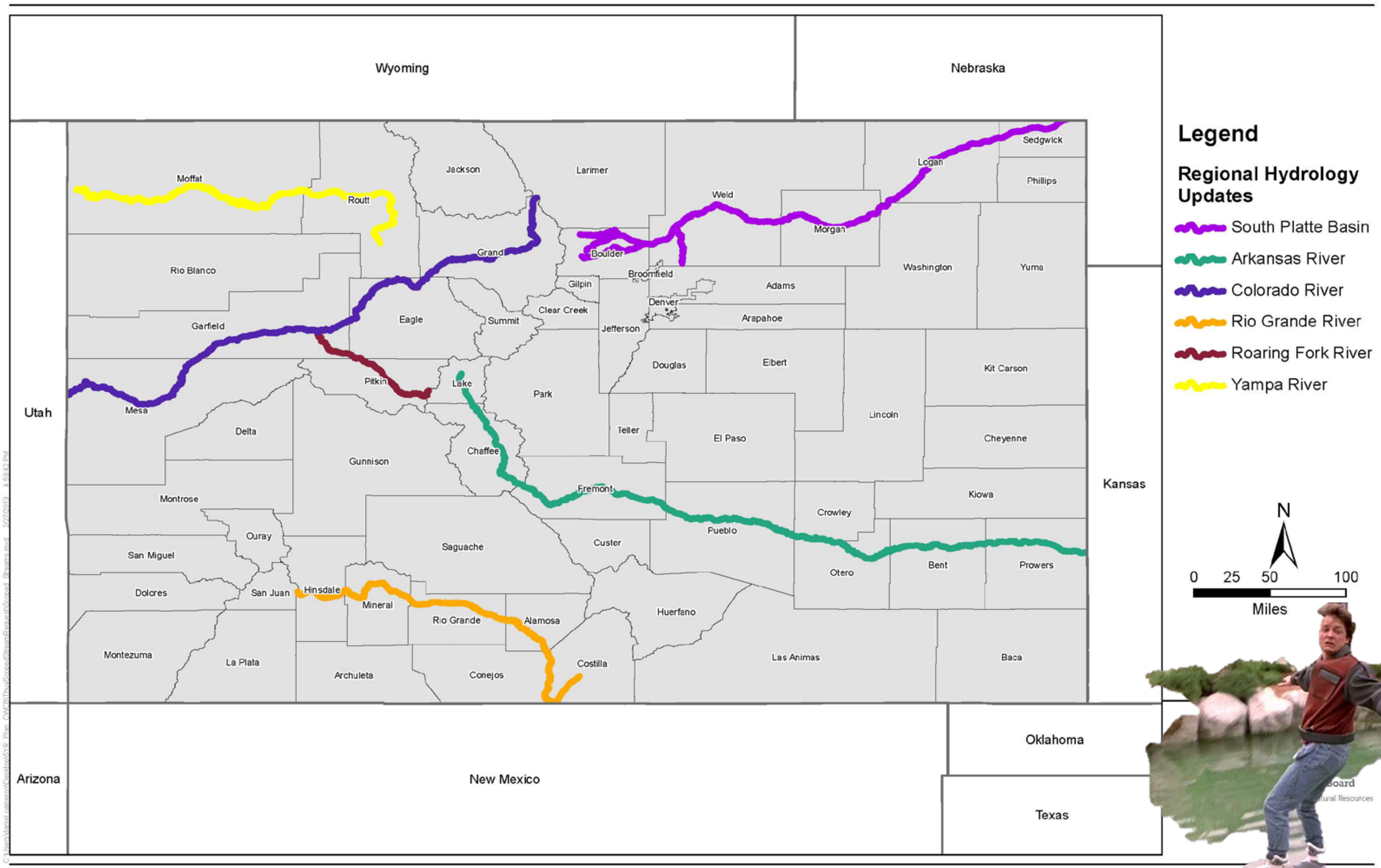
- Map Mod to Risk Map Phase
- Post 2013 Flood Affects
- Outreach and Engagement Trends
- Messaging and Local Understanding
- Flood recovery/CHAMP

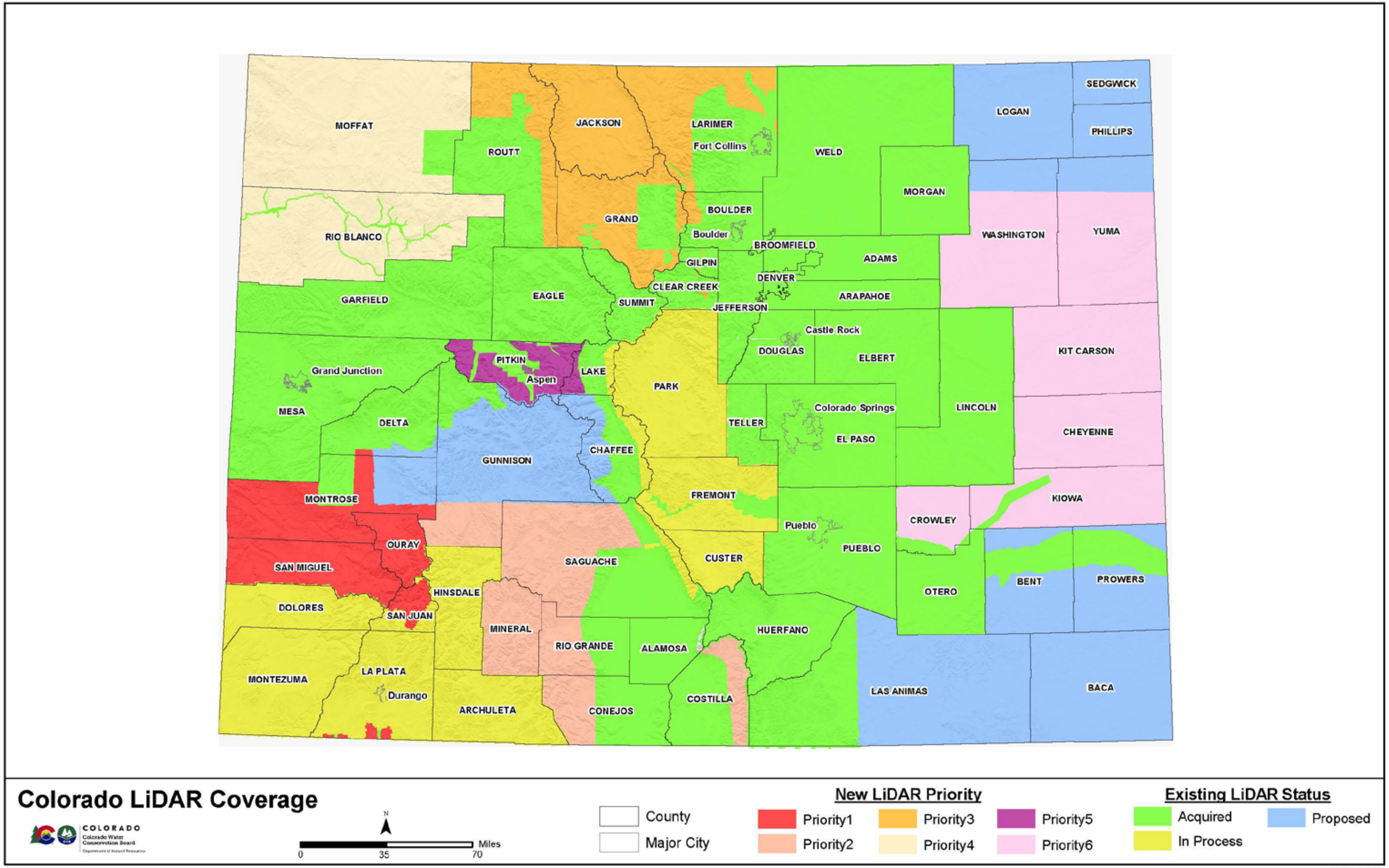
TURNING POINT FOR COLORADO



FUTURE

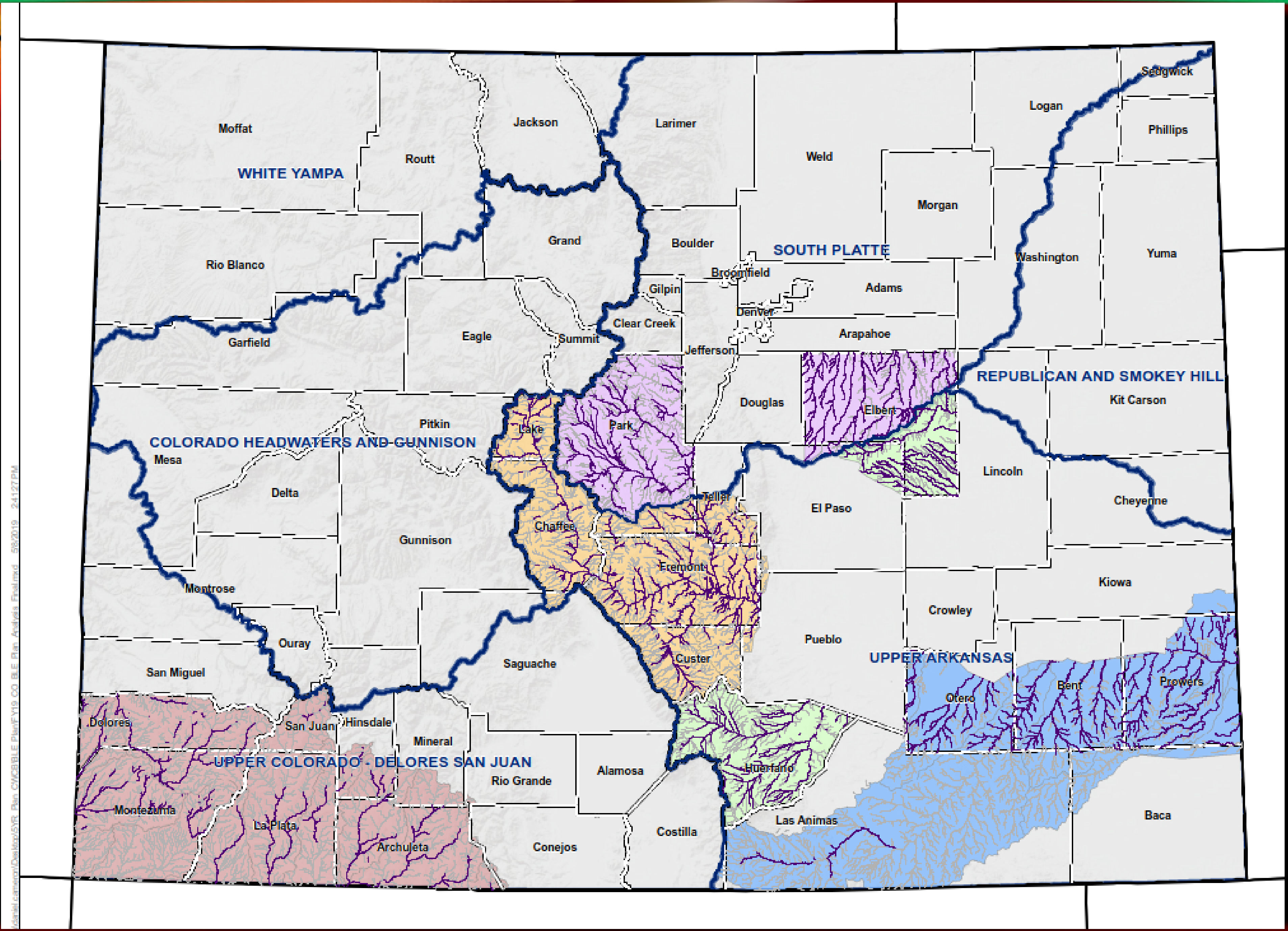


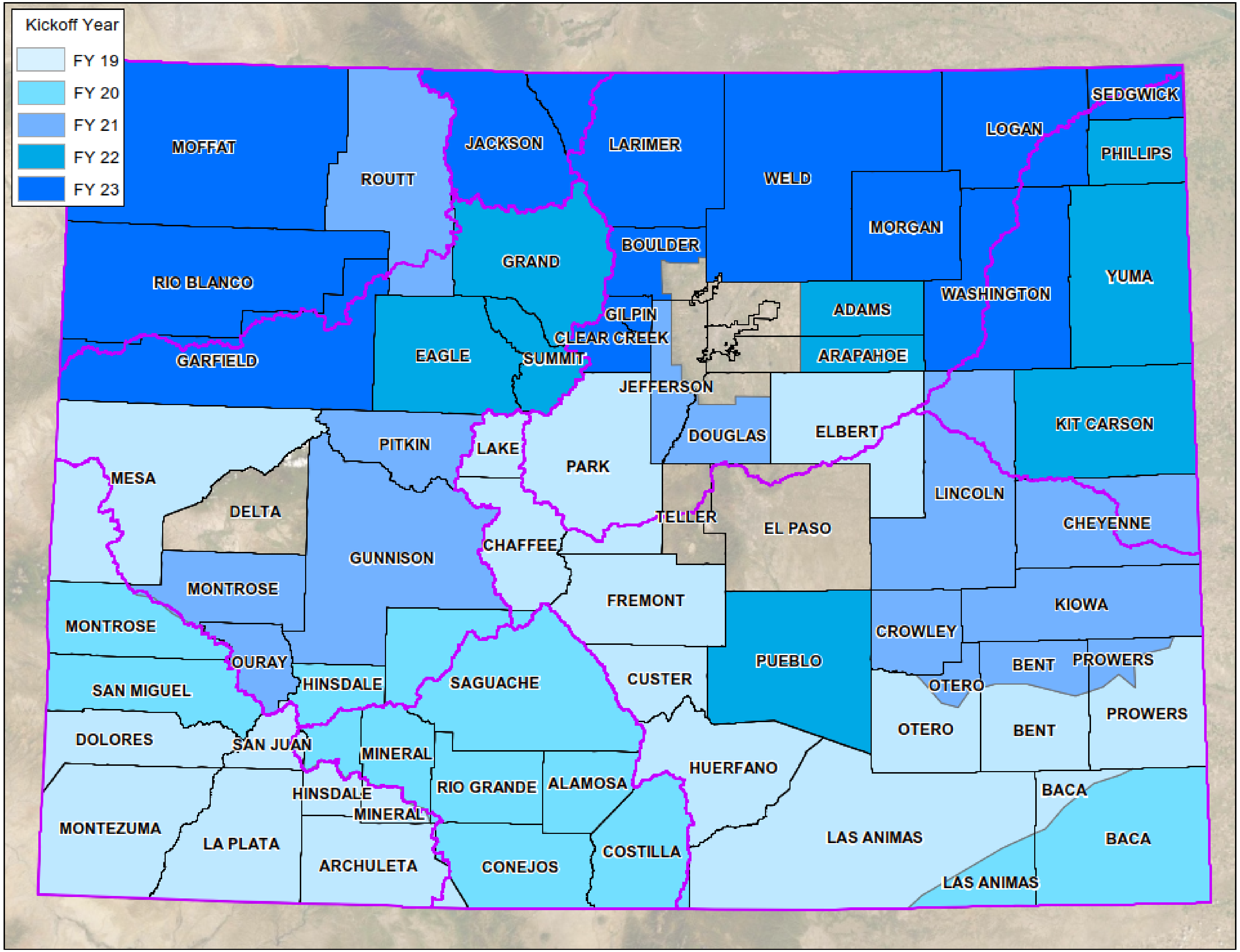

Wyoming
Nebraska
Utah
Kansas
Arizona
New Mexico
Oklahoma
Texas
Moffat
Routt
Jackson
Larimer
Weld
Logan
Sedgwick
Phillips
Rio Blanco
Grand
Boulder
Broomfield
Morgan
Washington
Yuma
Gilpin
Clear Creek
Denver
Adams
Arapahoe
Garfield
Eagle
Summit
Jefferson
Douglas
Elbert
Kit Carson
Mesa
Pitkin
Lake
Park
Lincoln
Delta
Teller
El Paso
Cheyenne
Gunnison
Chaffee
Fremont
Kiowa
Montrose
Crowley
Pueblo
Ouray
San Miguel
Saguache
Custer
Otero
Bent
Prowers
Dolores
San Juan
Hinsdale
Mineral
Rio Grande
Alamosa
Huerfano
Montezuma
La Plata
Archuleta
Conejos
Costilla
Las Animas
Baca
Legend
Regional Hydrology Updates
South Platte Basin
Arkansas River
Colorado River
Rio Grande River
Roaring Fork River
Yampa River
N
0 25 50 100
Miles

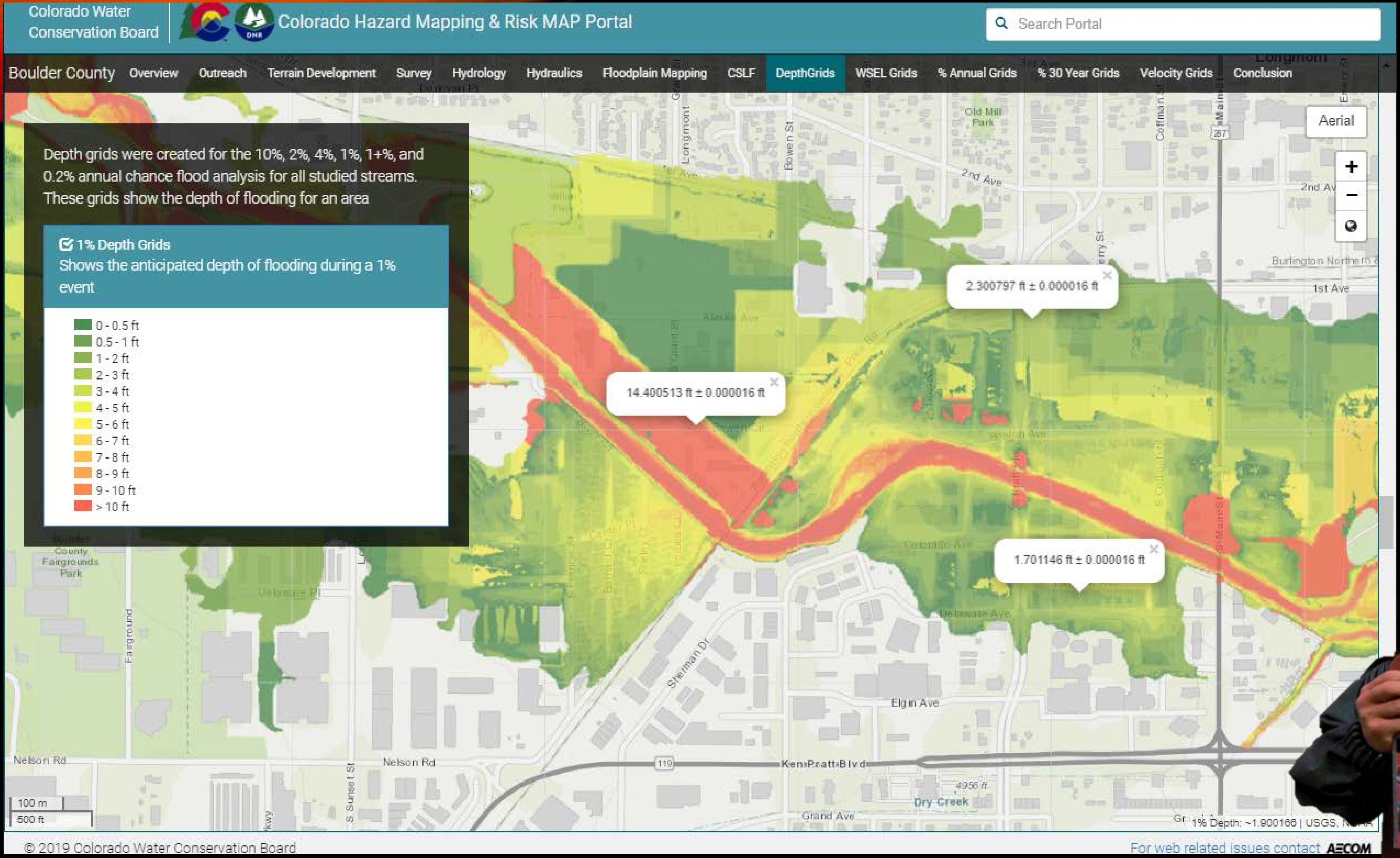


Colorado LiDAR Coverage

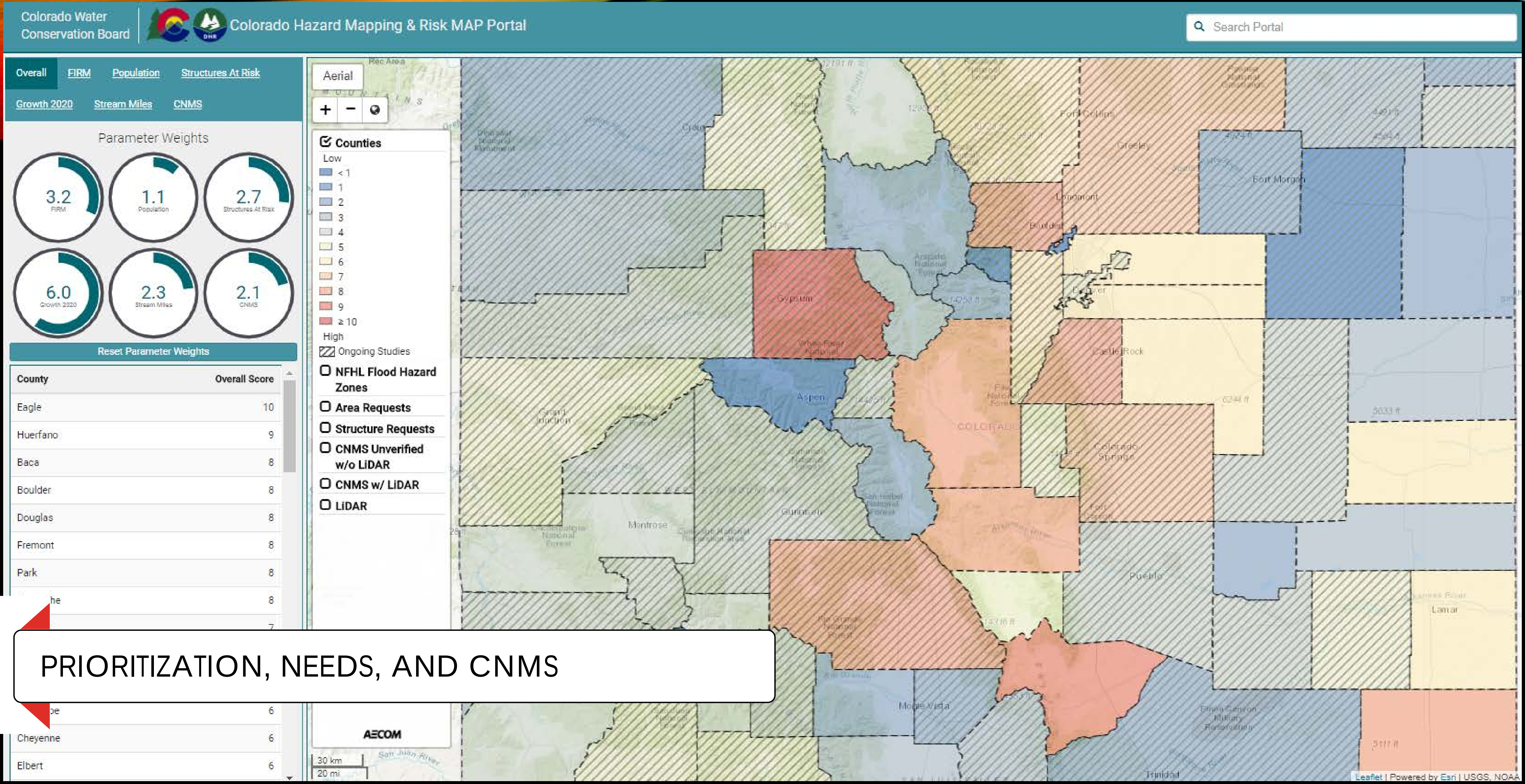
STATEWIDE LIDAR AND MAPPING


WHITE YAMPA
SOUTH PLATTE
REPUBLICAN AND SMOKEY HILL
COLORADO HEADWATERS AND GUNNISON
UPPER ARKANSAS
UPPER COLORADO - DELORES SAN JUAN
Moffat
Jackson
Larimer
Sedgwick
Logan
Phillips
Routt
Weld
Morgan
Grand
Boulder
Rio Blanco
Broomfield
Washington
Yuma
Gilpin
Adams
Denver
Garfield
Eagle
Summit
Clear Creek
Arapahoe
Jefferson
Elbert
Kit Carson
Douglas
Pitkin
Lake
Park
Mesa
Lincoln
Delta
Teller
El Paso
Cheyenne
Chaffee
Gunnison
Fremont
Montrose
Kiowa
Crowley
Ouray
Pueblo
Saguache
Custer
San Miguel
Bent
Prowers
Otero
Dolores
San Juan
Hinsdale
Mineral
Huerfano
Rio Grande
Alamosa
Montezuma
La Plata
Las Animas
Archuleta
Costilla
Baca
Conejos


Kickoff Year
FY 19
FY 20
FY 21
FY 22
FY 23
MOFFAT
ROUTT
JACKSON
LARIMER
WELD
LOGAN
SEDGWICK
PHILLIPS
MORGAN
BOULDER
GRAND
RIO BLANCO
GILPIN
CLEAR CREEK
ADAMS
WASHINGTON
YUMA
ARAPAHOE
GARFIELD
EAGLE
SUMMIT
JEFFERSON
DOUGLAS
ELBERT
KIT CARSON
PITKIN
LAKE
PARK
MESA
DELTA
LINCOLN
TELLER
EL PASO
CHEYENNE
GUNNISON
CHAFFEE
MONTROSE
FREMONT
KIOWA
MONTROSE
CROWLEY
OURAY
PUEBLO
BENT
PROWERS
HINSDALE
SAGUACHE
CUSTER
OTERO
SAN MIGUEL
DOLORES
SAN JUAN
MINERAL
OTERO
BENT
PROWERS
RIO GRANDE
ALAMOSA
HUERFANO
HINSDALE
MINERAL
BACA
MONTEZUMA
LA PLATA
ARCHULETA
CONEJOS
COSTILLA
LAS ANIMAS
BACA
LAS ANIMAS


Colorado Water Conservation Board
Colorado Hazard Mapping & Risk MAP Portal
Search Portal
Boulder County
Overview
Outreach
Terrain Development
Survey
Hydrology
Hydraulics
Floodplain Mapping
CSLF
DepthGrids
WSEL Grids
% Annual Grids
% 30 Year Grids
Velocity Grids
Conclusion
Depth grids were created for the 10%, 2%, 4%, 1%, 1+%, and 0.2% annual chance flood analysis for all studied streams. These grids show the depth of flooding for an area
1% Depth Grids
Shows the anticipated depth of flooding during a 1% event
0 - 0.5 ft
0.5 - 1 ft
1 - 2 ft
2 - 3 ft
3 - 4 ft
4 - 5 ft
5 - 6 ft
6 - 7 ft
7 - 8 ft
8 - 9 ft
9 - 10 ft
> 10 ft
Aerial
14.400513 ft ± 0.000016 ft
2.300797 ft ± 0.000016 ft
1.701146 ft ± 0.000016 ft
2nd Ave
1st Ave
Elgin Ave
Delaware Ave
Nelson Rd
Ken Pratt Blvd
Dry Creek
Grand Ave
100 m
500 ft
© 2019 Colorado Water Conservation Board
For web related issues contact AECOM


1950–2000



PRIORITIZATION, NEEDS, AND CNMS

TO THE FUTURE!

- LOMR Review Partnership with FEMA
- CWCB Mapping Partners Selection
- Tools for community non-regulatory use
- Model download per stream
- Lidar download portal
- Single repository for outreach information
- Quarterly Newsetter

COLORADO
Colorado Water Conservation Board
Department of Natural Resources

THANK YOU

Thuy Patton
(303) 866-3441 x3230
Thuy.patton@state.co.us
Rigel Rucker
(575) 545-1107
Rigel.rucker@aecom.com
www.coloradohazardmapping.com

What 4,000 HEC-RAS Runs Taught Us About Maintenance Prioritization

AURORA

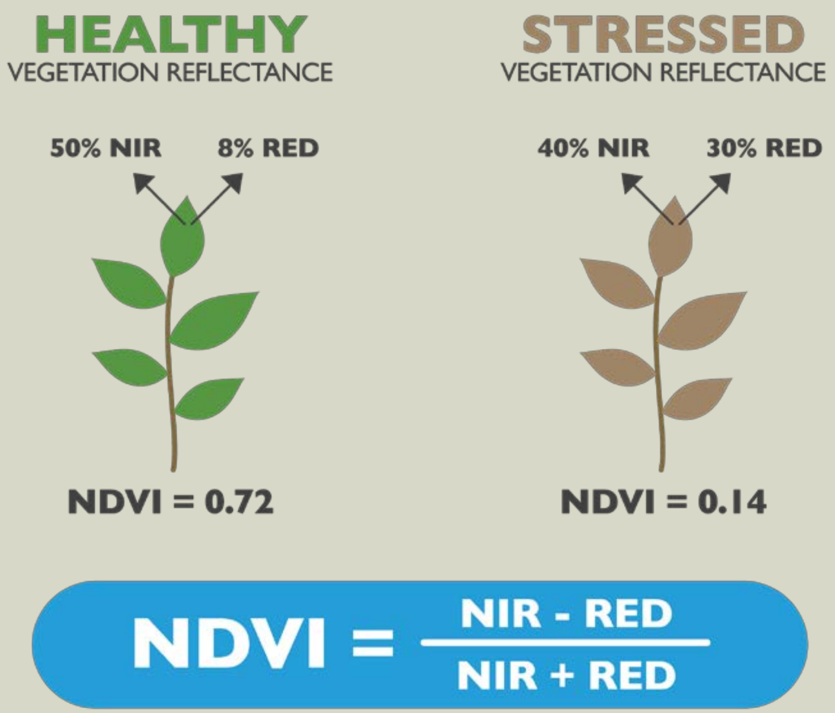
MHFD
MILE HIGH FLOOD DISTRICT

RESPEC

Are your streams “n”-sensitive?

History of the Project

- **Phase 1: Remote-sensed Manning's n analysis project**
  - Accurately estimate Manning's n values from high-resolution, remote-sensed datasets?
  - Utilize NDVI (infrared vegetation imagery) and LiDAR to remotely estimate n-values. Calibrated with effective RAS models.



History of the Project

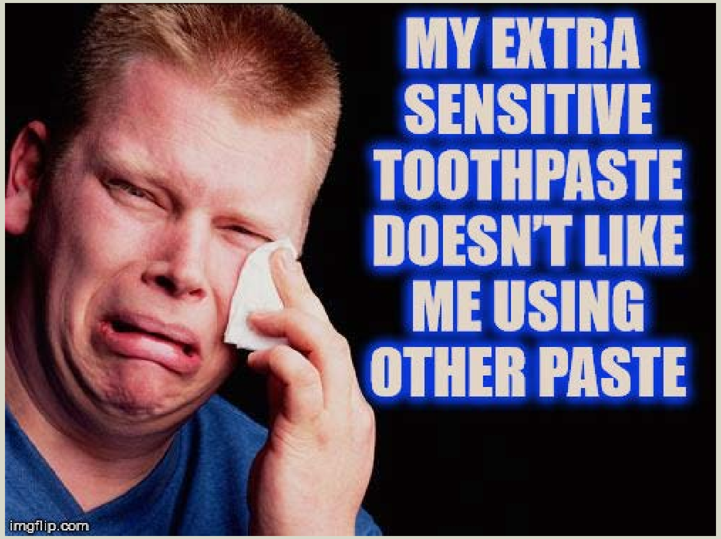
- **Phase 2: Channel Sensitivity Study**
  - Use statistical methods to determine channels' sensitivity to changes in n-values?
  - Aurora Water contributed additional funding, scope expanded to consider impacts of channel aggradation and culvert blockage.

Purpose of the Project

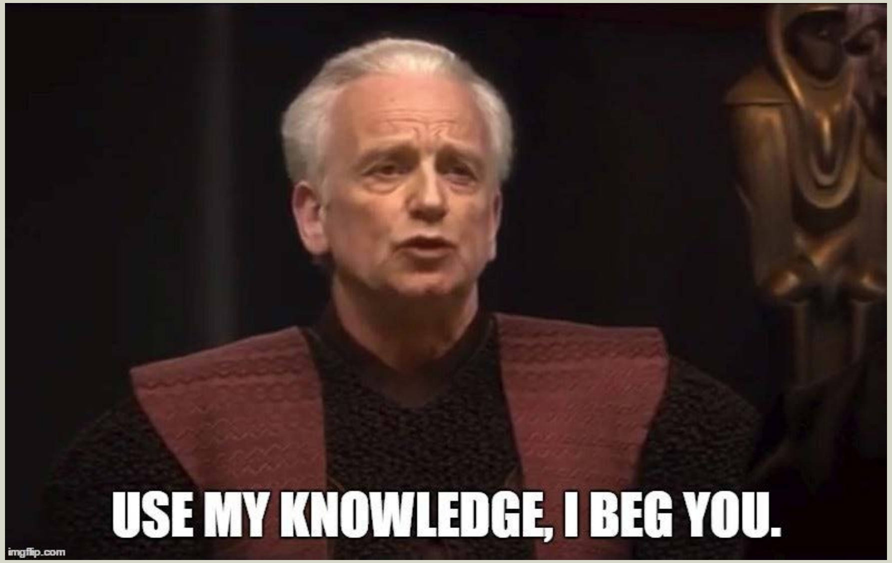
- **What is the real impact of vegetation growth, aggradation, and culvert blockage on floodplain water surface elevations and extents?**
  - Models assume static parameters, which isn't the case in reality.

Purpose of the Project

- **Some reaches may be more sensitive to these changes than others.**
  - Prioritize more sensitive reaches for inspections and maintenance.
  - Allow less sensitive reaches to remain in a more natural state.



Purpose of the Project



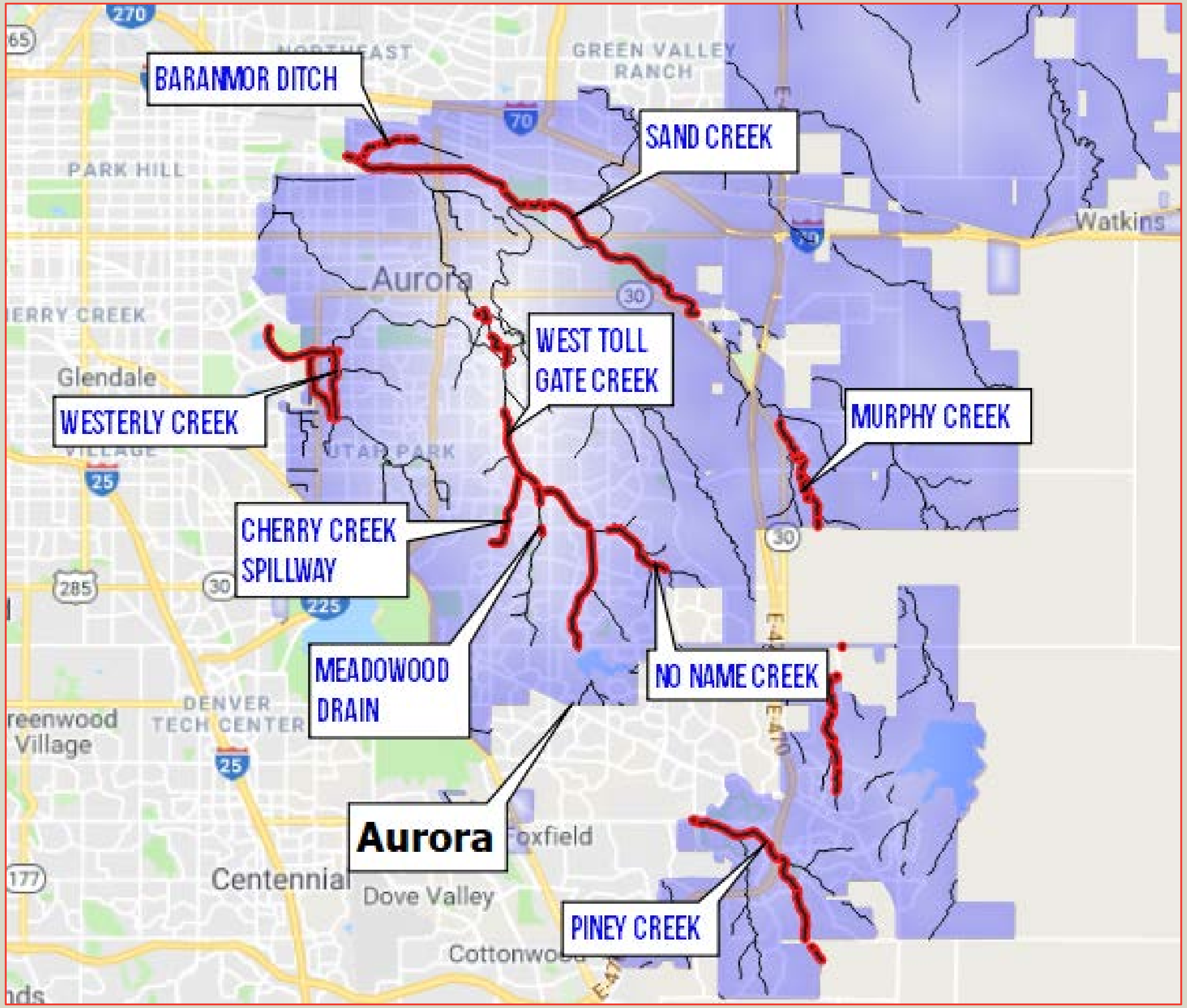
- **Operations crews not always aware of the “baseline” n-values and thalweg elevations that underlie the regulatory floodplain.**
  - Provide guidance about what level to cut vegetation and excavate sediment.

Purpose of the Project

- Non-regulatory statistical model allows users to examine impact of different scenarios, local impacts, varying maintenance levels, etc.
- Study provides context and prioritization for O&M activities based on real-world considerations.

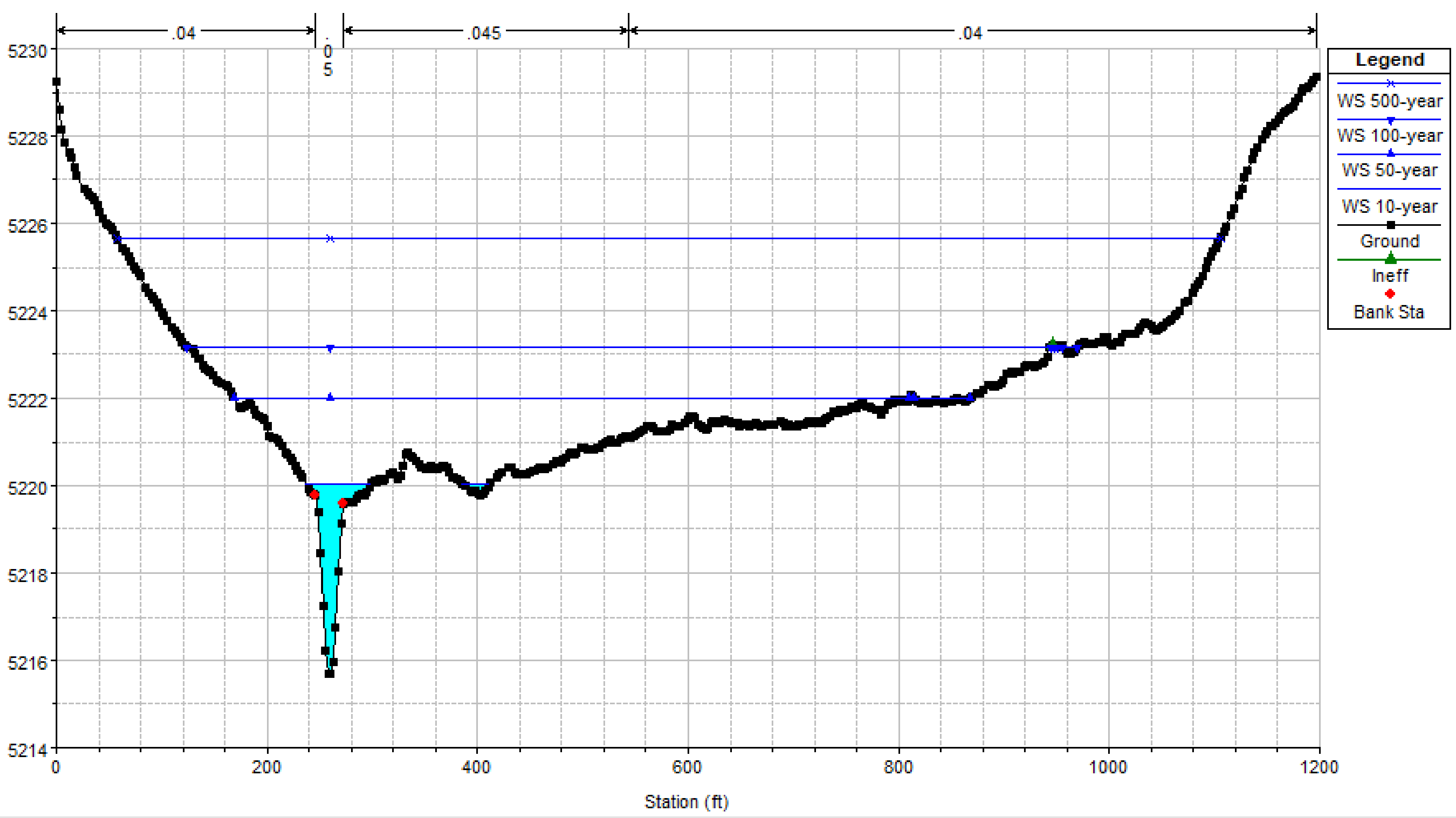
RESPEC

Study Area



Plants Grow

Everyone's Favorite 1D Model - HEC-RAS!



RESPEC

Wh row?

Too Many Runs

- **100 cross sections**
- **2 n values**
- **$2^{100} = 1.3 * 10^{30} =$ 1,300,000,000,000,000,000,000,000,000,000 simulations**
- **<u>$2.0 * 10^{23}$ years</u>**

RESPEC

Monte Carlo Simulation

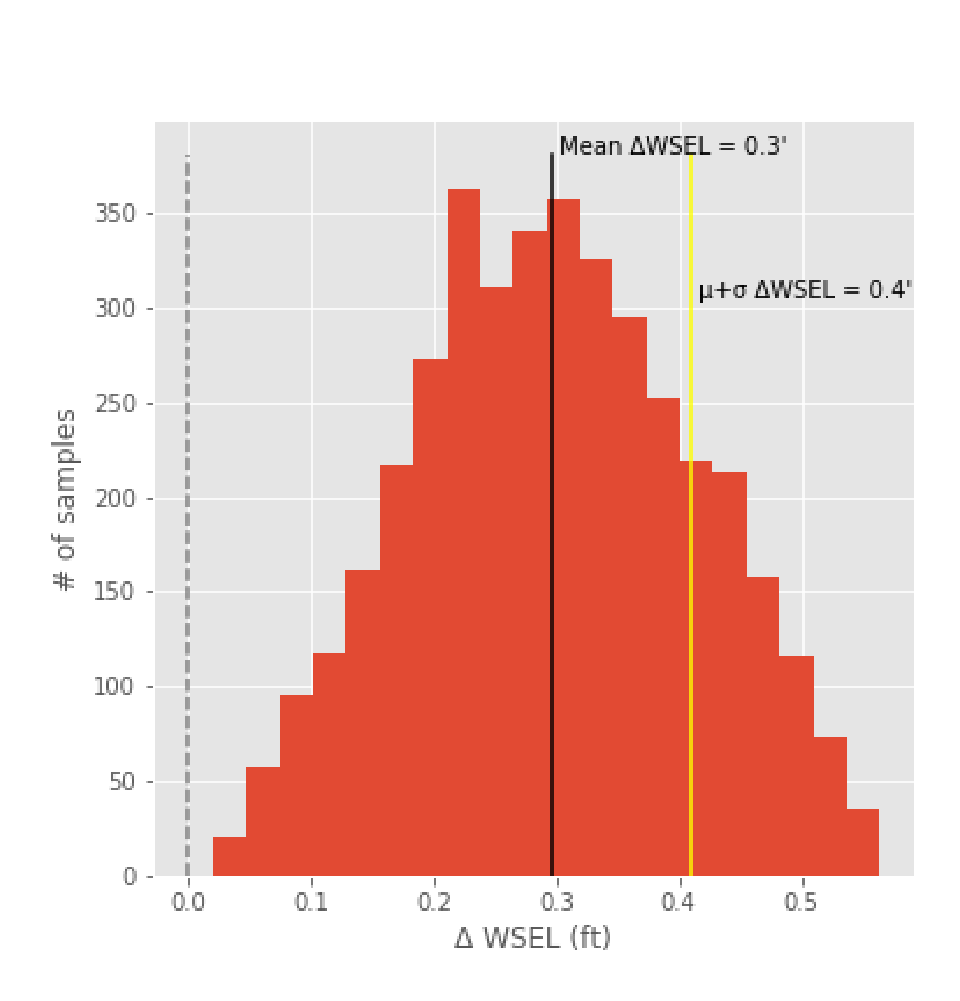
- **Random 0 to 75% increase in n value**
  - Overbanks have lesser increase
- **4,000 runs per model**
- **6 hours all 4,000 runs**

```
>>> print('Hello CASFM!’)

Hello CASFM!
```

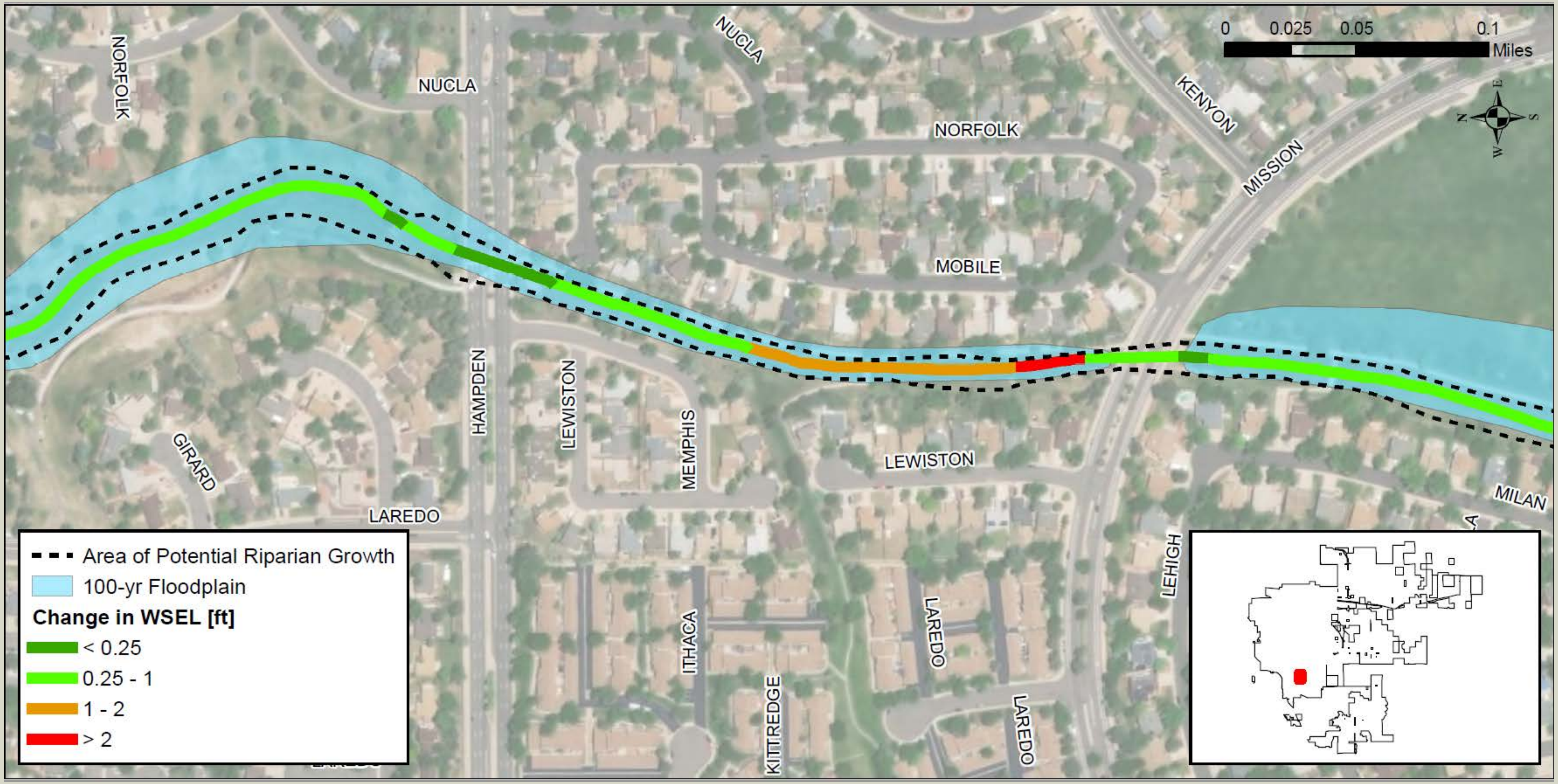
What Do The Results Look Like?

Unnamed Creek
Cross Section 2576



RESPEC

Results Map

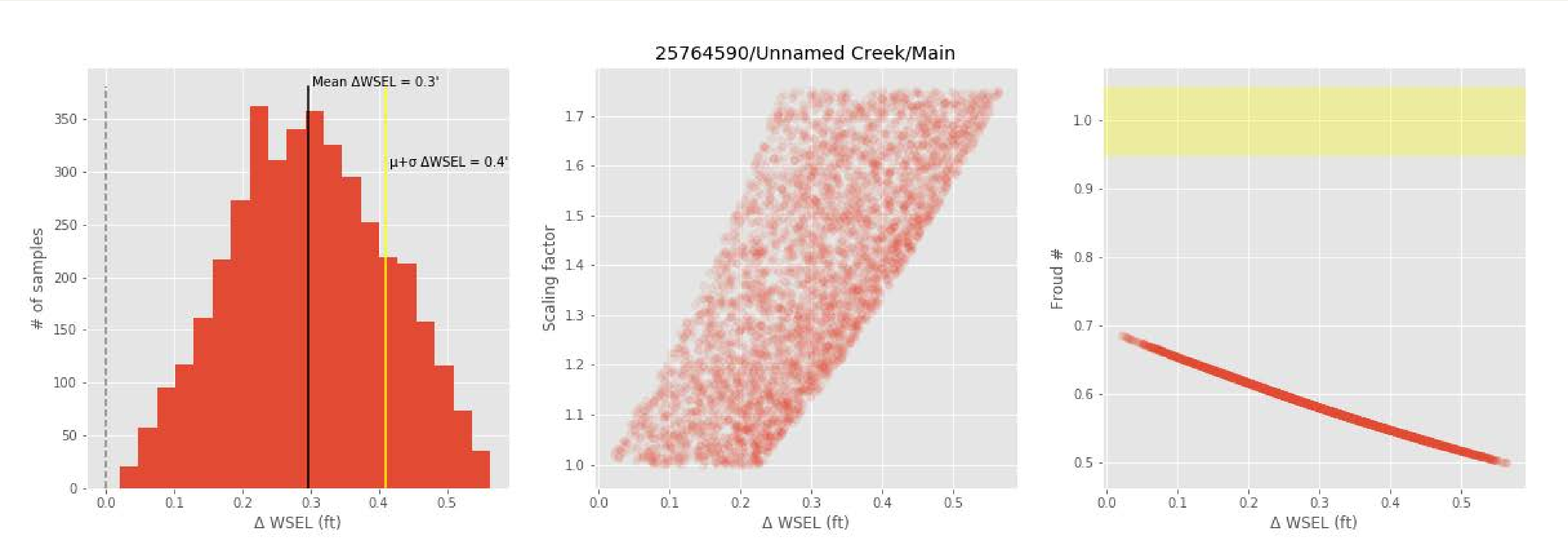


What Did We Learn?

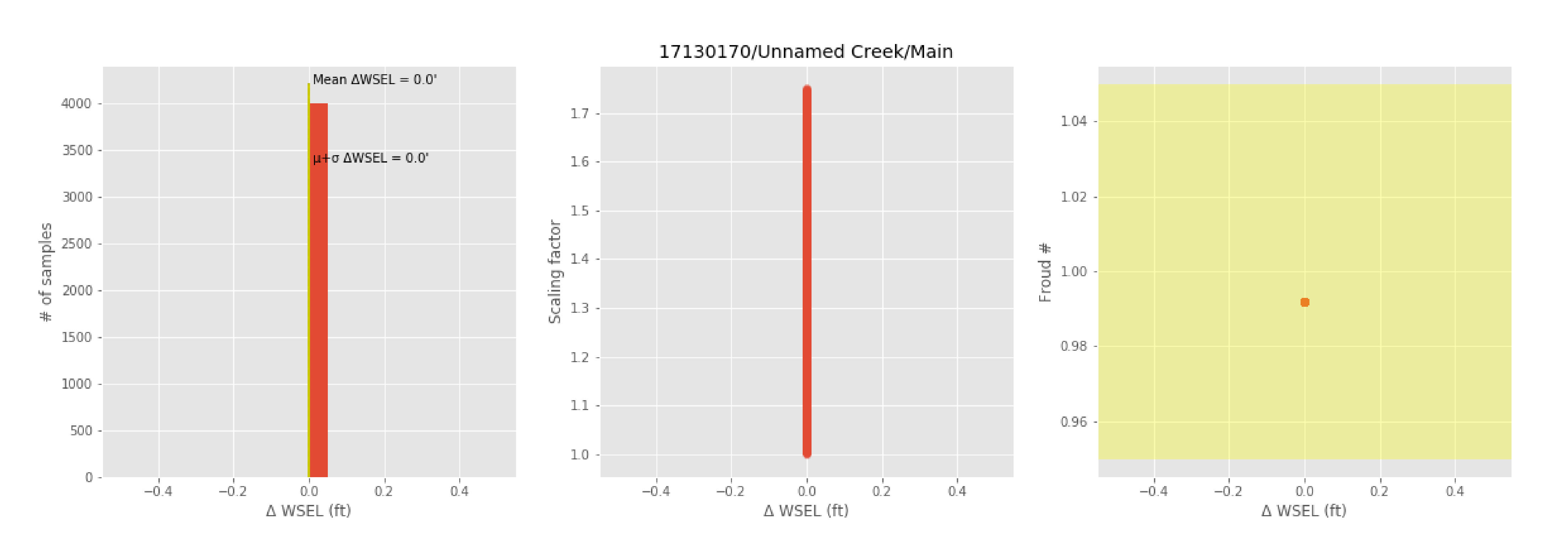
- **Vegetation growth can increase WSELs**
- **WSEL increases vary spatially**
  - Maintenance can be prioritized
- **Predicted increases are typically < 2’**

RESPEC

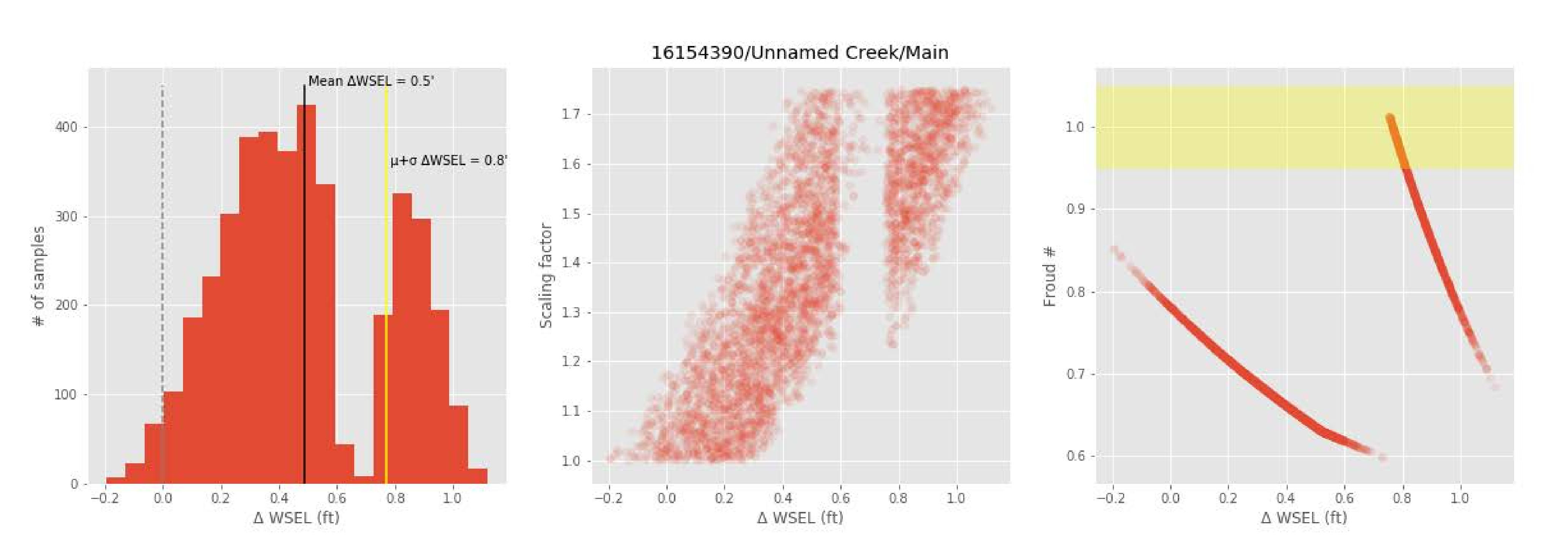
Typical, Well-Behaved Results



Insensitive Cross Section

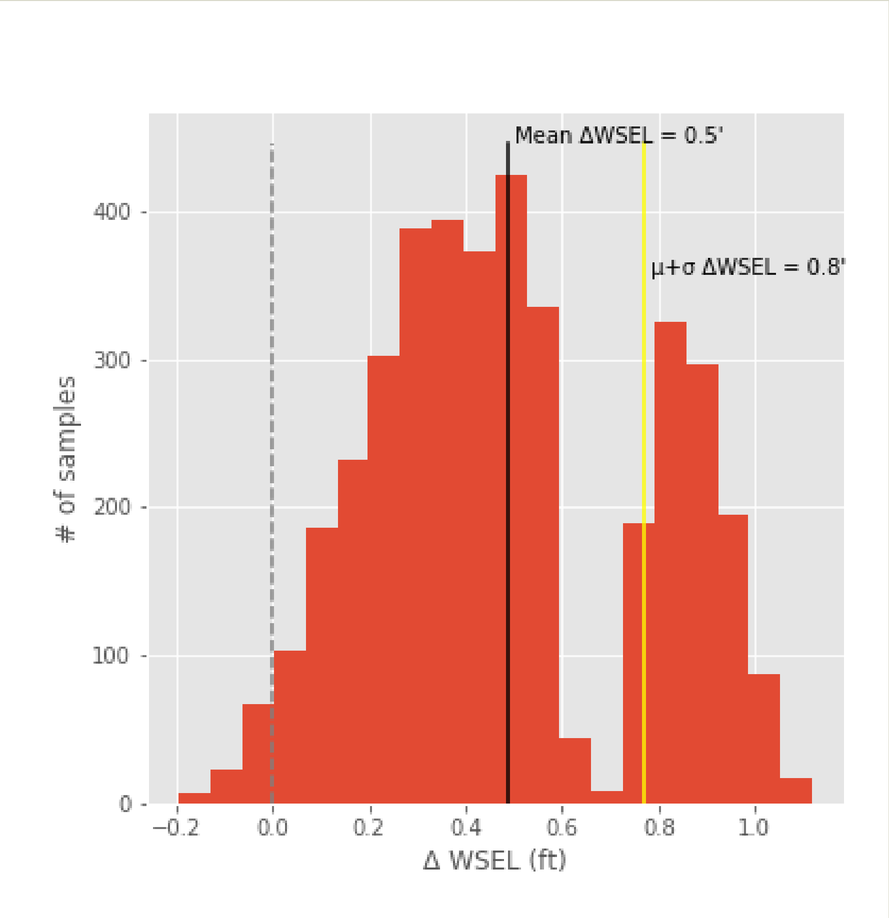


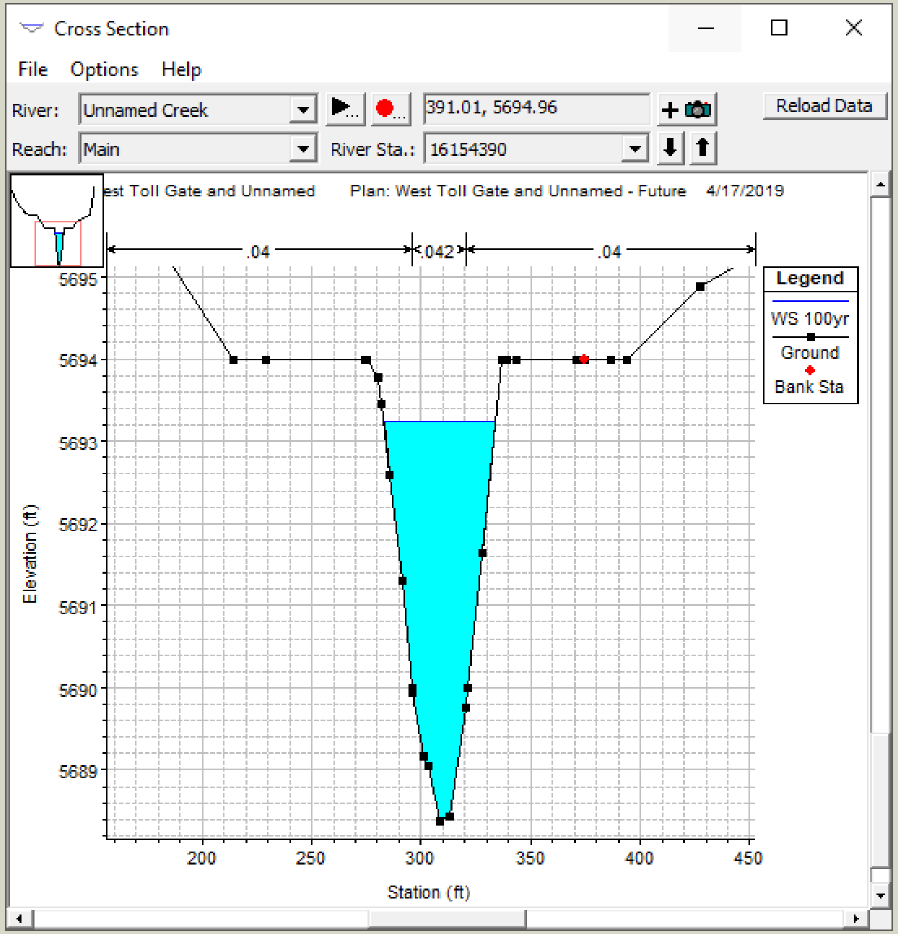
Weird - Holes in the Histogram



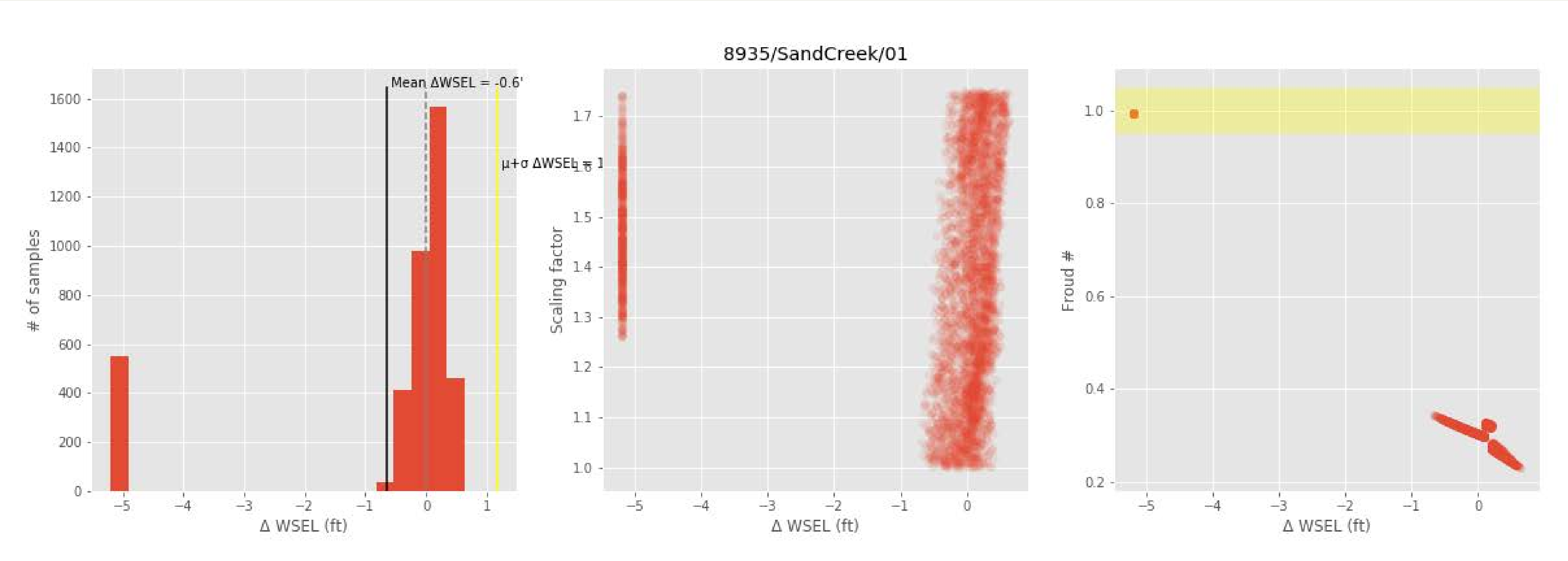
RESPEC

Weird - Holes in the Histogram



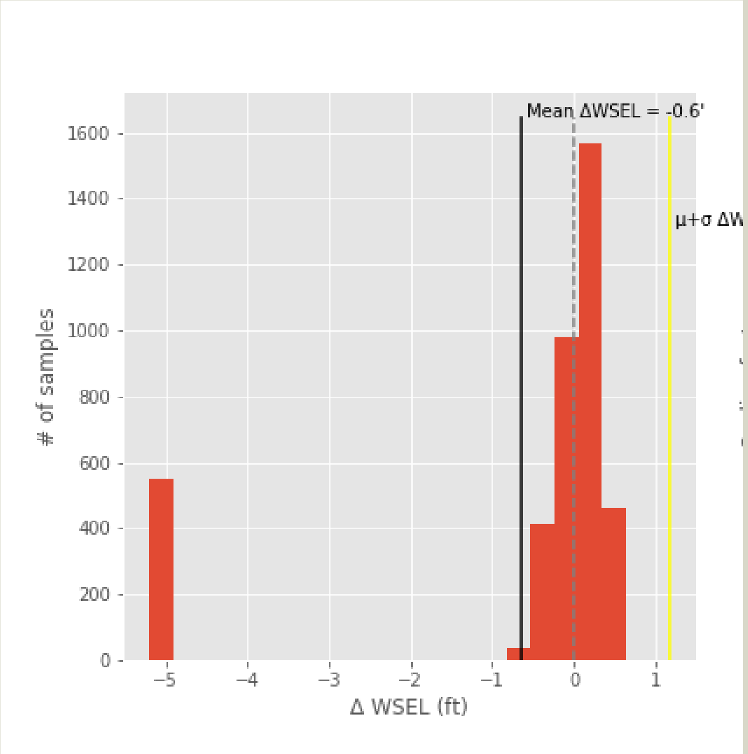


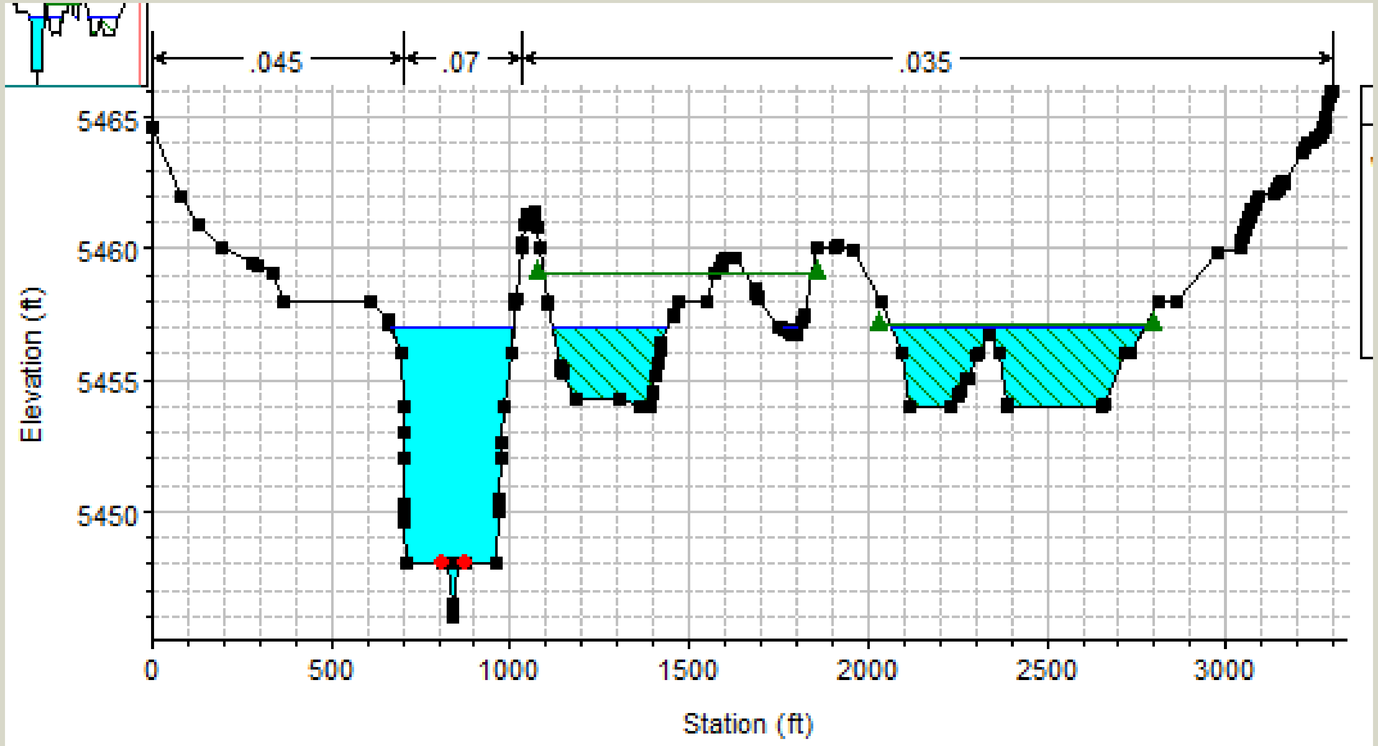
Unstable and Scary



RESPEC

Unstable and Scary





RESPEC

What Else Did We Learn?

- Most cross sections are well behaved
- Some are a little weird
- A few are scary – HEC-RAS does strange things sometimes
- Sensitivity analyses are a good thing

RESPEC

Want to Run a Monte Carlo Simulation?

- **Parse RAS Geo**
  - https://github.com/mikebannis/parserasgeo.git
- **RAS Control**
  - https://github.com/mikebannis/rascontrol.git

Aurora Water's Maintenance Responsibility

In 2017, the City of Aurora maintained approximately:

- **77 miles of channel**
- **91 ponds**
- **210 overflow tracts/easements**
- **3 dams**
- **1 levee.**

West Tollgate Creek at Buckley Street

Maintenance Prioritization

- **Field guide established for each type of vegetation**
  - Native grass/weed management
  - Woody vegetation management
  - Chemical vegetation management
  - Revegetation
- **Use of empirical knowledge to drive maintenance scheduling**
- **Inspections of existing conditions dictate maintenance activities**

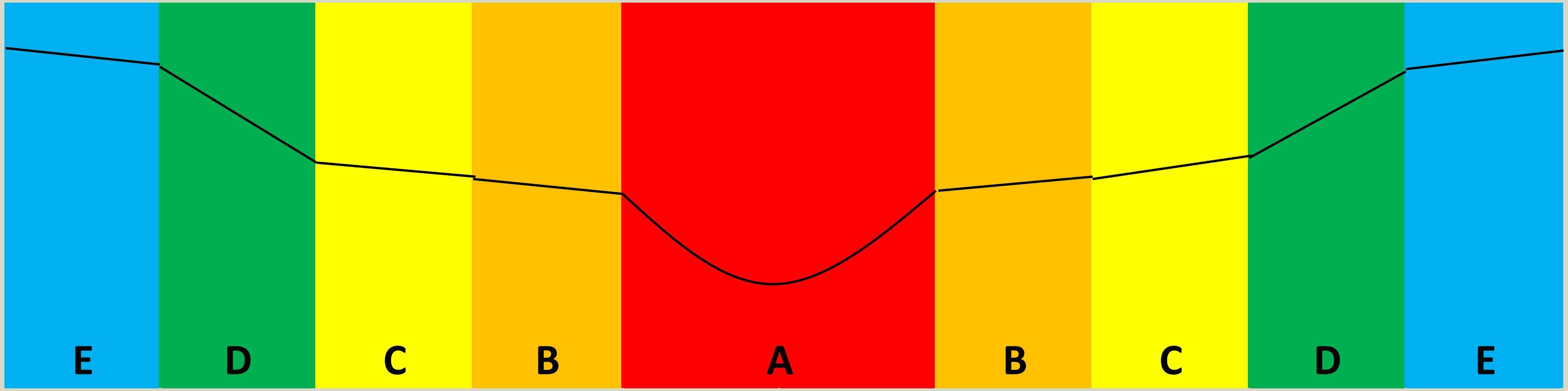
Ursula Pond

Example of Maintenance Methods

Before

After

Woody Vegetation



A= All woody vegetation will be removed from center of channel

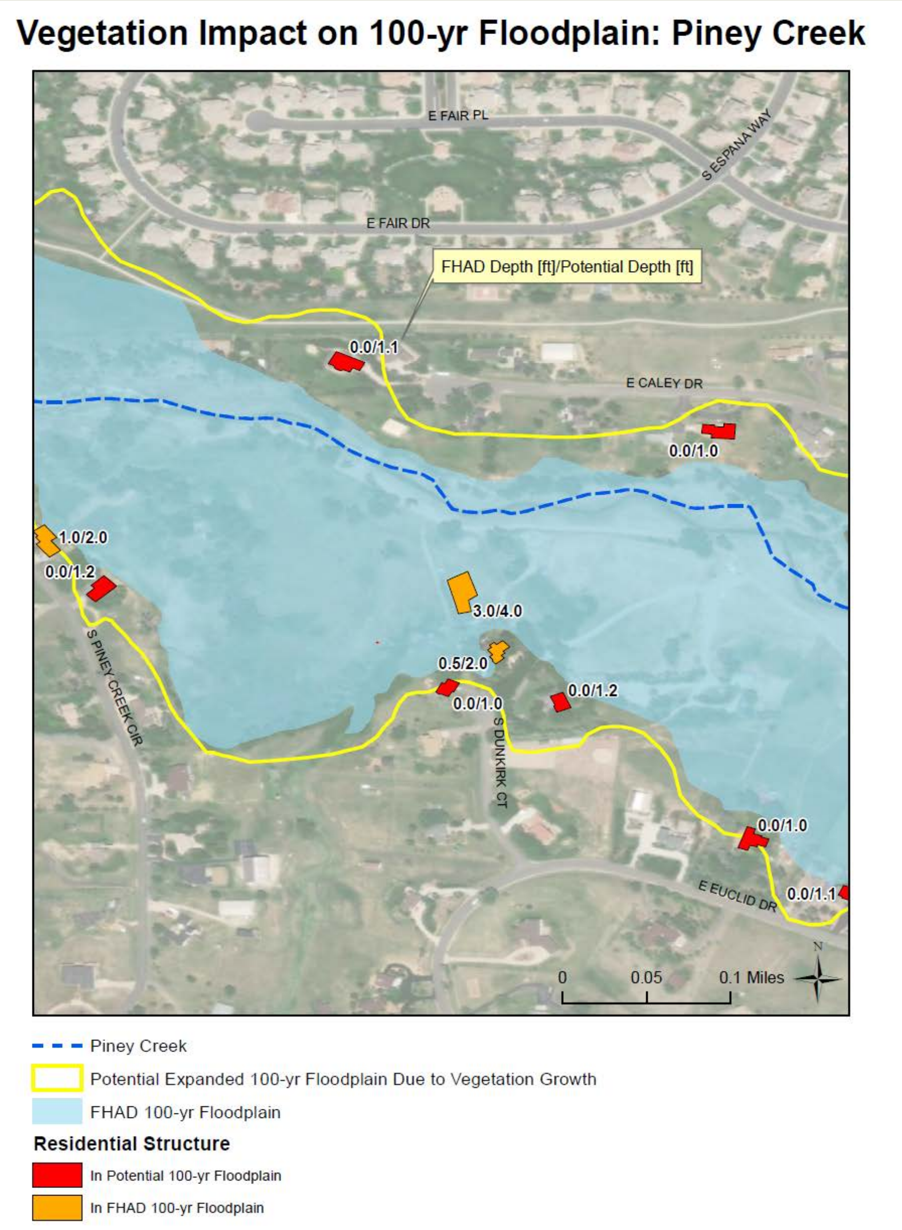
B= Remove all noxious, dead or fallen trees outward 15’ +/- from channel. Manage willows and trim trees as necessary within 15’ to allow for high flows

C= Remove all noxious trees, discretionary management of willows, trimming of trees and removal of dead and fallen trees.

D & E= Remove all noxious trees, discretionary management of willows, trimming of trees and removal of dead and fallen trees for maintenance access.

RESPEC

The Future of Prioritized Maintenance



Questions?

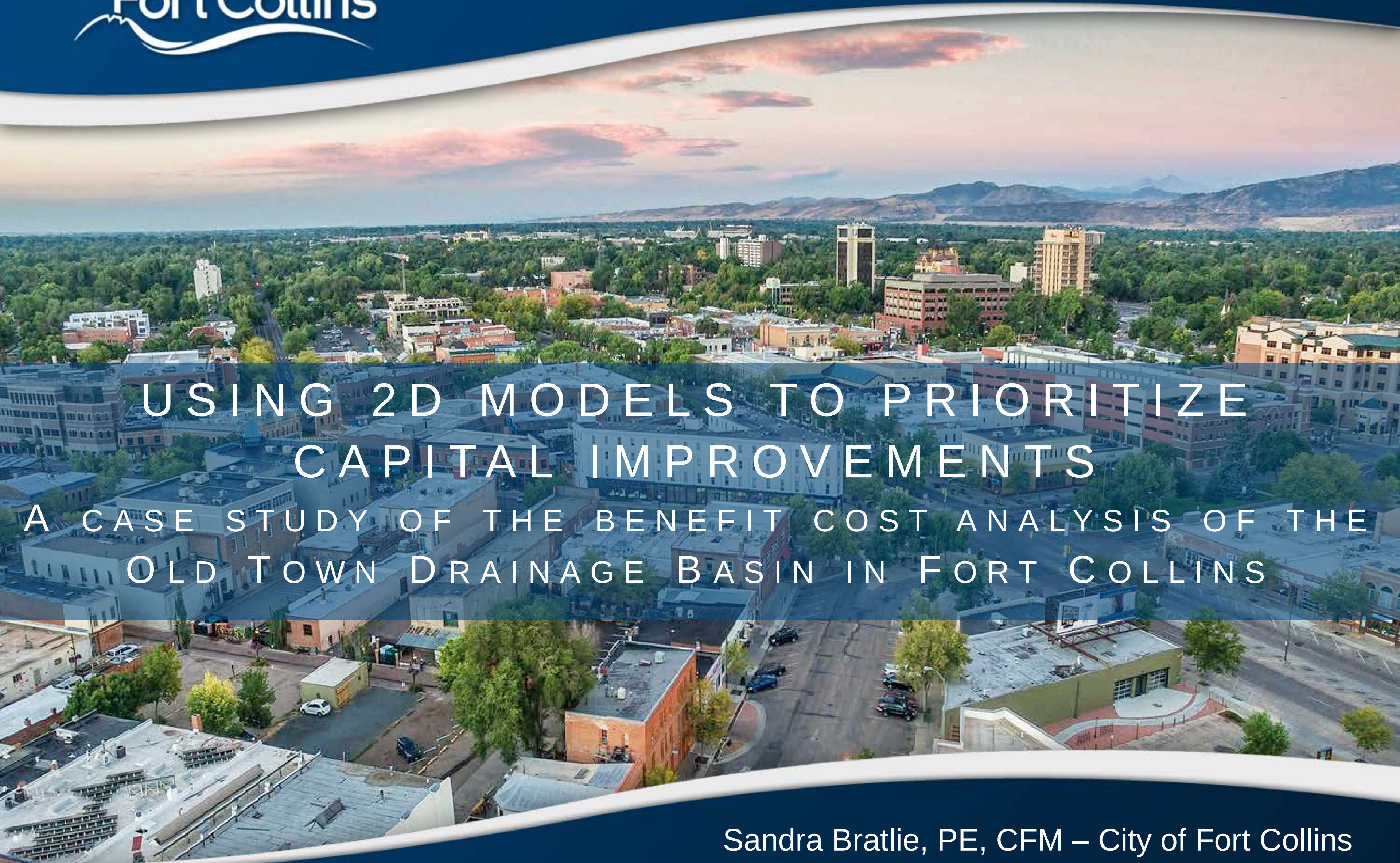
CASFM 2021?

Please?

Pretty please?

2019 Annual CASFM Conference

City of Fort Collins



USING 2D MODELS TO PRIORITIZE CAPITAL IMPROVEMENTS

A CASE STUDY OF THE BENEFIT COST ANALYSIS OF THE OLD TOWN DRAINAGE BASIN IN FORT COLLINS

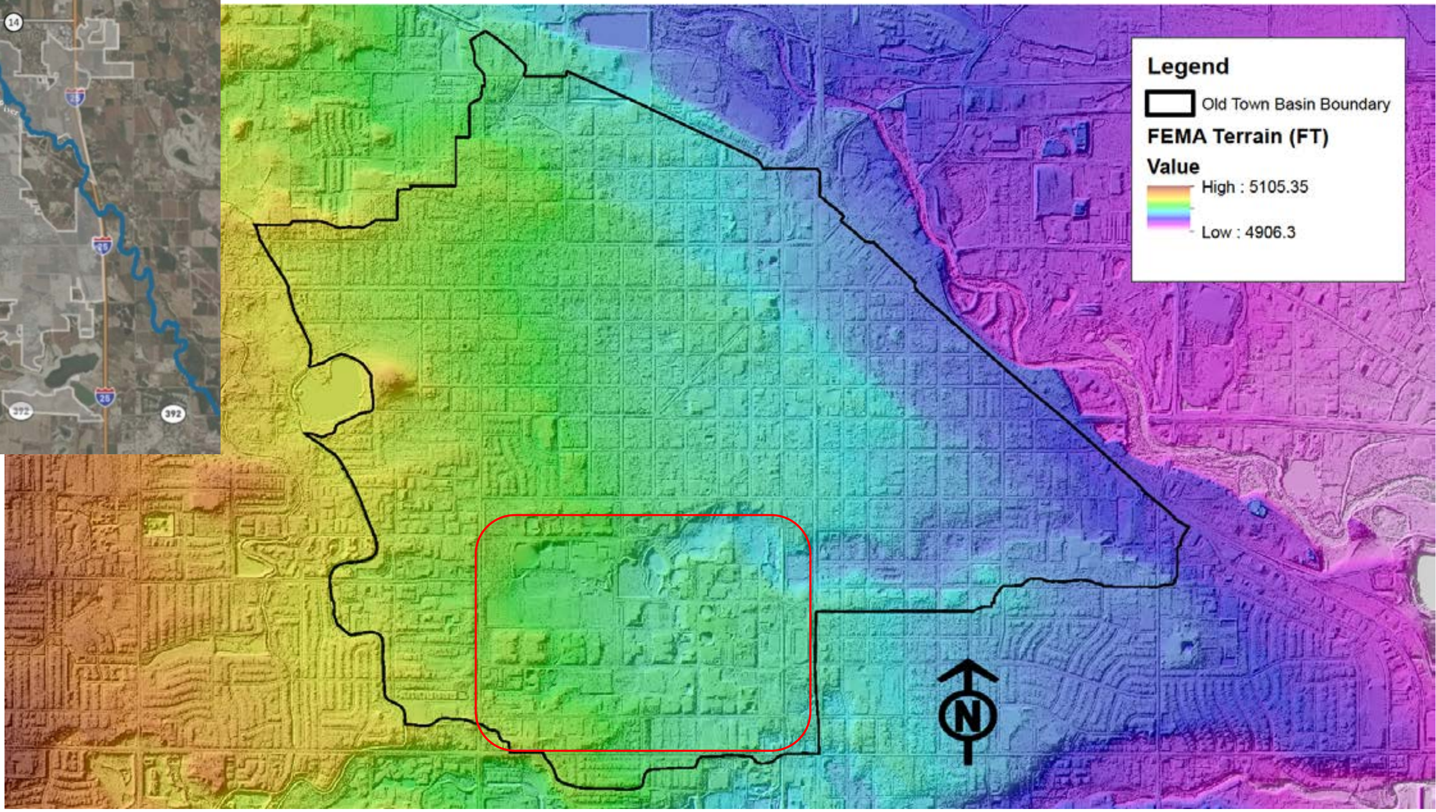
Sandra Bratlie, PE, CFM – City of Fort Collins

Jeremy Deischer, PE – ICON Engineering

ICON ENGINEERING, INC.

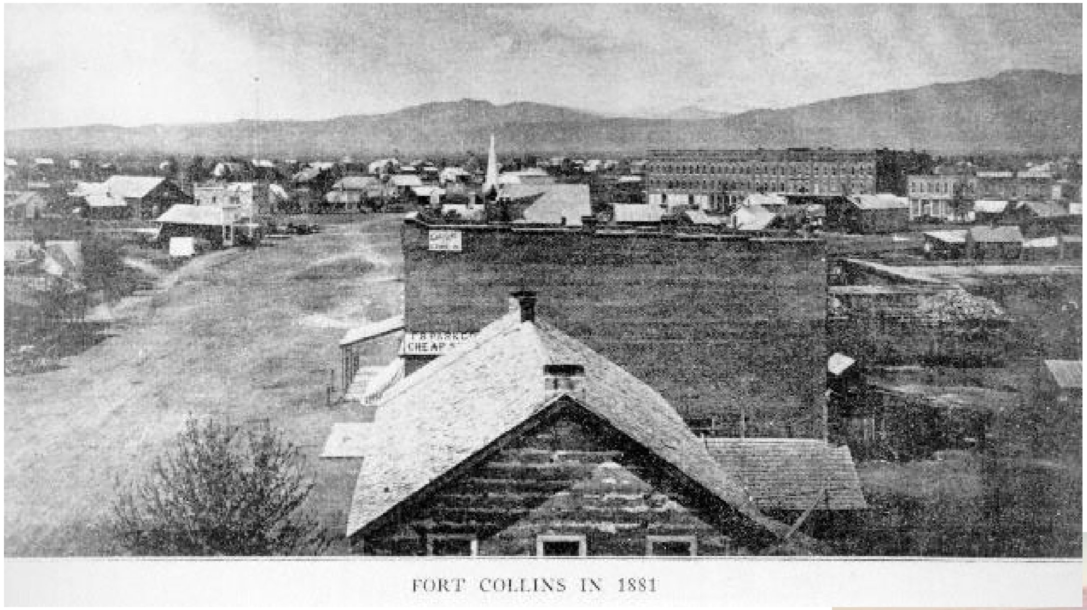
Old Town Basin

- Located in north-central Fort Collins
- Drainage area of approximately 2,120 acres
- 400 acres of the Colorado State University campus



City of Fort Collins

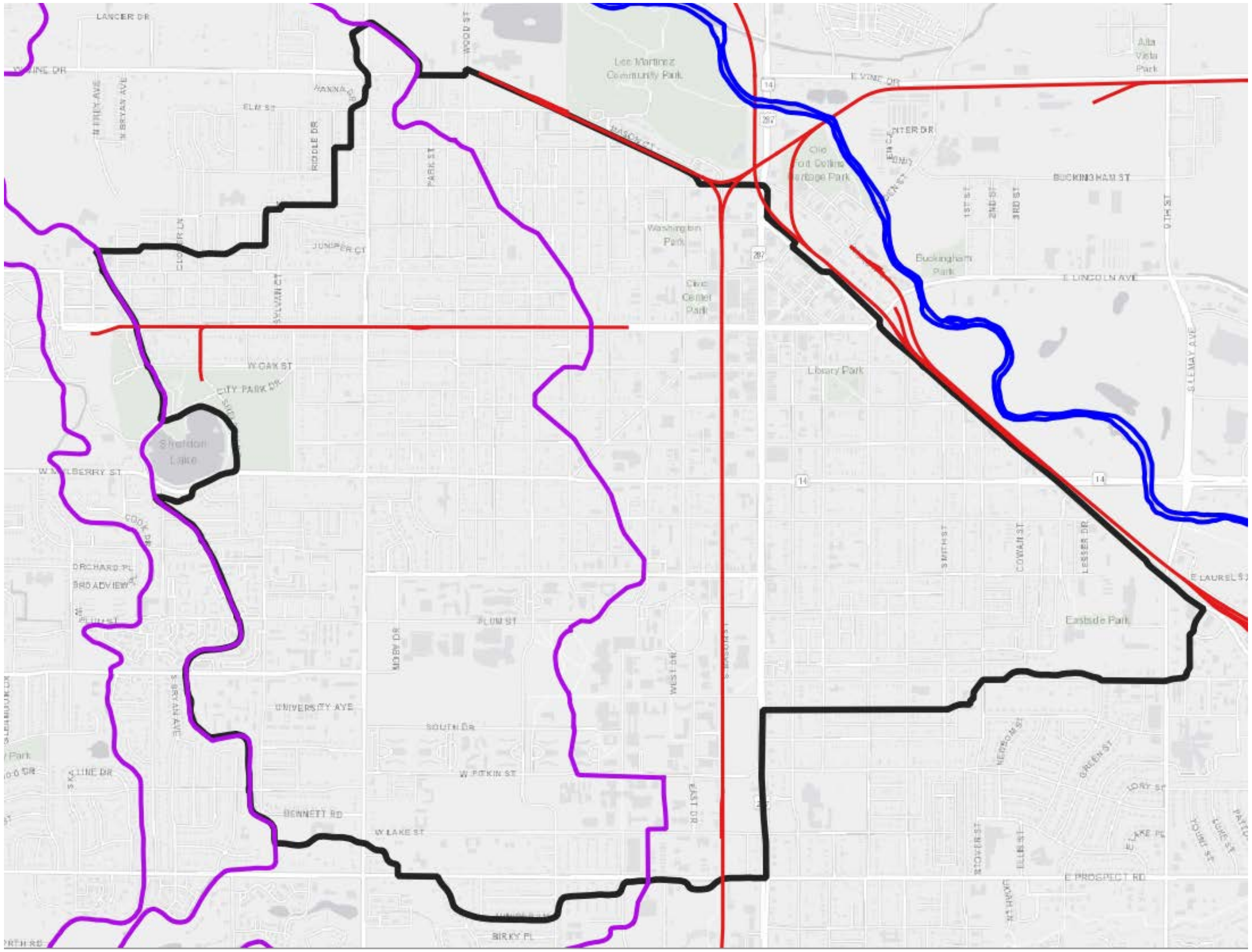
Old Town Basin



- Fully established basin
- Development starting in the 1880's

https://history.fcgov.com/thenandnow

Old Town Basin Infrastructure



- Irrigation
- Railroad
- Active historic trolley
- Street profile and grated area inlets
- 100 year old undersized clay storm drain
- Lots of alleys and basements

Flooding History

Fort Collins, Colorado A Gannett Newspa[per] 25 Cents

THURSDAY
June 25, 1992

FORT COLLINS
COLORADOAN

High 78, Low 54
Details, Page A10

'Like opening a faucet'

Relentless hour of rain floods streets, buildings

By KEVIN VAUGHAN
The Coloradoan

A record-breaking thunderstorm pummeled Fort Collins on Wednesday afternoon, flooding streets and buildings and causing widespread damage.

The storm hit quickly shortly after 3 p.m., bringing with it one of the most intense hours of rain in city history, pea- to marble-sized hail, lightning and a possible funnel cloud.

"There were a couple of big drops, and then it was just like somebody opening a faucet," said Rick Gavaldon, a supervisor with the Larimer County Road and Bridge Department who was working to repave a residential street when the storm moved in.

No dollar value had been assigned to the damage Wednesday night, and no injuries were reported.

Officially, the storm dumped 2.49 inches of rain — nearly all of it in one hour — at the Fort Collins Weather Station on the Colorado State University campus.

That shattered the rainfall record for the date. The old record, set on June 24, 1958, was .66 of an inch of rain.

In other locations in and around Fort Collins, weather spotters reported as little as .22 of an inch of rain and as much as 3.09 inches from the storm.

"For — I would say — 30 minutes, I could barely see across the street," said Jim Wirshborn, chief meteorologist at Mountain States Weather Services.

Wednesday's storm was reported to be one of the most intense in city history in terms of the amount of rain that fell in one hour.

Although weather data has been collected since the 1930s, nobody has analyzed it to find the most intense storm on record.

Wirshborn compared Wednesday's onslaught to two other storms, one that brought 4.45 inches of rain in a 24-hour period on July 24 and 25, 1977, and one that was responsible for 3.5 inches of rain on Aug. 2 and 3, 1951.

Wednesday's storm led to damage across a wide swath of Fort Collins:

■ At Poudre Valley Hospital, 1024 S. Lemay Ave., overburdened drains caused flooding in several areas, the most severe in the patient financial ser-

See STORM, Page A2

Inside

■ Downpour drenches downtown
■ Surging storm a surprise
■ City flooded with calls
■ Apartment takes a beating
■ Notebook

— Page A2

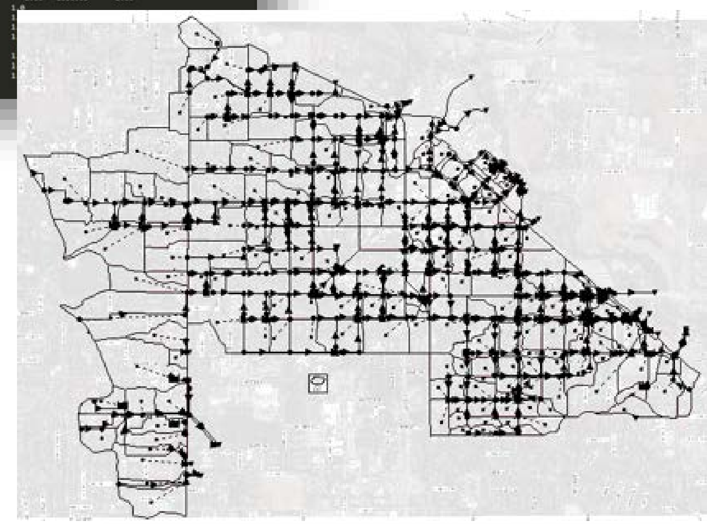
Michael Madrid/The Coloradoan

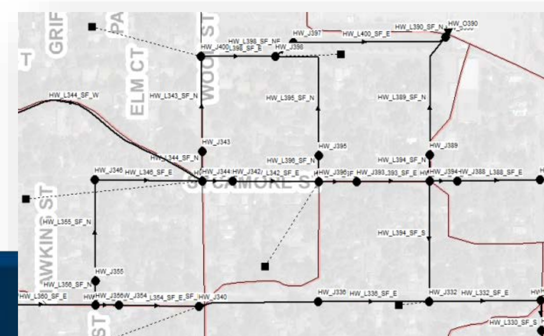
UNLUCKY RABBIT: Mike Mossburgh, far right, and Charley Deringer push a stranded car from the flooded intersection of College Avenue and Mulberry Street. The car's driver, Kimberly Roberts, was one of many motorists stranded Wednesday by the storm that drenched the city. Nearly 2½ inches of rain fell in about an hour.

This article appeared in the local paper following a 1992 flood in Old

Photo 3 – College Ave and Mulberry St. Intersection looking south. Photo by Linsey Chalfant.

Old Town Basin Master Plan Update





2003

- Baseline Hydrology (MODSWMM)
- City Floodplain
- Selected Plan of Improvements

2005

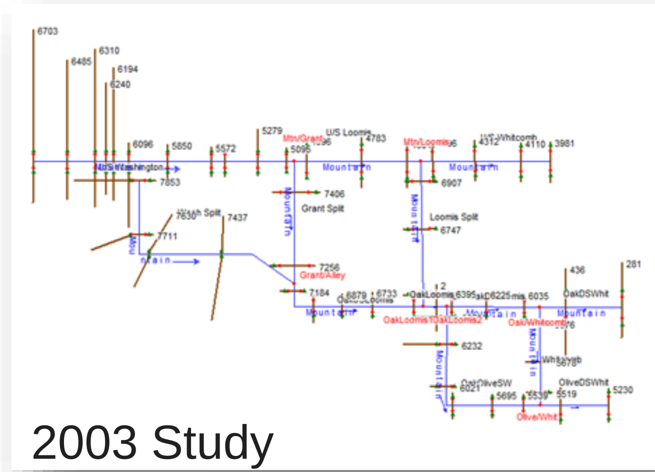
- Trans-basin inflows updated

2016

- Hydrology updated
  - MODSWMM model converted to EPA SWMM
  - FLO-2D used to calibrate surface flow diversions
- Potential Inundation Area (PIA)

Potential Inundation Area (PIA)

- Effective Regulatory Floodplain developed with 2003 study
- HEC-RAS used to model locations where peak flows exceeded 200 cfs
- 2016 Update developed PIA with FLO-2D for 100-yr design event

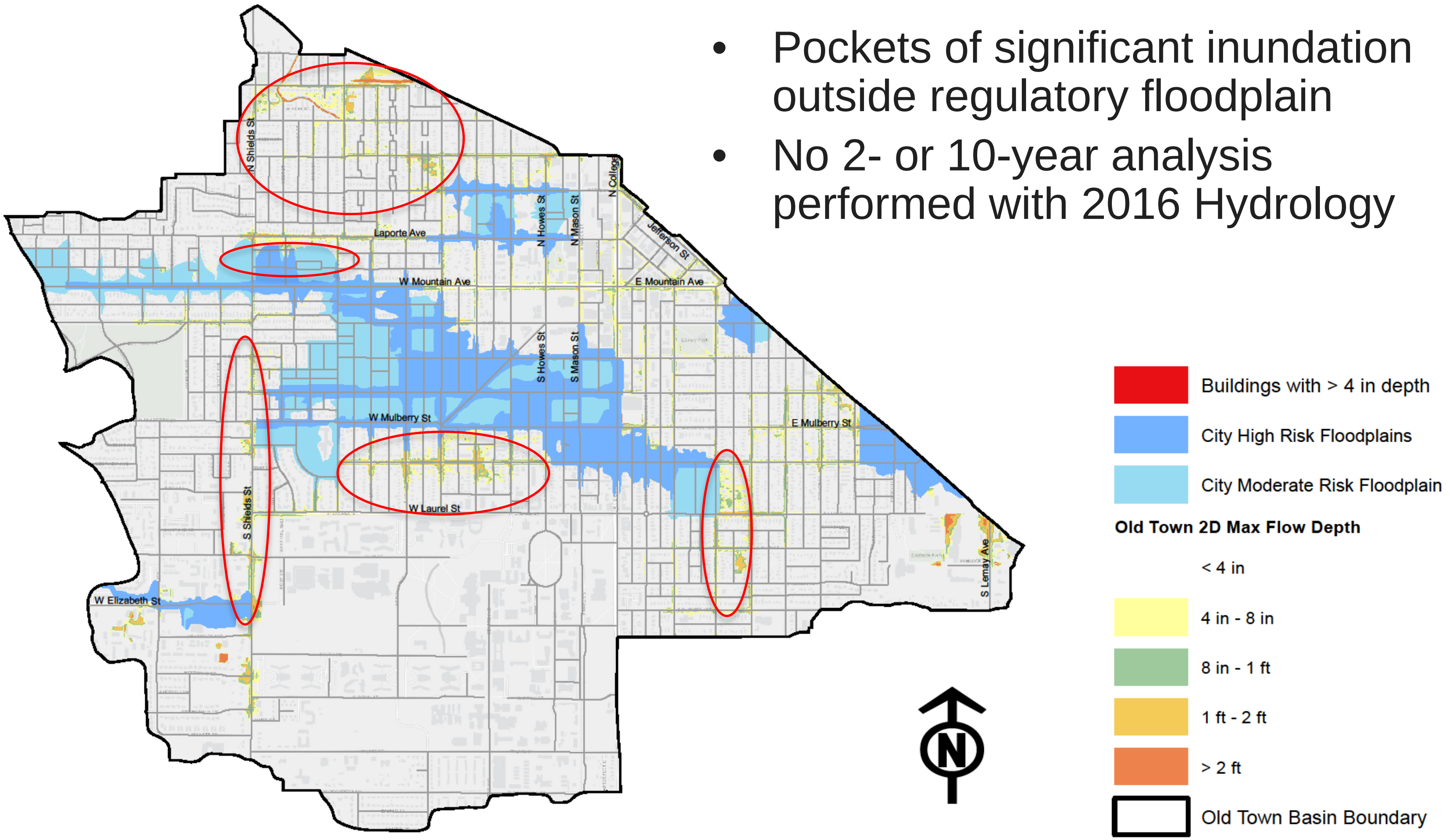


2003 Study

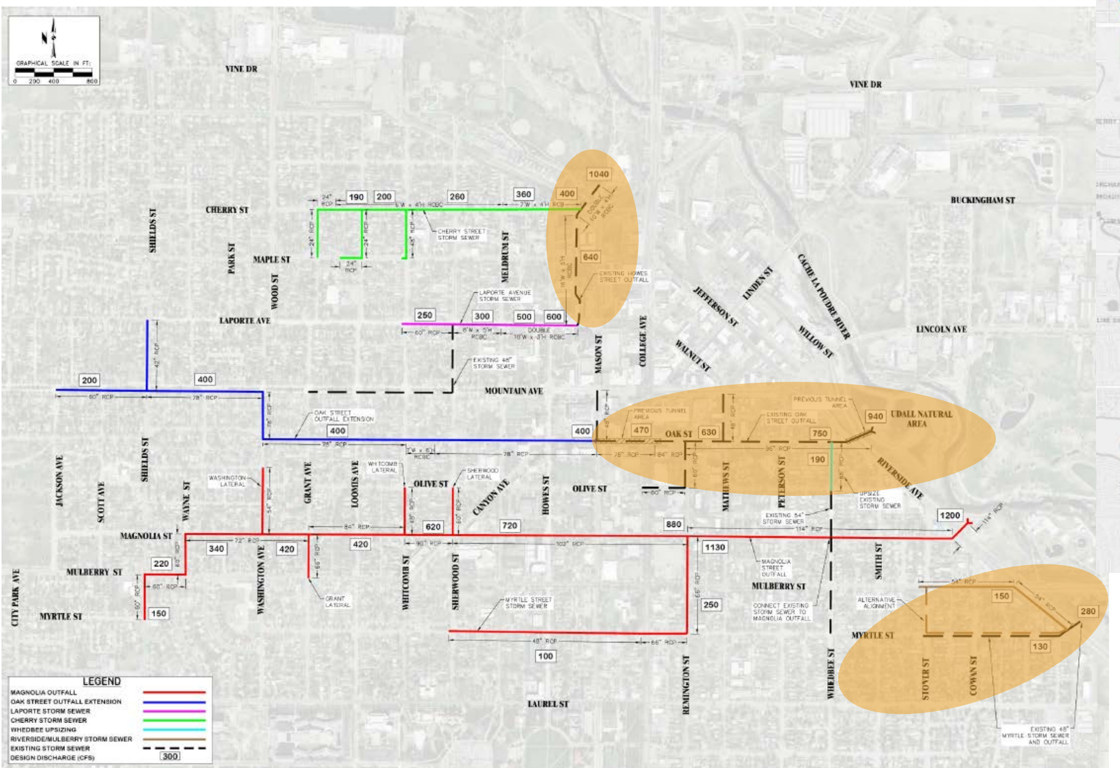
2016 Update

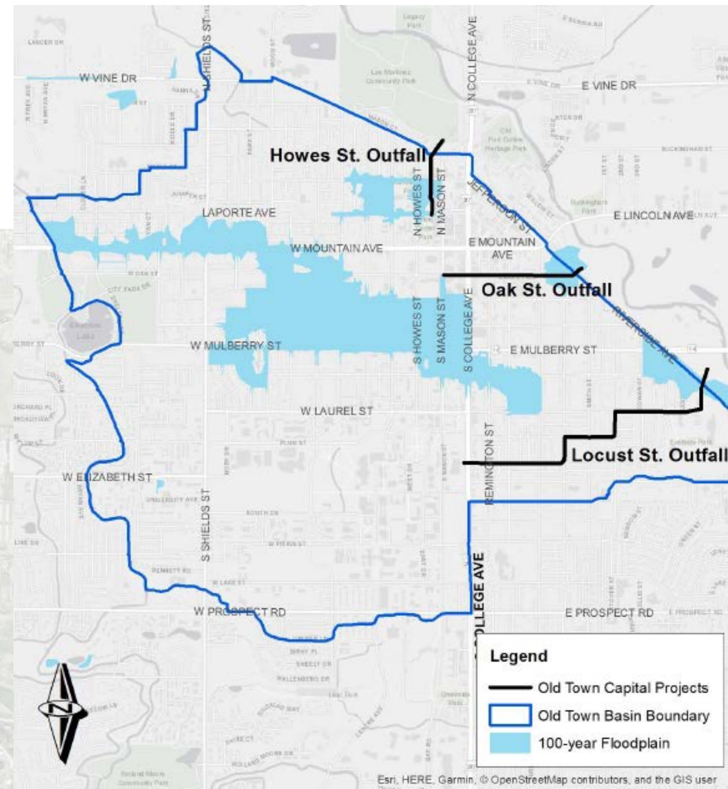
Effective Regulatory vs. Potential Inundation Area

- Pockets of significant inundation outside regulatory floodplain
- No 2- or 10-year analysis performed with 2016 Hydrology



Optimization of Existing Infrastructure & Outfalls





Damage Assessment Project Goals

Evaluate existing condition damages

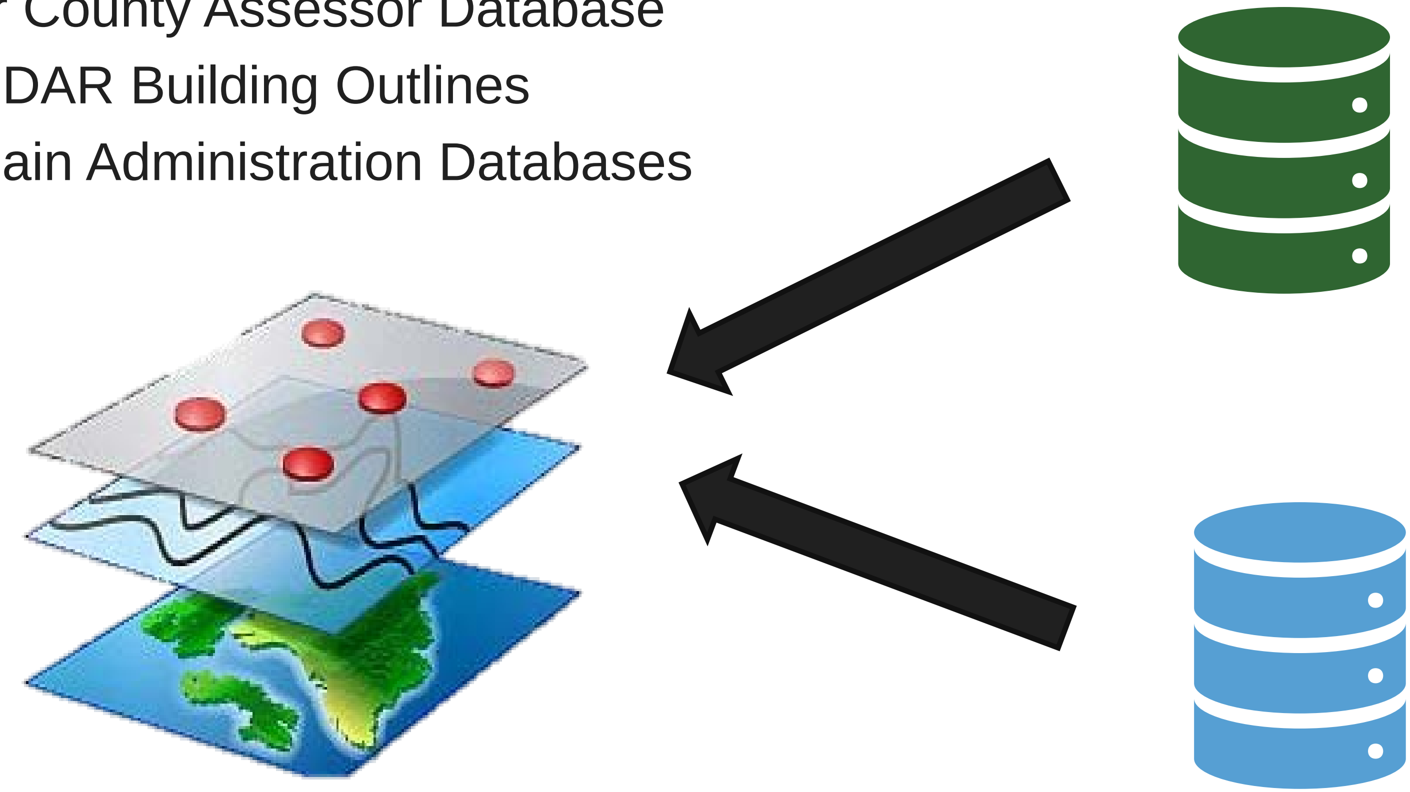
Develop Potential Flood Inundation for 2- & 10-year events

Develop FLO-2D simulating post project conditions

Scalable process for city-wide implementation

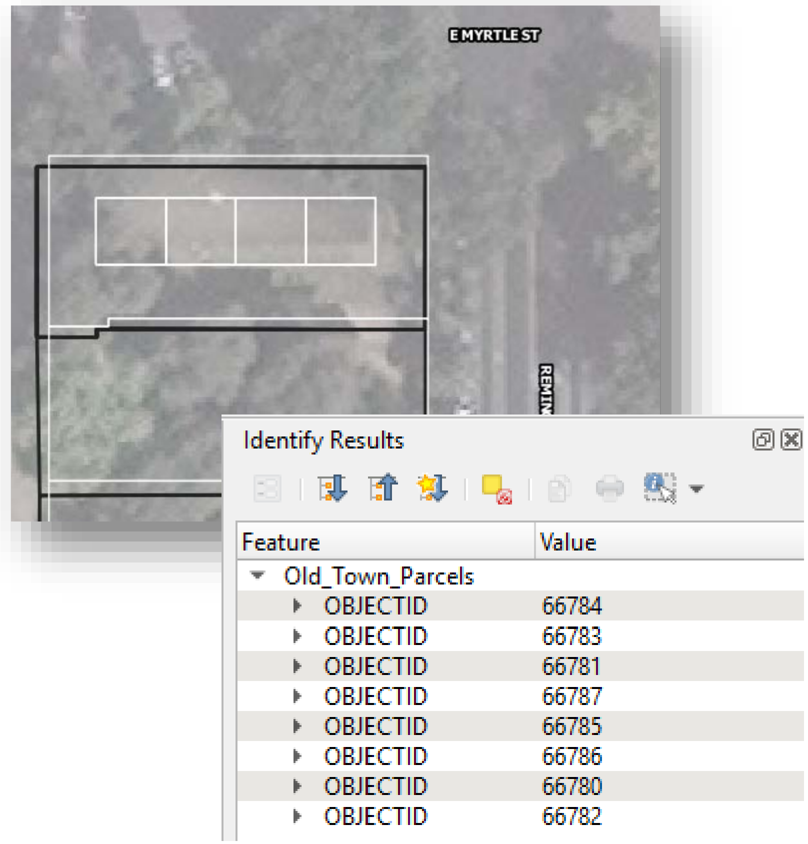
Datasets

- Parcels
- Larimer County Assessor Database
- 2013 LiDAR Building Outlines
- Floodplain Administration Databases



Assessor / Parcel Dataset

- City of Fort Collins Parcel Dataset
- Dataset developed for notifications purposes
- City parcels in same extent merged together
- Not 1:1 relationship
- Replaced with Larimer County parcel shapefile



Larimer County Assessor Database

Several datasets combined to establish relevant property information:

- Address
- Property Type
- Building Type
- Occupancy Code
- Building Square Footage
- Basement Type
- Basement Square Footage
- Improvement Value

City of Fort Collins

Building Outline Dataset

- Dataset developed from LiDAR returns in 2013
- 8,250 structures
- Develop routines to isolate largest structure on each parcel
- Utilized demolition database to update dataset for development since 2014
- Street view and Dashboard QC

Floodplain Administration Database

LOMA

- LAG

Floodplain Use Database

- LAG
- FFE
- Floodproofing

Permit Databases

- Demo Permits

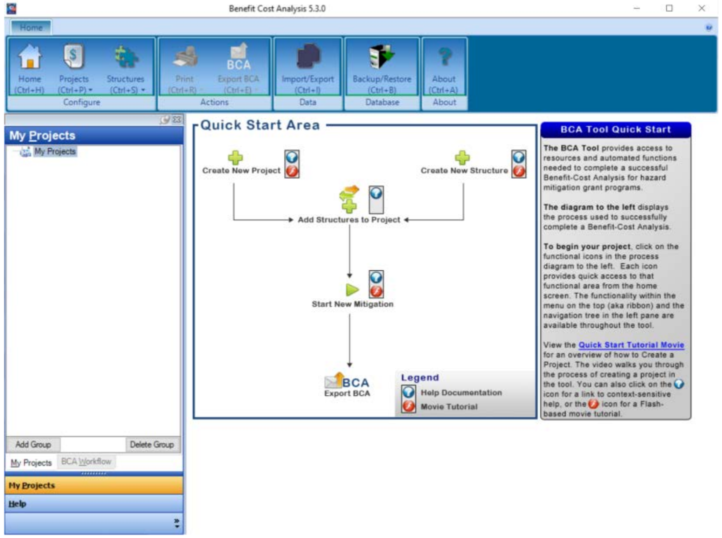
Sample Point Database

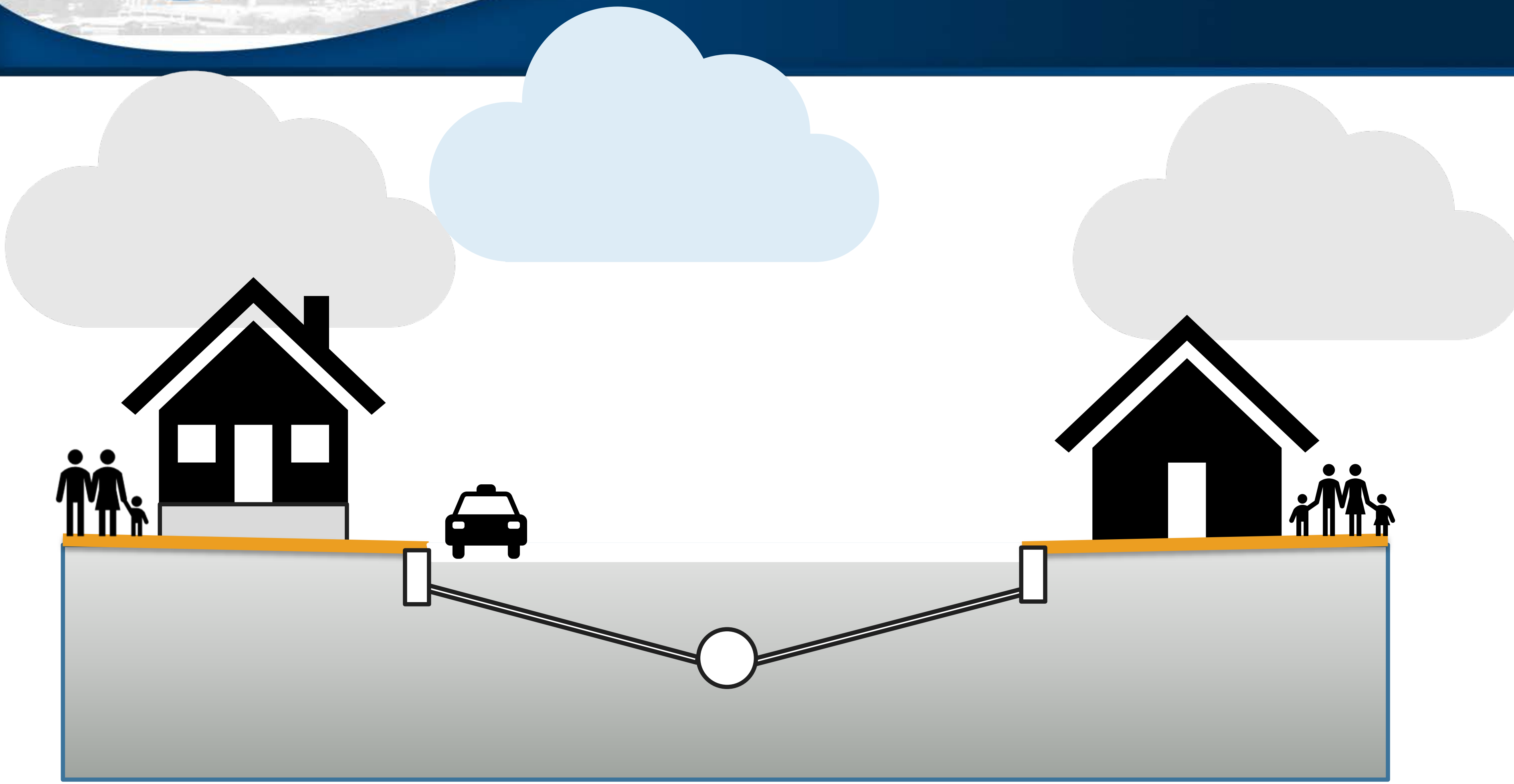
- LAG
- Number of Steps

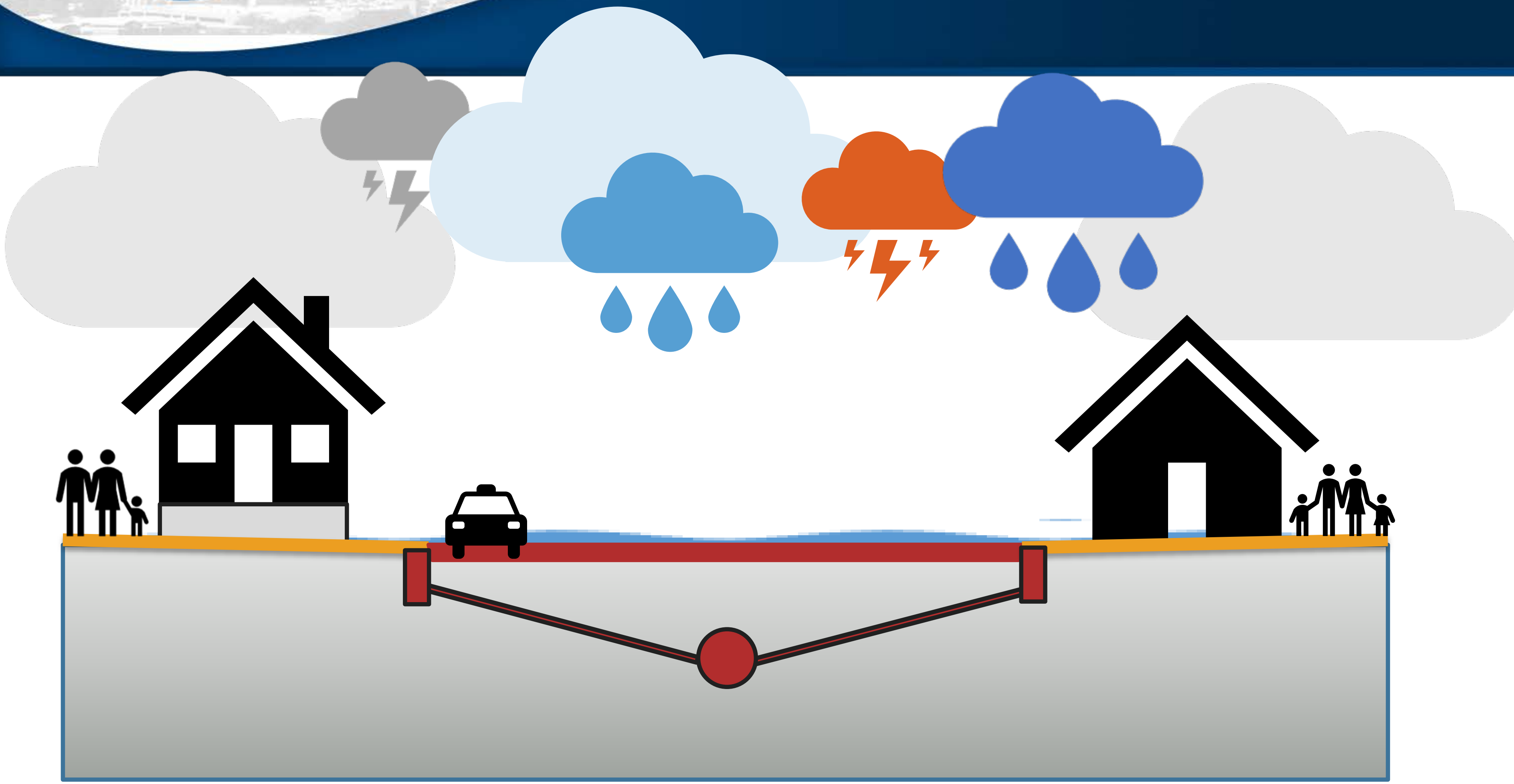
Damage Assessment Approach

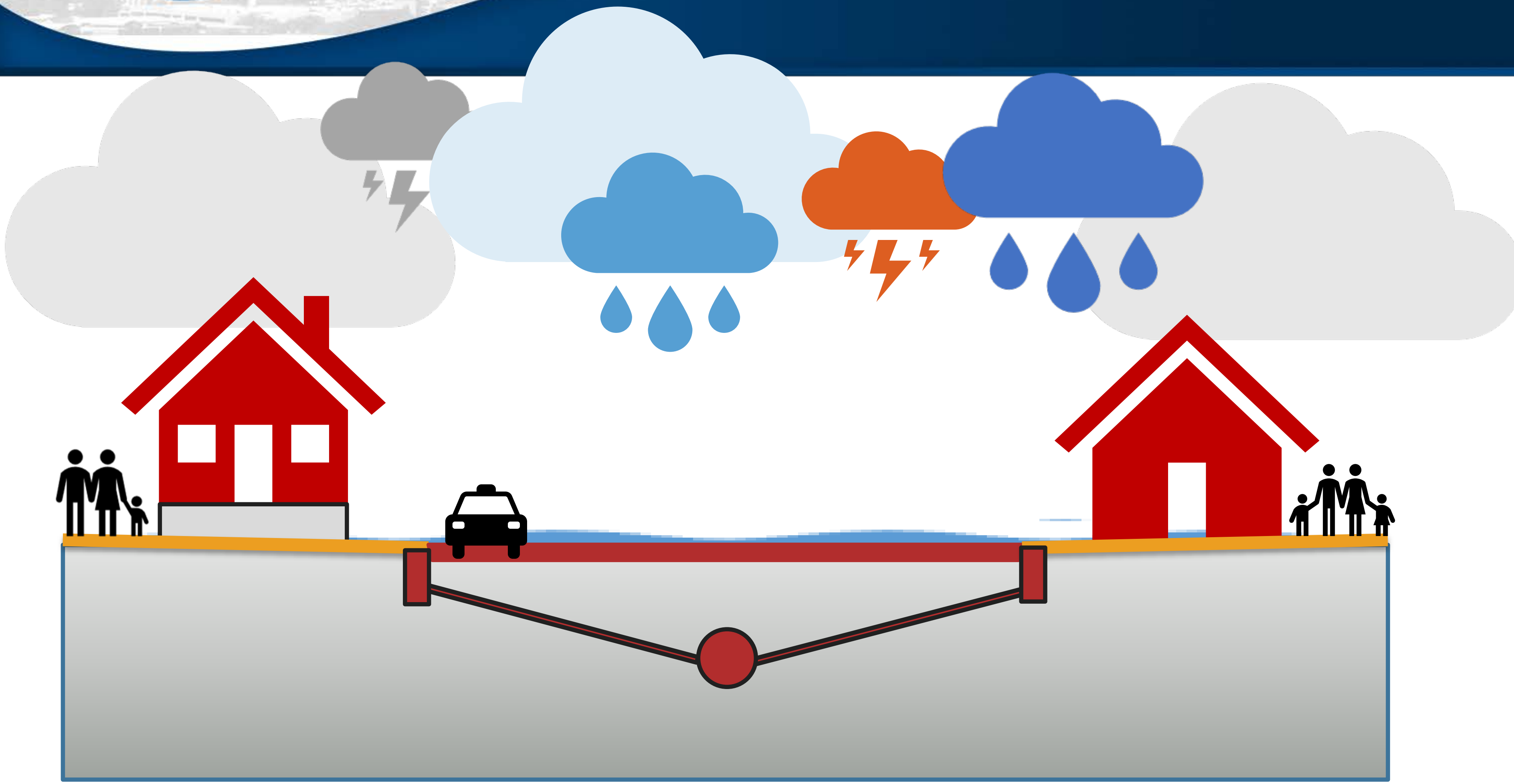
- FEMA Benefit-Cost Analysis
- Used to evaluate cost effectiveness of proposed improvement
- Future benefits are compared to project cost to develop Benefit-Cost Ratio (BCR)
- Requires:
  - Building Classification
  - Building Replacement Value
  - Flooding Depth
- Incorporates other damages
  - Loss of Function
  - Displacement
  - Social Benefits

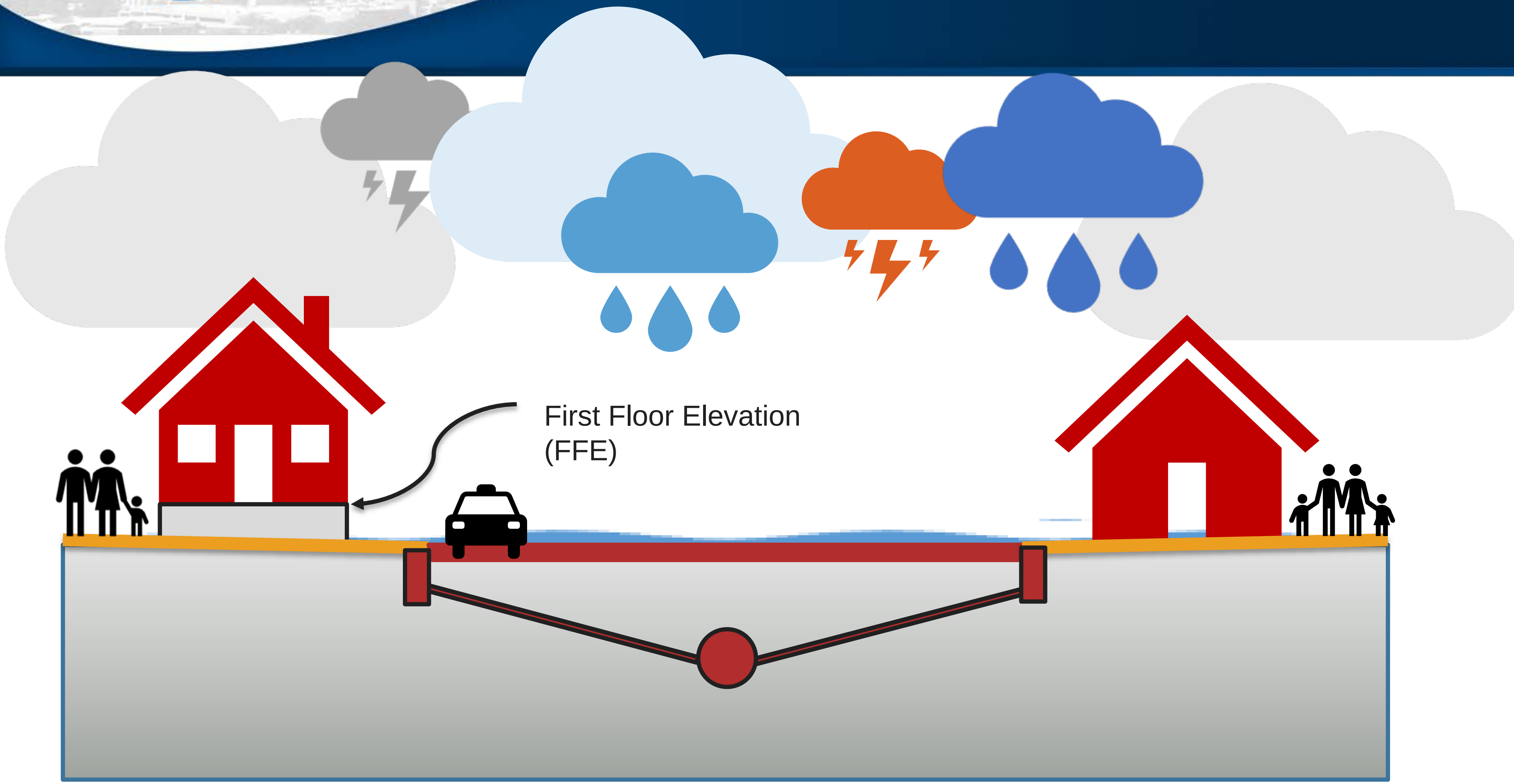
Understanding the FEMA Benefit-Cost Analysis Process

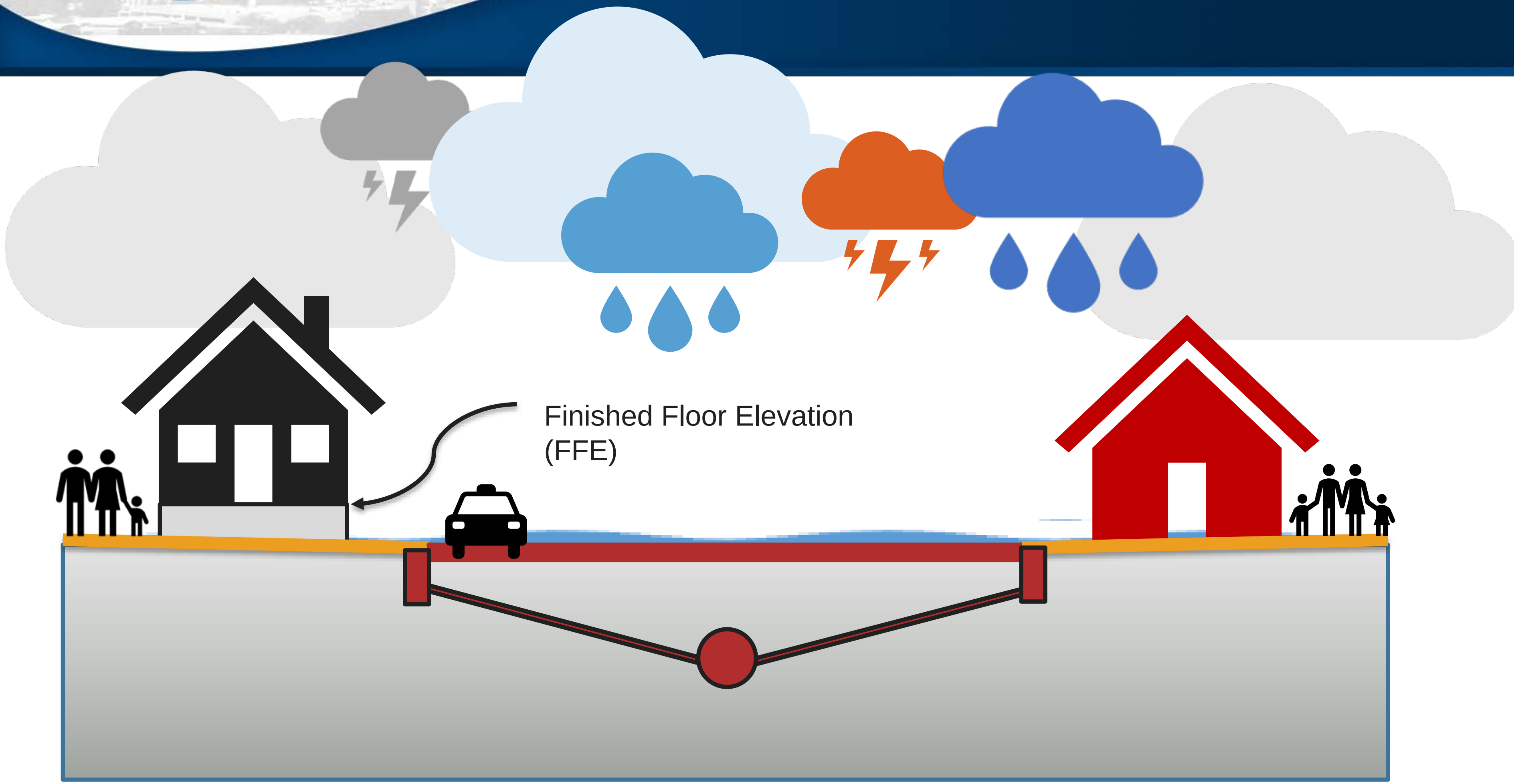


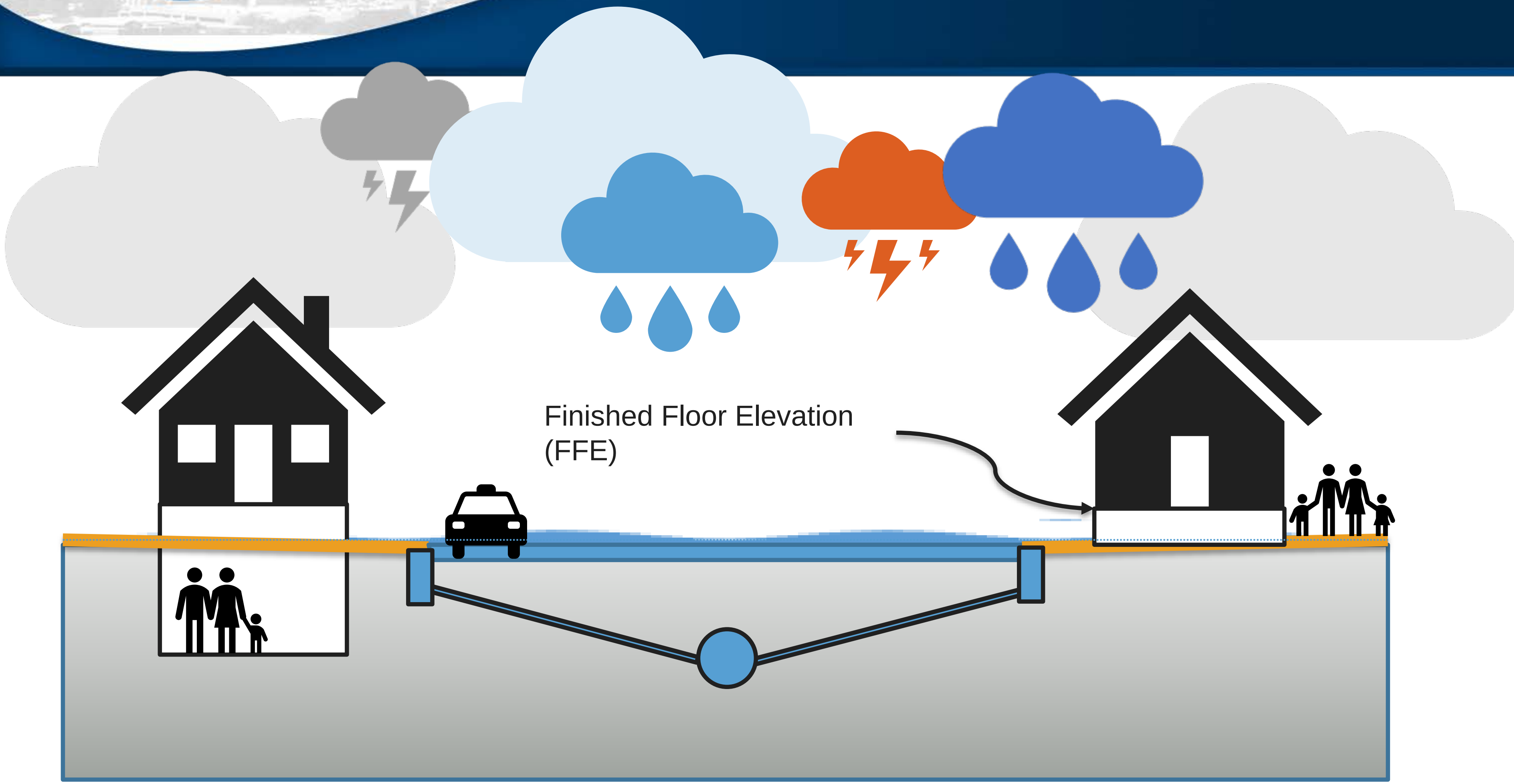


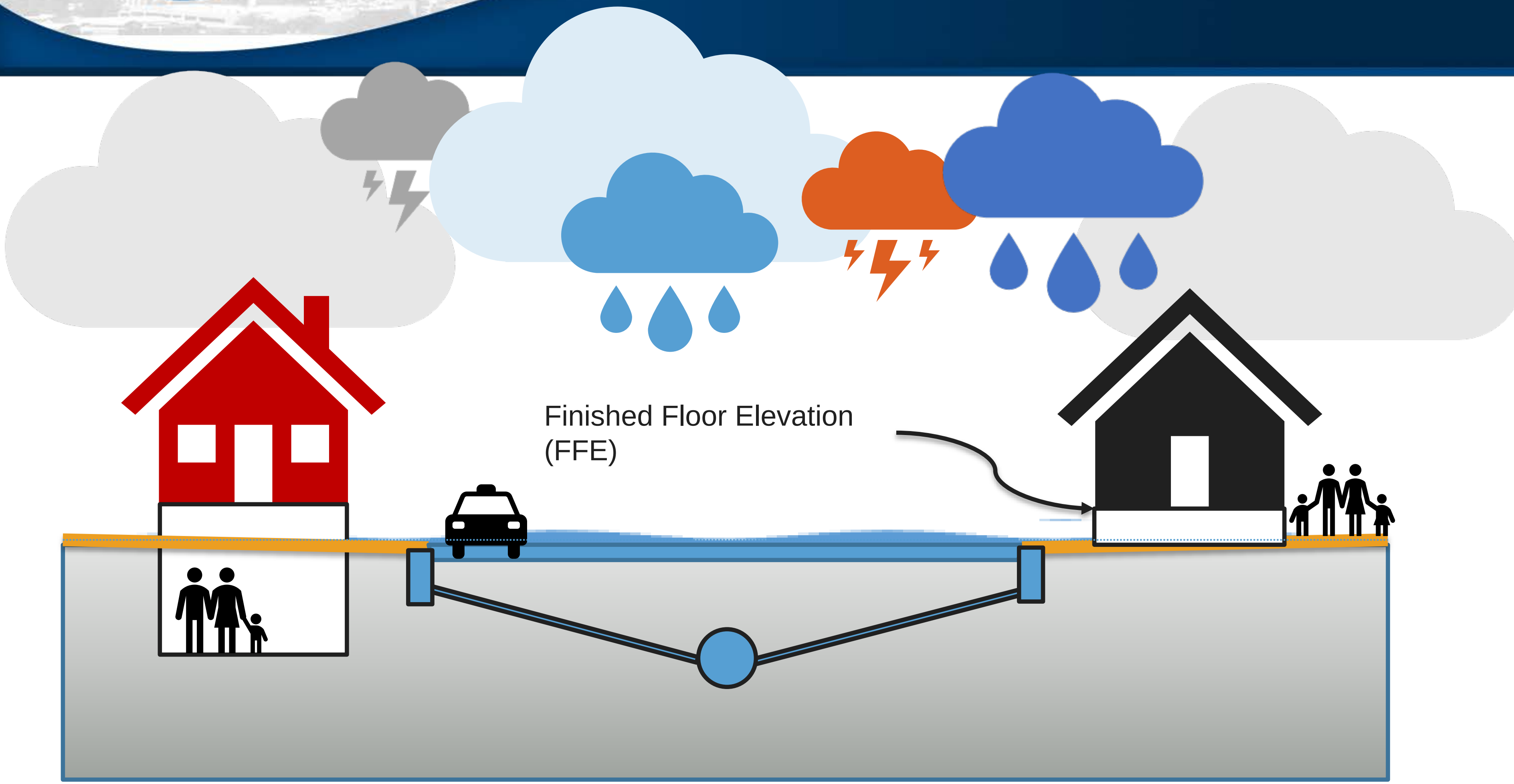


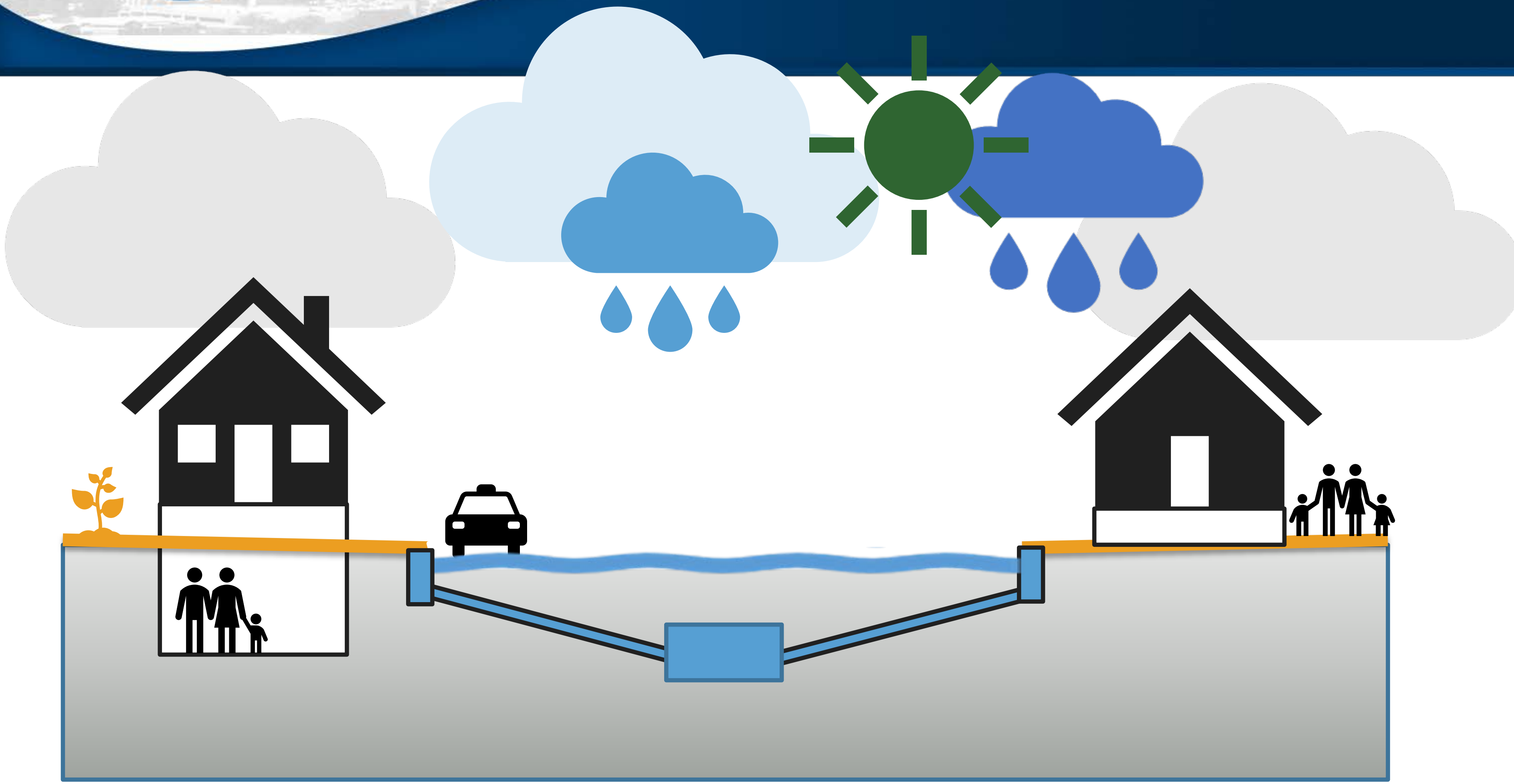



First Floor Elevation
(FFE)


Finished Floor Elevation
(FFE)


Finished Floor Elevation
(FFE)


Finished Floor Elevation (FFE)



City of Fort Collins

Structure Classification

BCA Toolkit Classification

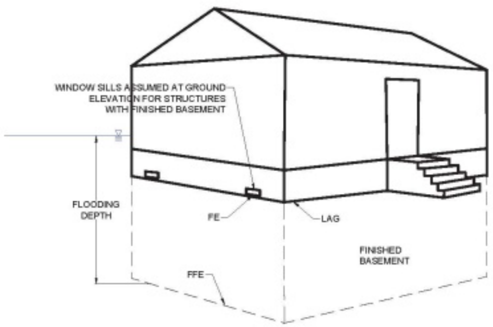
- 7 Residential
- 21 Non-Residential

Each has unique depth / damage curve

Building Number	FEMA BCA Classification	Building Number	FEMA BCA Classification
1	Mobile Home	15	Medical Offices
2	One Story, With Basement	16	Protective Services
3	Split Level, With Basement	17	Correctional Facility
4	Two or more levels, With Basement	18	Recreation
5	One Story, No Basement	19	Religious Facilities
6	Split Level, No Basement	20	Schools
7	Two or more levels, No Basement	21	Service Station
8	Retail - Furniture	22	Office, One-Story
9	Retail - Electronic	23	Convience Store
10	Retail-Clothing	24	Grocery
11	Hotel	25	Apartment
12	Fast Food	26	Industrial Light
13	Non-Fast Food	27	Warehouse, Non-Refrig
14	Hospital	28	Warehouse, Refrig

Structure Key Elevations

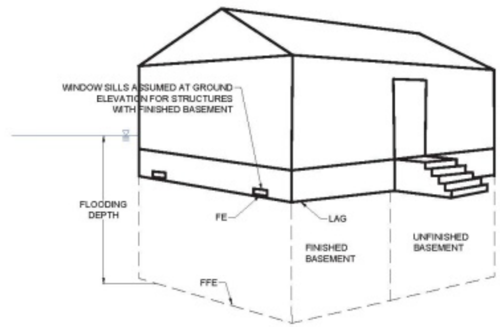
FINISHED BASEMENT



STRUCTURE CLASSIFIED AS FINISHED BASEMENT IF:
1. FINISHED BASEMENT SQ. FOOTAGE > 0
2. FINISHED BASEMENT SQ. FOOTAGE = TOTAL BASEMENT SQ. FOOTAGE

FEMA DAMAGE CURVE:
TWO OR MORE STORIES WITHOUT BASEMENT

PARTIAL FINISHED BASEMENT

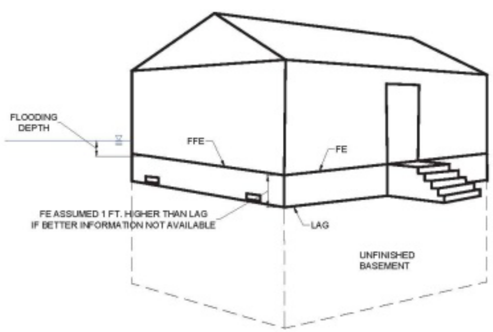


STRUCTURE CLASSIFIED AS PARTIALLY FINISHED BASEMENT IF:
1. FINISHED BASEMENT SQ. FOOTAGE > 0
2. FINISHED BASEMENT SQ. FOOTAGE NOT = TOTAL BASEMENT SQ. FOOTAGE

FEMA DAMAGE CURVE USED:
TWO OR MORE STORIES WITHOUT BASEMENT

UNFINISHED BASEMENT SQ. FT. NOT USED WHEN CALCULATING STRUCTURE UNIT COST

UNFINISHED BASEMENT

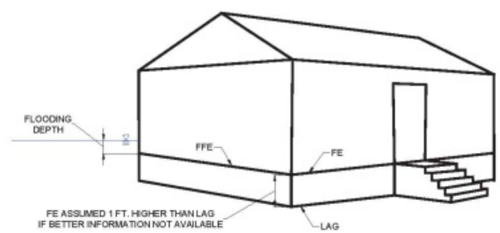


STRUCTURE CLASSIFIED AS UNFINISHED BASEMENT IF:
1. TOTAL BASEMENT SQ. FOOTAGE > 0
2. FINISHED BASEMENT SQ. FOOTAGE = 0

FEMA DAMAGE CURVE:
ONE OR TWO OR MORE STORIES WITH BASEMENT

FEMA BCA GUIDANCE DICTATES FE = FFE FOR UNFINISHED BASEMENTS AND DOES NOT EQUAL LOWEST OPENING

NO BASEMENT

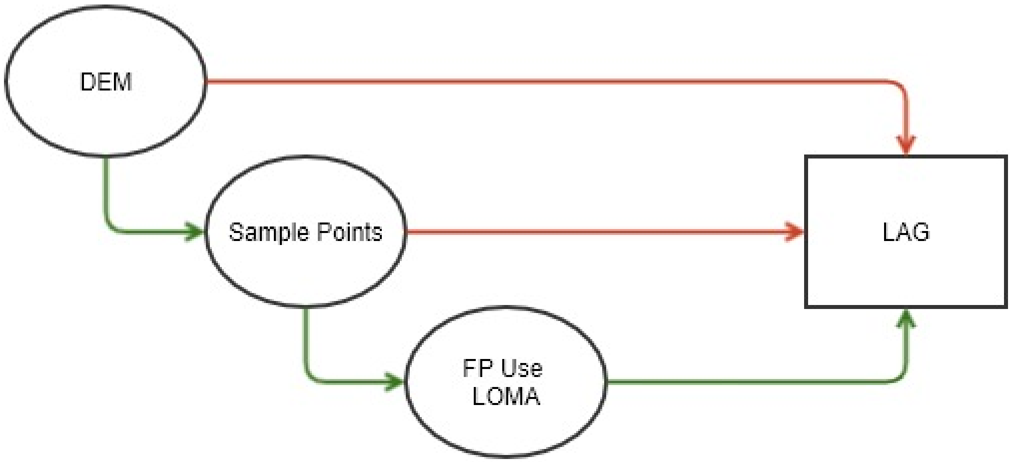


STRUCTURE CLASSIFIED AS NO BASEMENT IF
1. TOTAL BASEMENT SQ. FOOTAGE = 0

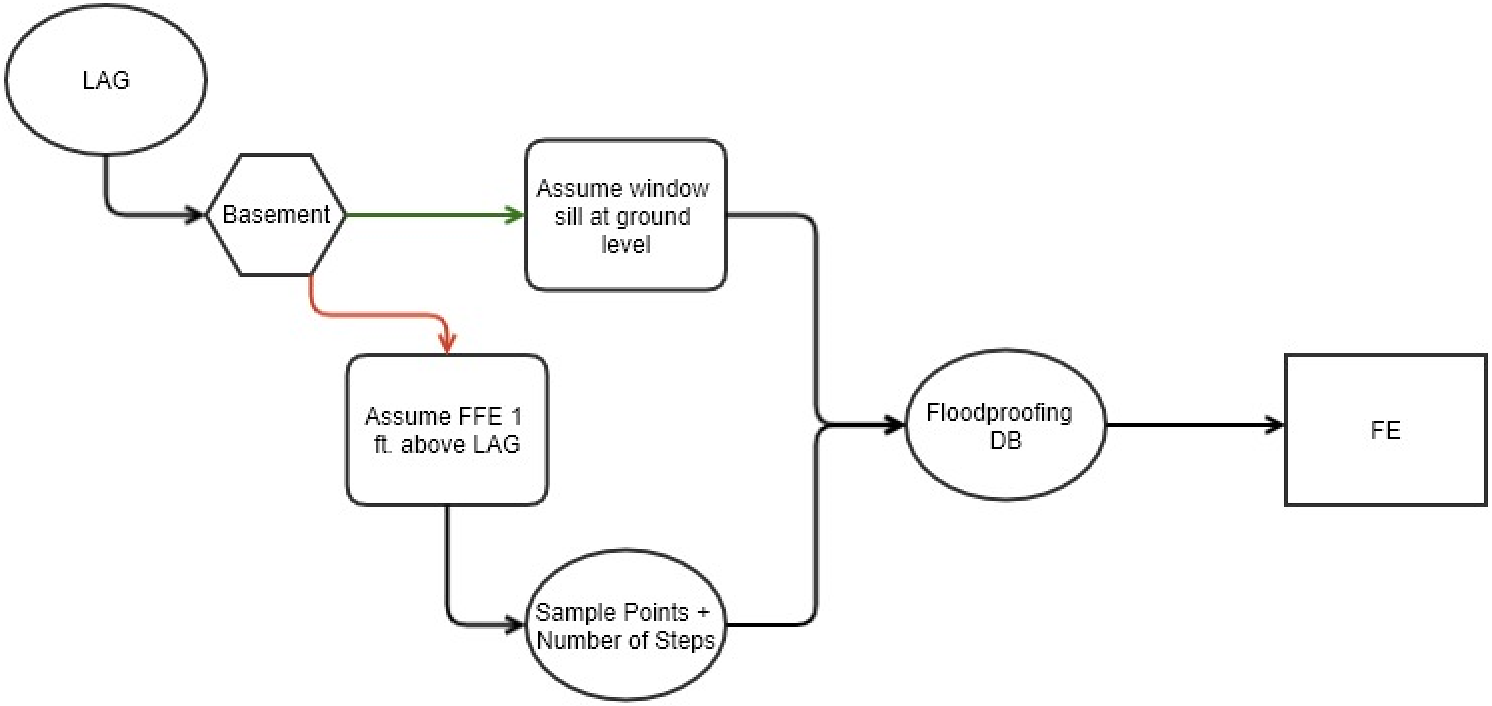
FEMA DAMAGE CURVE:
ONE OR TWO OR MORE STORIES WITHOUT BASEMENT

No.	DATE	REVISIONS	APPR	811 Know what's below. Call before you dig.	PREPARED FOR: City of Fort Collins	PREPARED BY: ICON ENGINEERING, INC.	OLD TOWN BASIN BENEFIT - COST ANALYSIS BASEMENT CLASSIFICATION FOR RESIDENTIAL STRUCTURES ICON PROJECT No. 18-045-OTB	DATE APR 2019 SHEET 1 OF 1

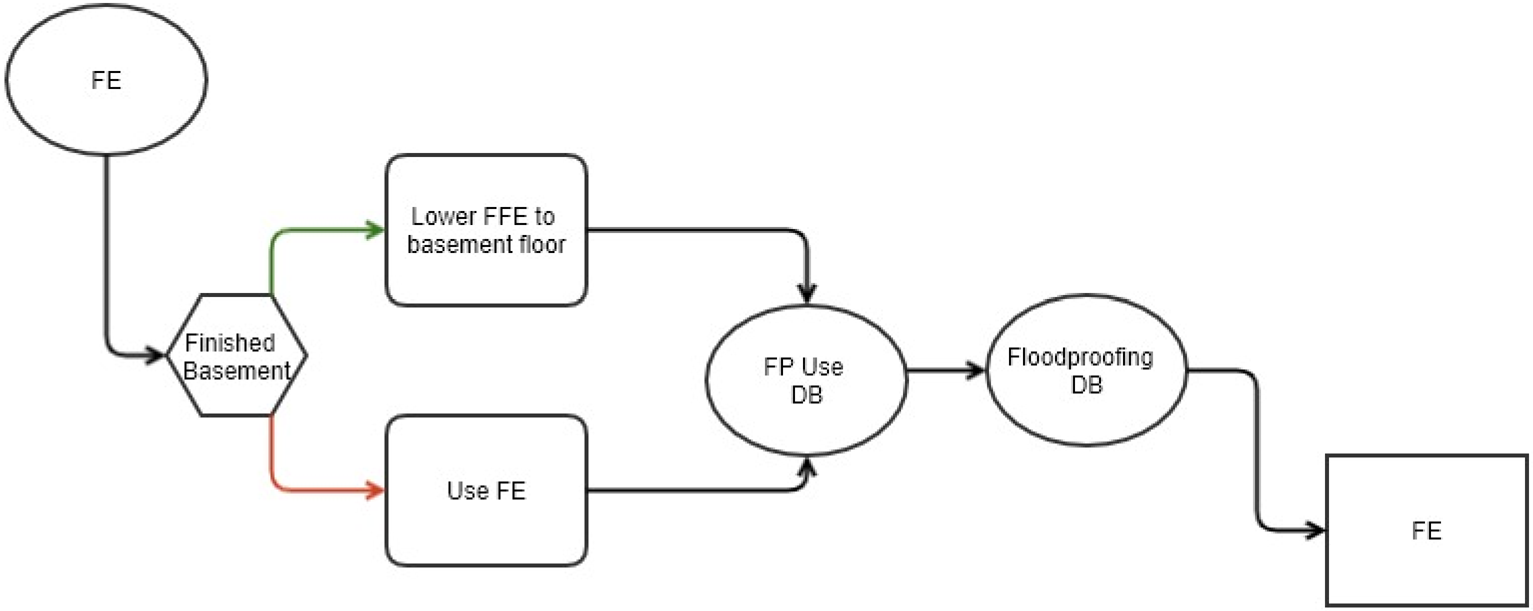
Structure Key Elevations
Lowest Adjacent Grade (LAG)



Structure Key Elevations
Flooding Elevation (FE)



Structure Key Elevations
First Floor Elevation

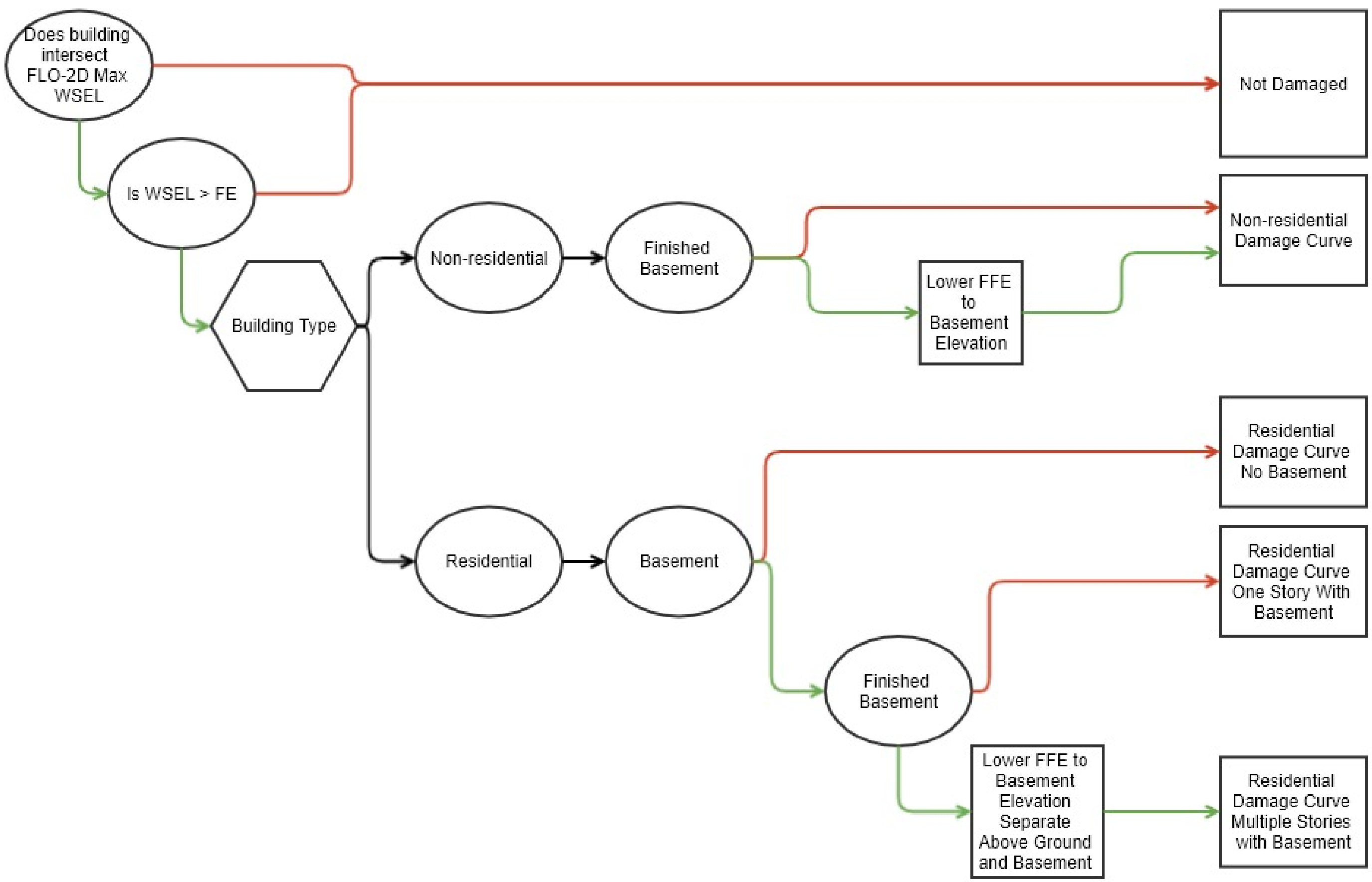


City of Fort Collins

Modifications to FEMA Approach

- FEMA approach led to structures with finished basements incurring > 50% of damage
- Basements and Above Ground separated by unit cost / finished square foot
- Compared to recent insurance claims
- Removed demolition threshold

Damage Workflow



Damage Assessment Approach

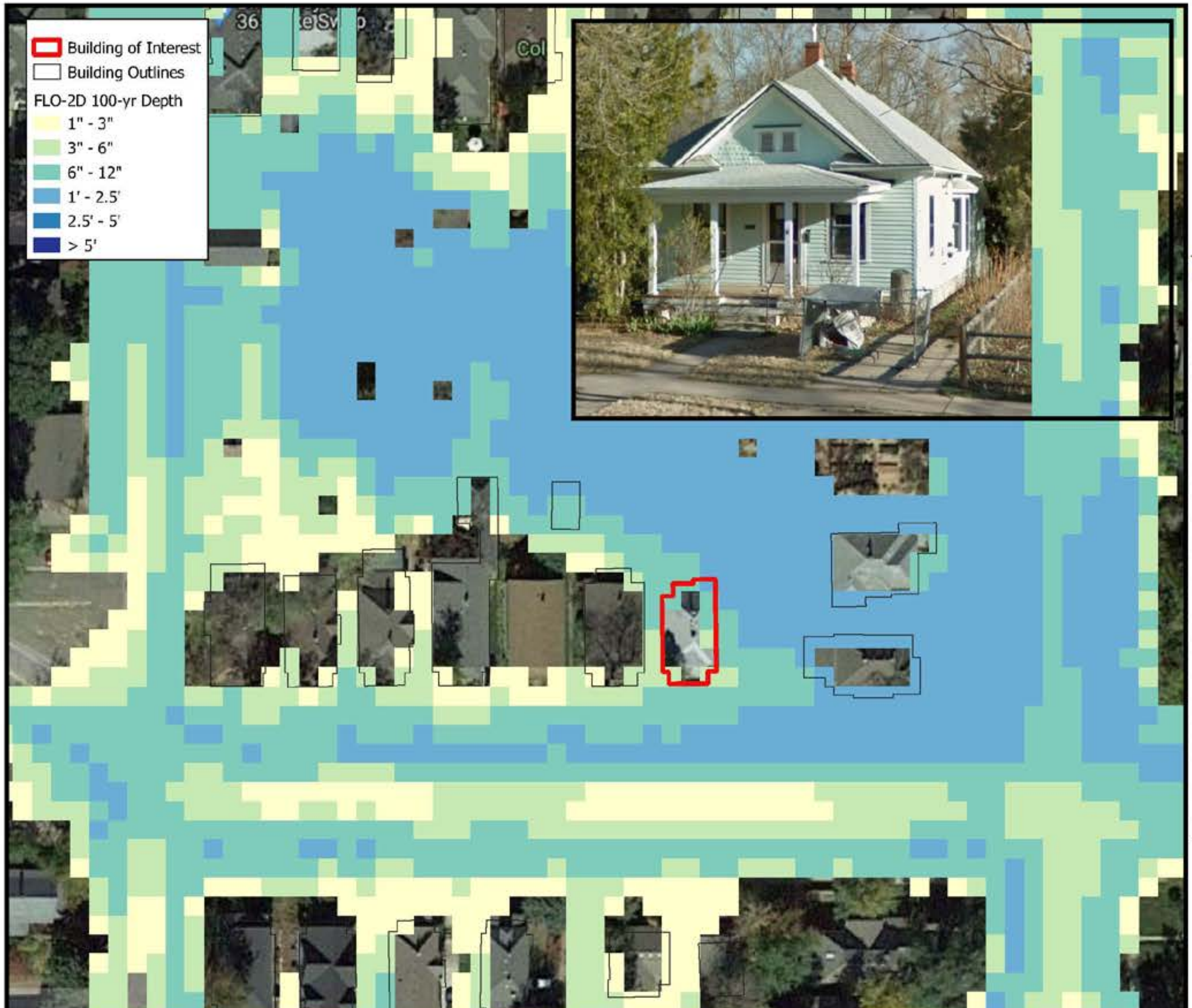
FEMA BCA Approach

- FEMA BCA Toolkit
- Building Replacement Value
- Damage applied to entire structure
- Demolition Threshold (50%)
- Incorporates other damages

Modified Approach

- Spreadsheet to mimic calculations
- Assessor's Improvement Value
- Damage applied to basement and above ground
- Demolition Threshold not considered
- Other damages not considered

Old Town BCA

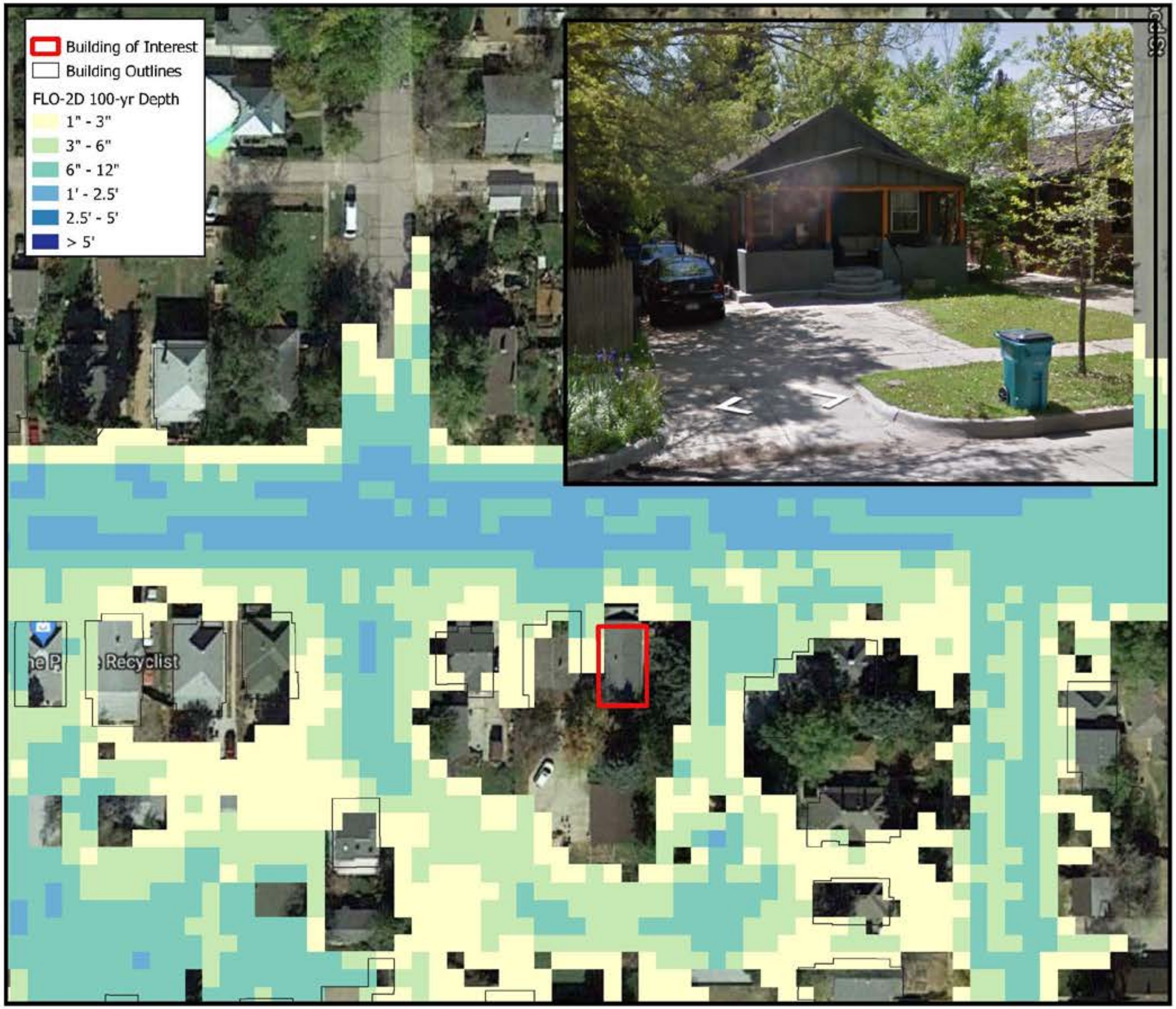


Building Property	Value
Parcel No:	
Address:	
LAG DEM:	5010.89
LAG FP Use:	5010
LAG LOMA:	--
LAG_Pts	--
LAG:	5010
Flooding Elevation:	5011
FFE - FP Use:	5011.2
FFE - Flood Proof:	--
First Floor Elevation:	5011.2
Building Sq. Ft.:	936
Total Basement Sq. Ft.:	648
Finished Basement Sq. Ft.:	--
WSEL - 2yr:	--
WSEL - 10 yr:	5011.29
WSEL - 100yr:	5012.01
Structure Value	$332,448
Ground Level Value	$332,448
Basement Value	0
Flooding Depth (Ground Level):	0.8 ft.
Flooding Depth (Basement):	--
Ground Level Damage (2-yr):	$0
Ground Level Damages (10-yr):	$91,041
Ground Level Damages (100-yr):	$106,606
Basment Damages (2-yr):	$0
Basement Damages (10-yr):	$0
Basement Damages (100-yr):	$0

N

0 50 100 ft

ICON ENGINEERING, INC.



Old Town BCA

Building Property	Value
Parcel No:	
Address:	
LAG DEM:	5018.84
LAG FP Use:	--
LAG LOMA:	--
LAG_Pts	--
LAG:	5018.84
Flooding Elevation:	5018.84
FFE - FP Use:	--
FFE - Flood Proof:	--
First Floor Elevation:	5010.84
Building Sq. Ft.:	1008
Total Basement Sq. Ft.:	1008
Finished Basement Sq. Ft.:	1008
WSEL - 2yr:	--
WSEL - 10 yr:	--
WSEL - 100yr:	5019.14
Structure Value	$330,532
Ground Level Value	$165,266
Basement Value	$165,266
Flooding Depth (Ground Level):	0.3 ft.
Flooding Depth (Basement):	8.3 ft.
Ground Level Damage (2-yr):	$0
Ground Level Damages (10-yr):	$0
Ground Level Damages (100-yr):	$18,295
Basment Damages (2-yr):	$0
Basement Damages (10-yr):	$0
Basement Damages (100-yr):	$82,435

N

0 50 100 ft

ICON ENGINEERING, INC

Existing Conditions Results

Expected Annual Benefit

- Estimates total damages to generally be expected over a certain period of years

Project Benefits

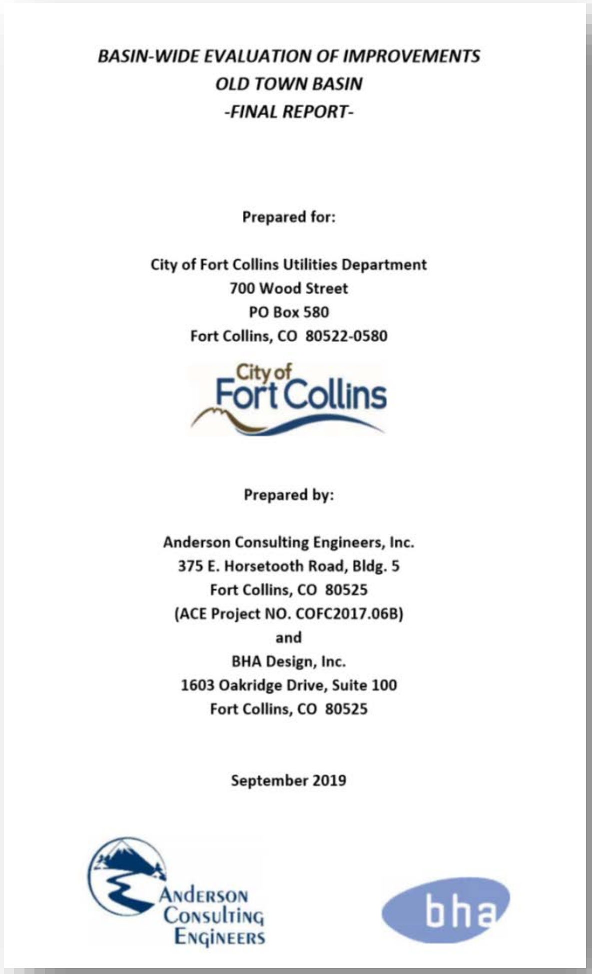
- Represents the future benefits of the mitigation project to current day costs

$$EAD = (50\% - 10\%) * \frac{TD_{2yr} + TD_{10yr}}{2} + (10\% - 1\%) * \frac{TD_{10yr} + TD_{50yr}}{2} + 1\% * TD_{100-yr}$$

$$Project\ Benefits: EAD * \frac{1 - (1 + Discount\ rate)^{-Project\ Useful\ Life(yrs)}}{Discount\ Rate}$$

Selected Plan of Improvements

- Completed by Anderson Consulting Engineers
- Proposed improvements to remove 100-yr flooding
- Combination storm drain / surface flow system



BASIN-WIDE EVALUATION OF IMPROVEMENTS
OLD TOWN BASIN
-FINAL REPORT-

Prepared for:

City of Fort Collins Utilities Department
700 Wood Street
PO Box 580
Fort Collins, CO 80522-0580

City of Fort Collins

Prepared by:

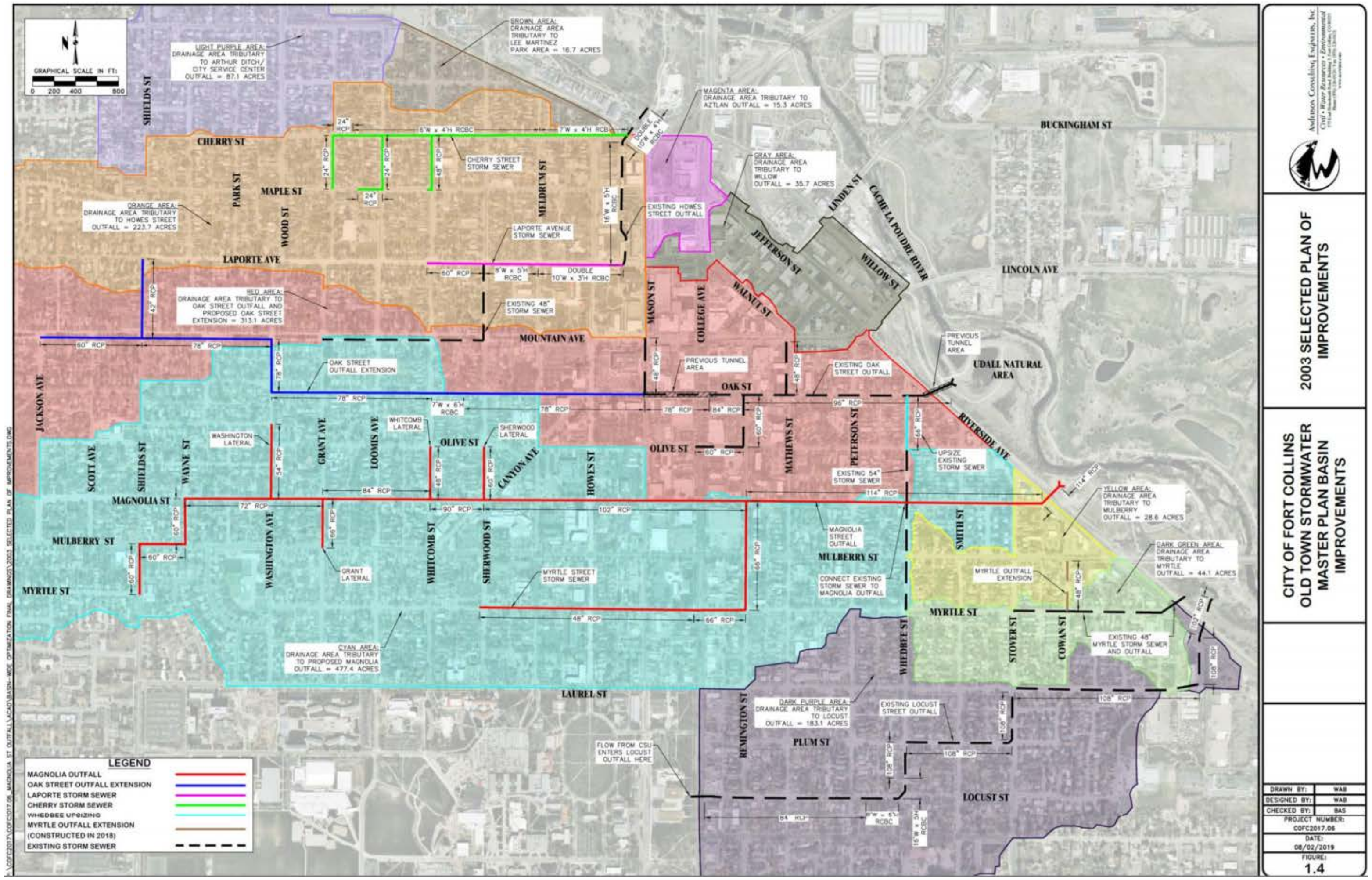
Anderson Consulting Engineers, Inc.
375 E. Horsetooth Road, Bldg. 5
Fort Collins, CO 80525
(ACE Project NO. COFC2017.06B)
and
BHA Design, Inc.
1603 Oakridge Drive, Suite 100
Fort Collins, CO 80525

September 2019

Anderson Consulting Engineers

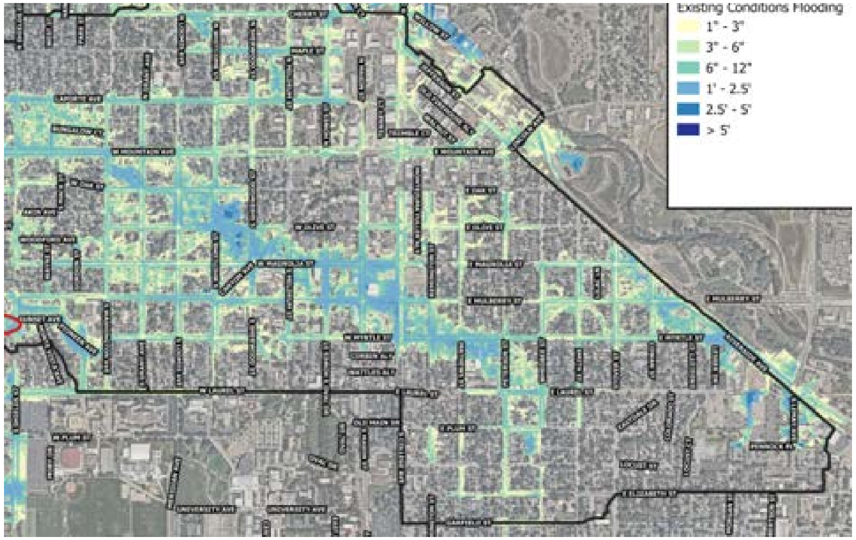
bha

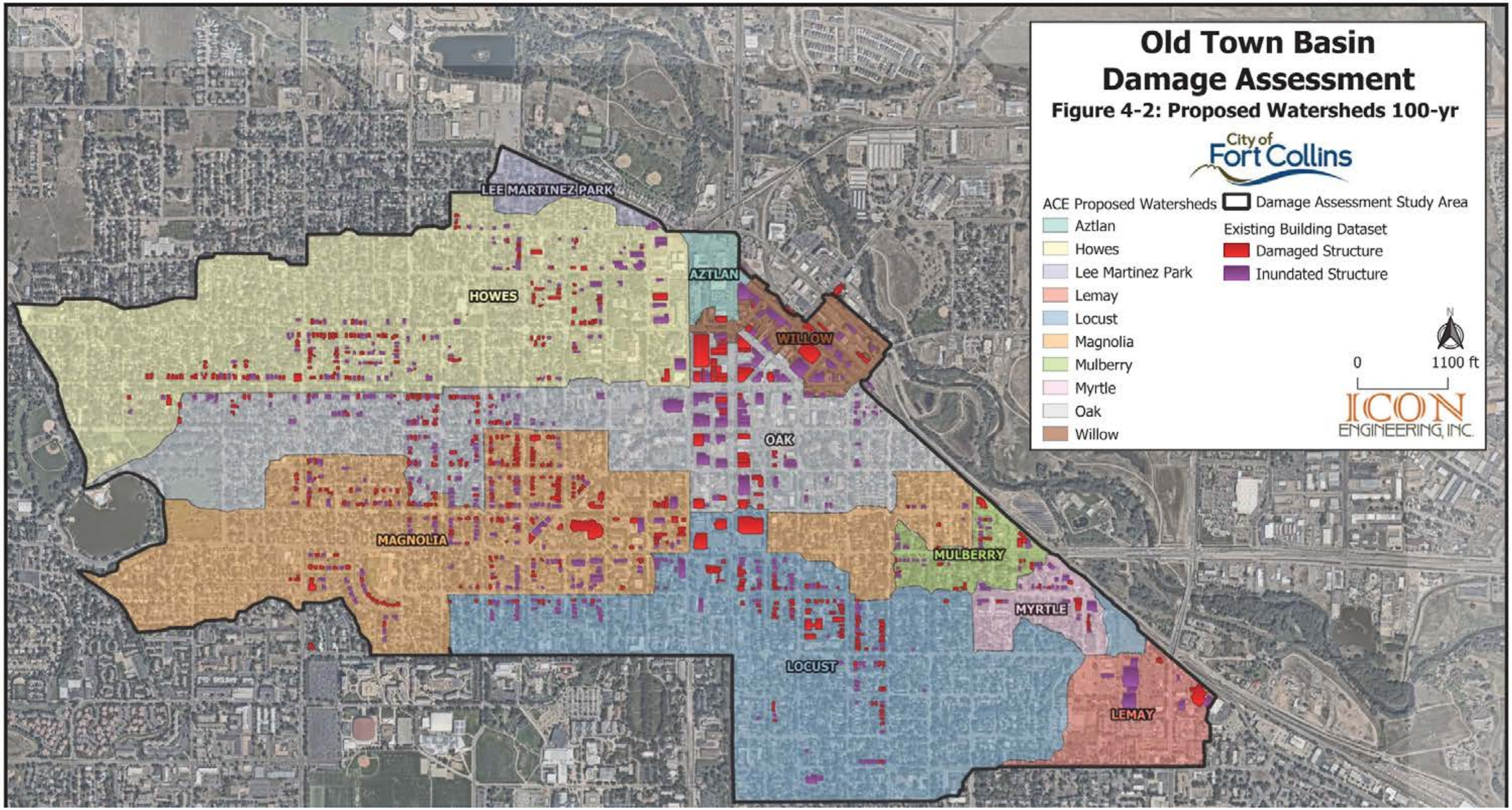
Selected Plan of Improvements



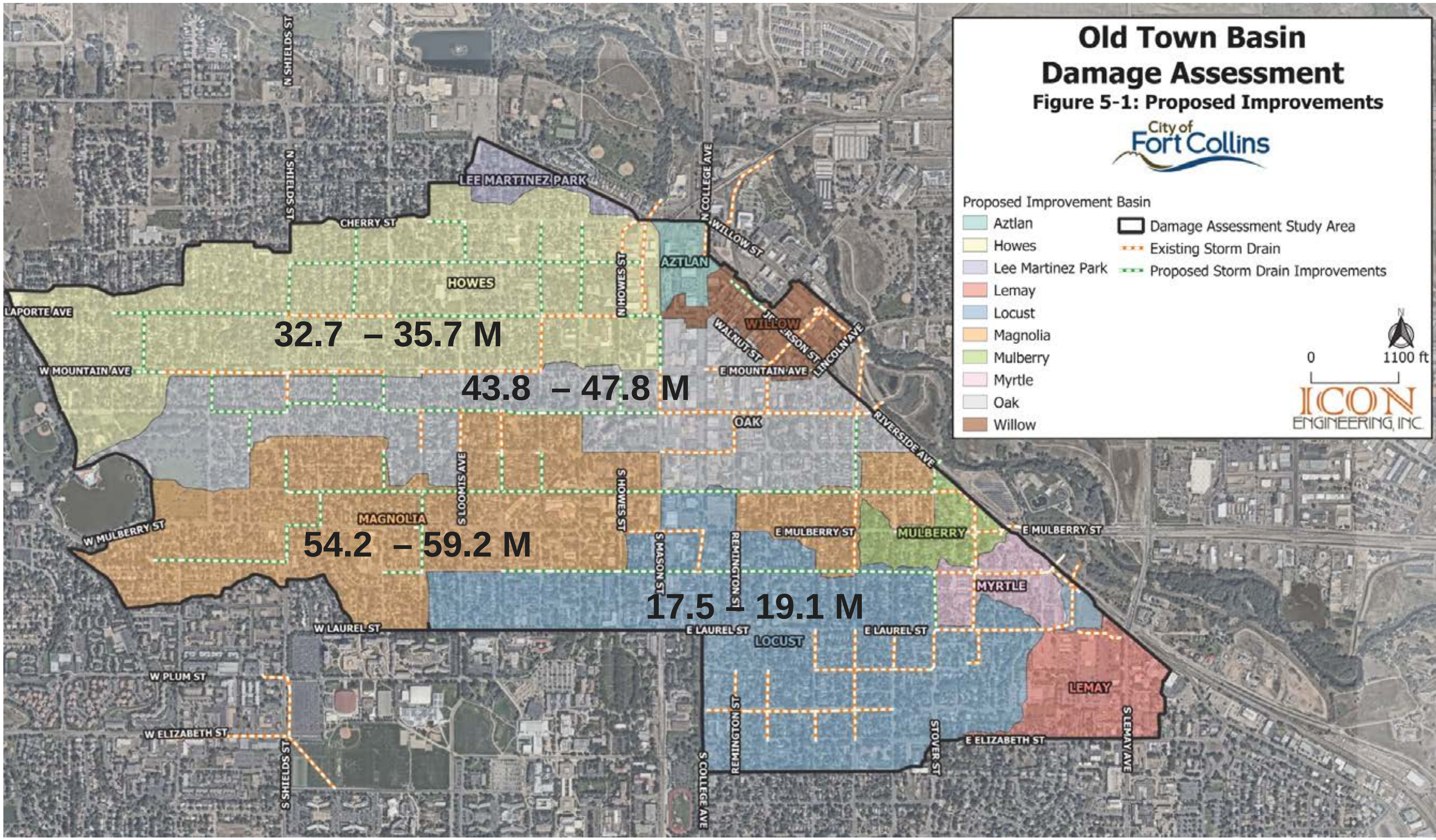
Prioritizing Capital Improvements

- Each structure spatially classified
- Allowed comparison by watershed
- Complicated by trans-basin flows
- Not the only criteria when deciding phasing implementation





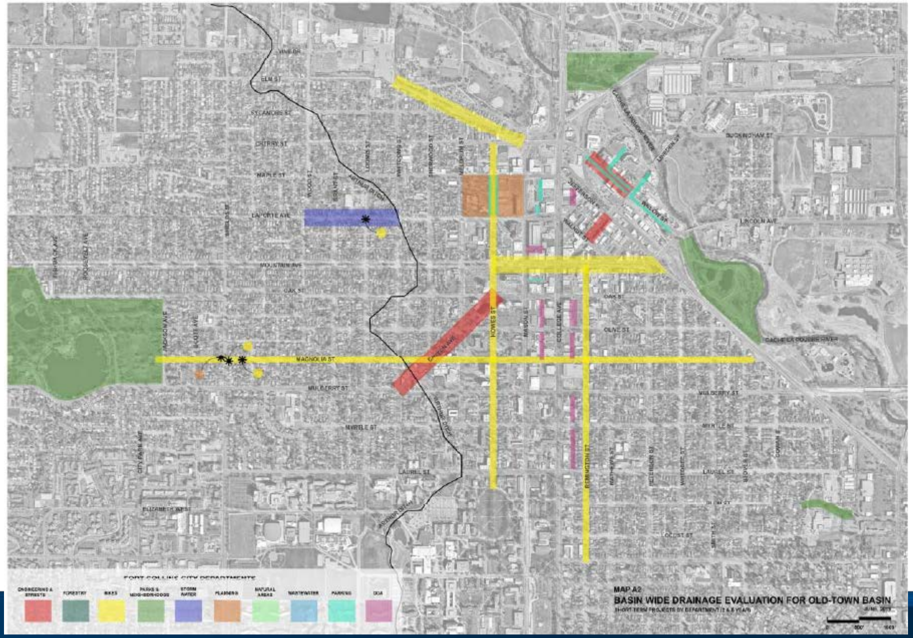
Old Town Basin
Damage Assessment
Figure 4-2: Proposed Watersheds 100-yr
City of Fort Collins
ACE Proposed Watersheds
Damage Assessment Study Area
Aztlan
Howes
Lee Martinez Park
Lemay
Locust
Magnolia
Mulberry
Myrtle
Oak
Willow
Existing Building Dataset
Damaged Structure
Inundated Structure
N
0
1100 ft
ICON ENGINEERING, INC.
LEE MARTINEZ PARK
HOWES
AZTLAN
WILLOW
OAK
MAGNOLIA
MULBERRY
MYRTLE
LOCUST
LEMAY


Old Town Basin
Damage Assessment
Figure 5-1: Proposed Improvements
City of Fort Collins
Proposed Improvement Basin
Aztlan
Howes
Lee Martinez Park
Lemay
Locust
Magnolia
Mulberry
Myrtle
Oak
Willow
Damage Assessment Study Area
Existing Storm Drain
Proposed Storm Drain Improvements
0
1100 ft
ICON ENGINEERING, INC.
32.7 – 35.7 M
43.8 – 47.8 M
54.2 – 59.2 M
17.5 – 19.1 M
LEE MARTINEZ PARK
HOWES
AZTLAN
WILLOW
OAK
MAGNOLIA
MULBERRY
MYRTLE
LOCUST
LEMAY
N SHIELDS ST
CHERRY ST
LAPORTE AVE
W MOUNTAIN AVE
N HOWES ST
N COLLEGE AVE
WILLOW ST
WALNUT ST
LINCOLN AVE
E MOUNTAIN AVE
RIVERSIDE AVE
S LOOMIS AVE
S HOWES ST
W MULBERRY ST
E MULBERRY ST
S MASON ST
REMINGTON ST
W LAUREL ST
E LAUREL ST
W PLUM ST
W ELIZABETH ST
E ELIZABETH ST
S SHIELDS ST
S COLLEGE AVE
STOVER ST
S LEMAY AVE

Old Town Basin – Next Steps

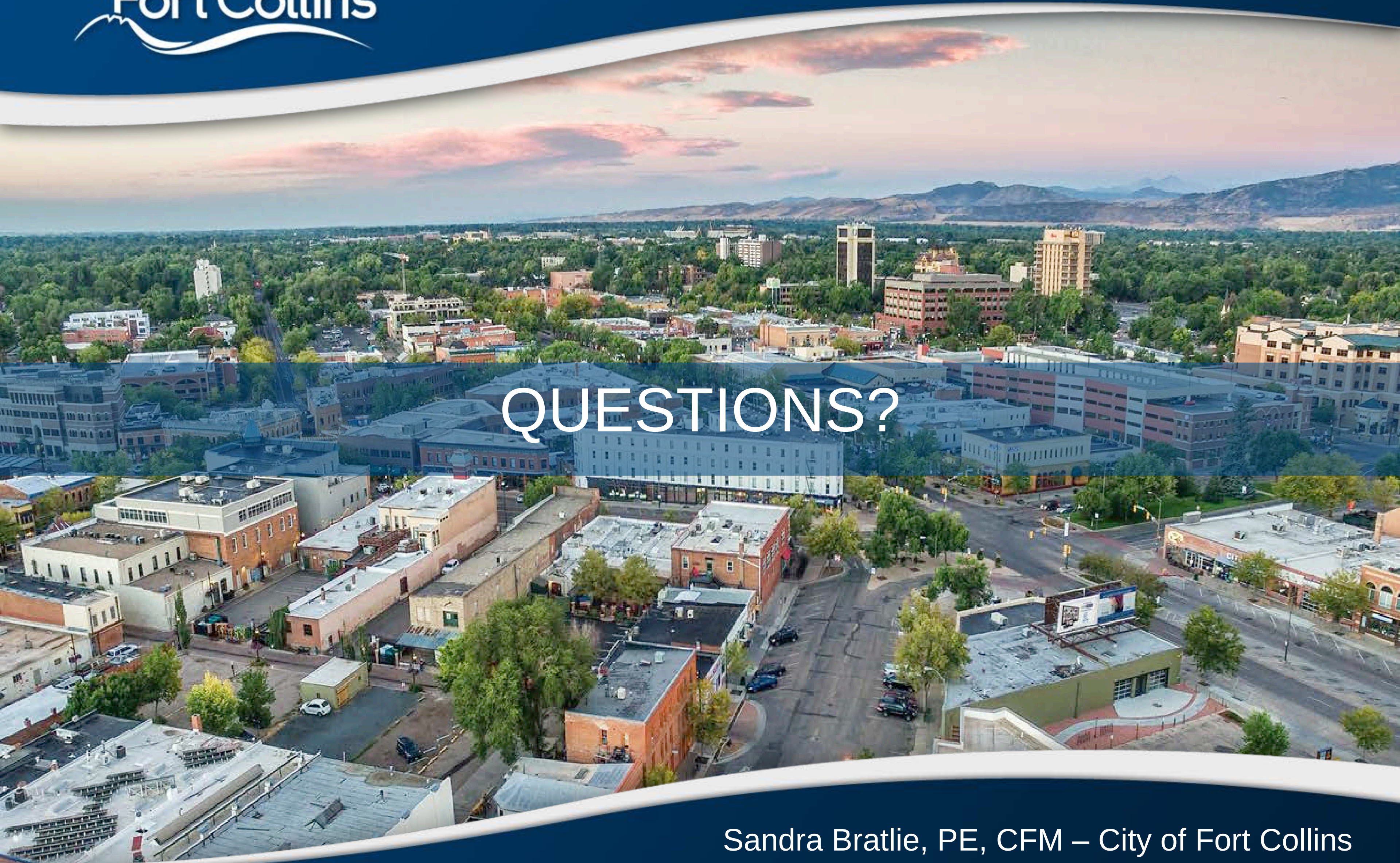
Selected Plan Project Prioritization & Phasing

- Utilize / Optimize existing infrastructure and outfall
- Constructability
- Temporary Risk Impacts / Reliance on adjacent outfalls
- Public Impact / Construction Duration
- Permitting Requirements
- Flood Risk Reduction
- Collaboration Opportunities
  - FC Moves Bike Program
  - Water/Wastewater Master Plan
  - Engineering & Streets Projects
  - Parks
  - Natural Areas
  - Forestry
  - Planning



Damage Assessment - Next Steps

- Apply City-wide
    - Automate the process (GIS Model Builder?)
- Mature our GIS data
    - Ownership of datasets
        - Building Outline
    - Automate our manual tasks
        - Parcel Datasets
    - Use of GPS tools / Collector
- Incorporates other damages
    - Loss of Function
    - Displacement
    - Social Benefits



QUESTIONS?

Sandra Bratlie, PE, CFM – City of Fort Collins

Jeremy Deischer, PE – ICON Engineering

City of Fort Collins

ICON ENGINEERING, INC.

City of Fort Collins

Residual Damages

- Modelled as FLO-2D outflow nodes
- Residual FLO-2D used to help identify areas still inundated