Geomorphic-Based Profile Control Techniques
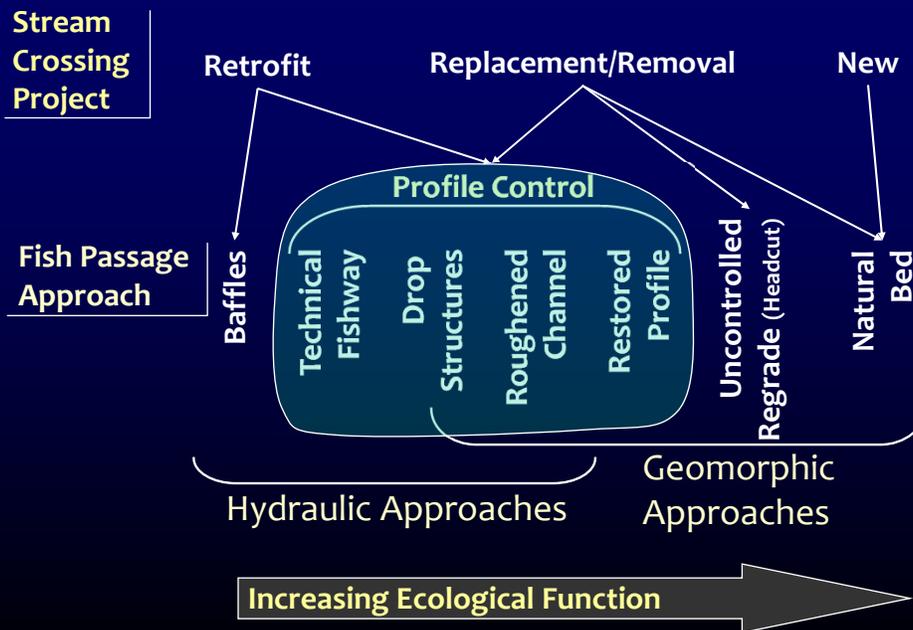

Michael Love, P.E.

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1

Design Approaches for Aquatic Organism Passage

Stream Crossing Project

Retrofit **Replacement/Removal** **New**

Fish Passage Approach

Profile Control

Baffles | Technical Fishway | Drop Structures | Roughened Channel | Restored Profile | Uncontrolled Regrade (Headcut) | Natural Bed

Hydraulic Approaches   Geomorphic Approaches

Increasing Ecological Function

2

Profile Control Options

	Slope	Pros / Cons
Restored Profile	Limited by channel type	+ Passage diversity, Habitat - Scale/cost
Roughened Channel	Durability, bedload limit	+ Passage diversity - Species, failure risk
Boulder Weirs	$\leq$5%	+ Passage diversity, Habitat - Failure risk
Rigid Weirs (log, concrete)	$\leq$5%	+ Rigid, durable - Species, habitat
Technical Fishway	10% or "vertical"	+ Small footprint - Species specific, flow, sediment, debris

3   3

3

Design Profiles for Incised Channels: Replacement

new culvert

Design Profile: Forced Profile
(rock weirs, roughened channel…)

new culvert

HEADCUT

Design Profile: Stream Simulation with
Uncontrolled Regarde (headcutting)

new culvert

Design Profile: Combined
Forced Profile & Stream Simulation

4

4
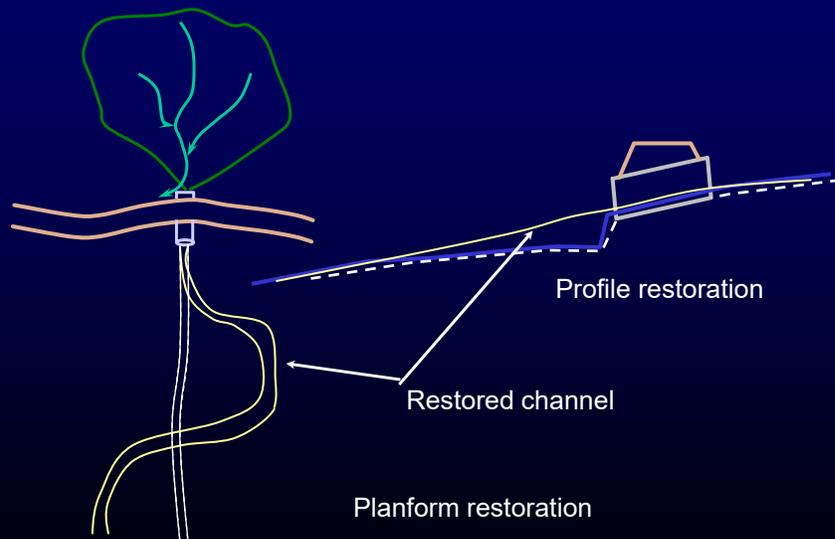
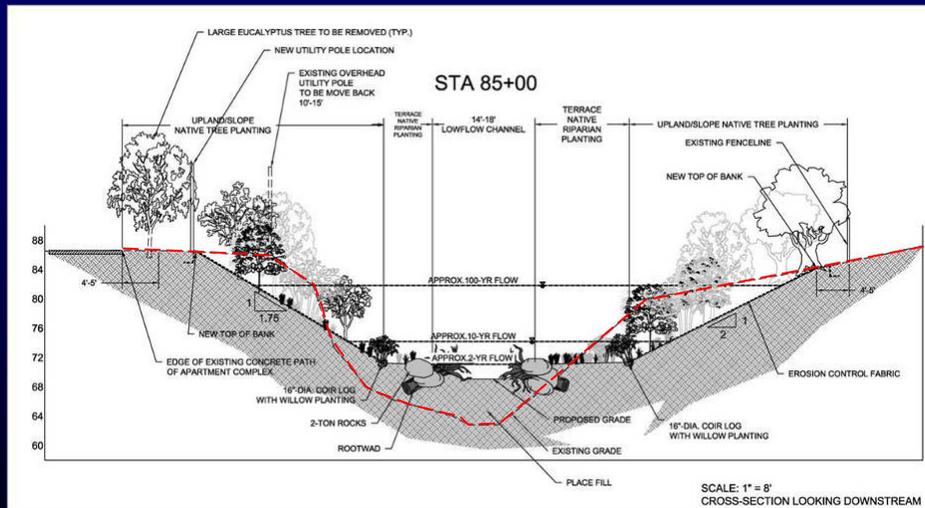Design Profiles for Incised Channels
- Retrofit or Replacement -

culvert

Design Profile:
Downstream Forced Profile

culvert

Design Profile:
Restored Channel Profile

5
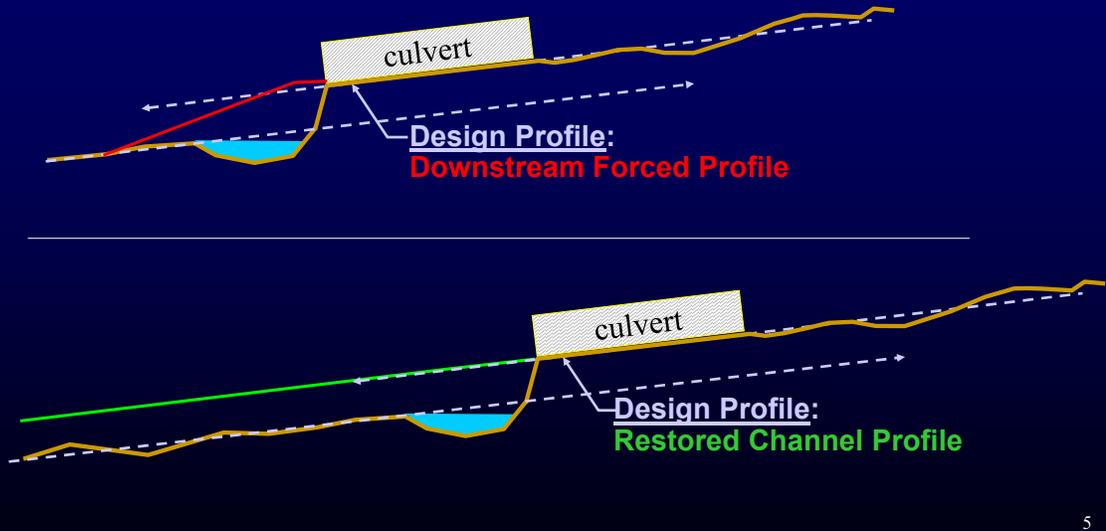
5

Channel Restoration for Passage of Aquatic Organisms

Profile restoration

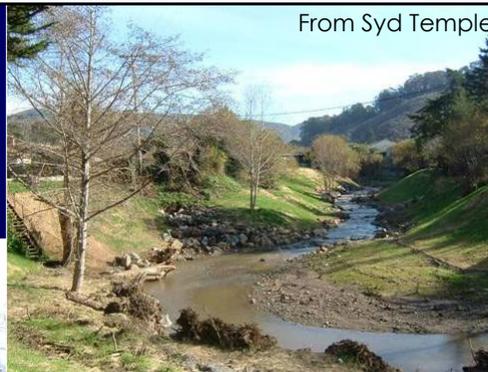Restored channel

Planform restoration

6

6

Profile Restoration

STA 85+00

From Christine Chann,
San Pedro Creek
Watershed Coalition

7

Profile Restoration

From Syd Temple

- Sloped-back banks to reduced entrenchment
- Raised channel bed as much as 8 feet using native and imported fill
- Increase bankfull width by 20% and built floodplains
- Installed profile control to force riffles and pool

From Christine Chann

8

Profile Restoration
Outlet Creek

Upstream of Culvert
No Incision Experienced

Downstream of Project
Channel Remains Incised

Photos from Kozmo Bates

9

Profile Restoration
Outlet Creek

Channel restoration
for fish passage correction
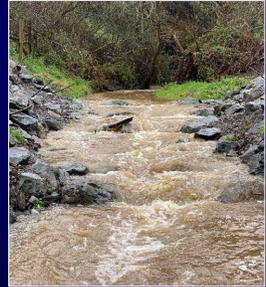
Constructed 2000
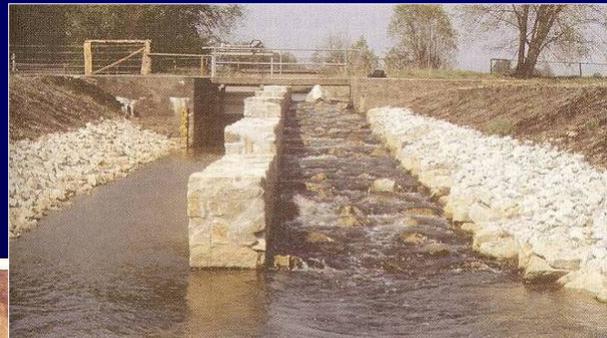Photos from 2005
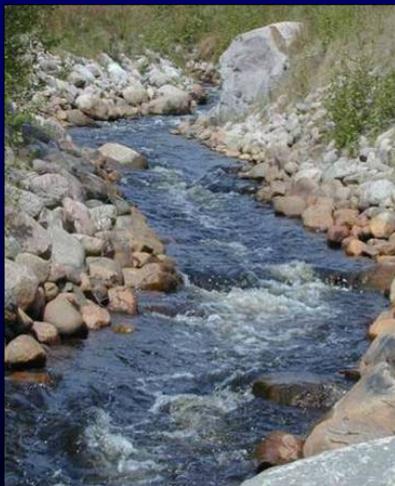
Photos from Kozmo Bates

10

Geomorphically-Based Roughened Channels

➢ Channel constructed **steeper** than the adjacent channel (profile control)

➢ Based on morphology of steeper stream channel

➢ Stable *engineered streambed material (ESM)* forms channel bed & banks

➢ Quazi-hydraulic design for target species/lifestages (velocity, depth, drop, EDF)
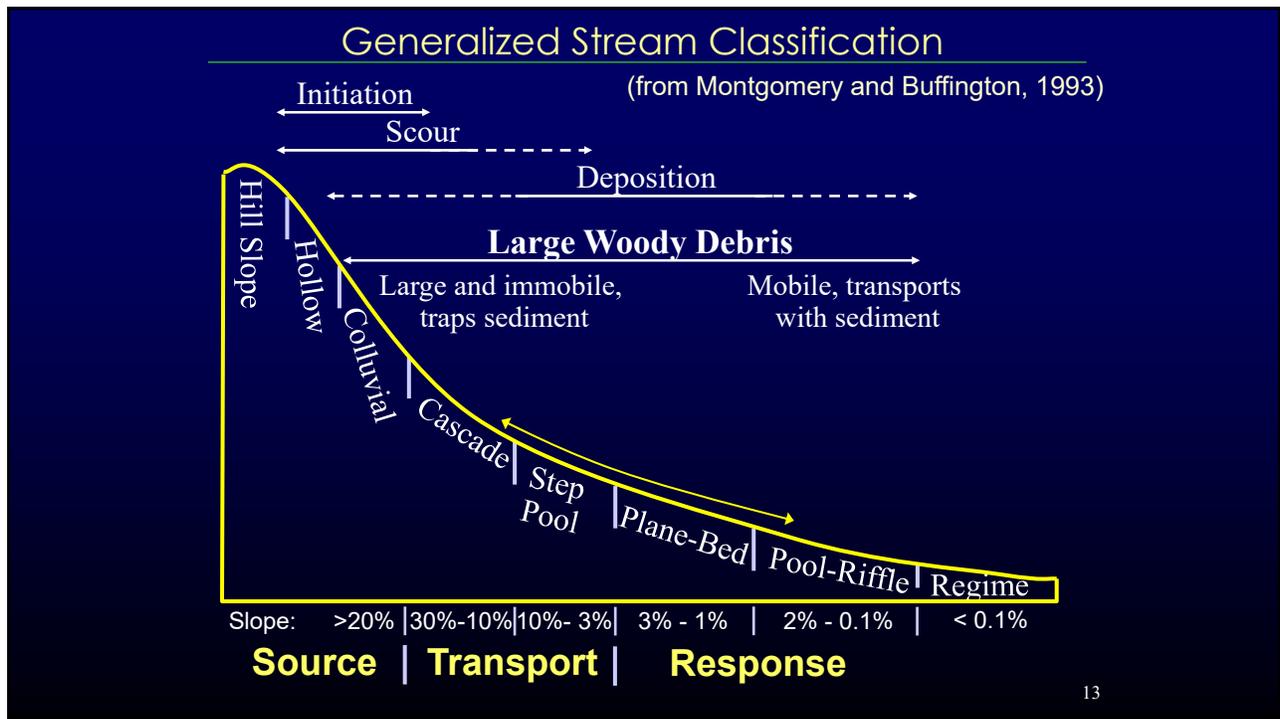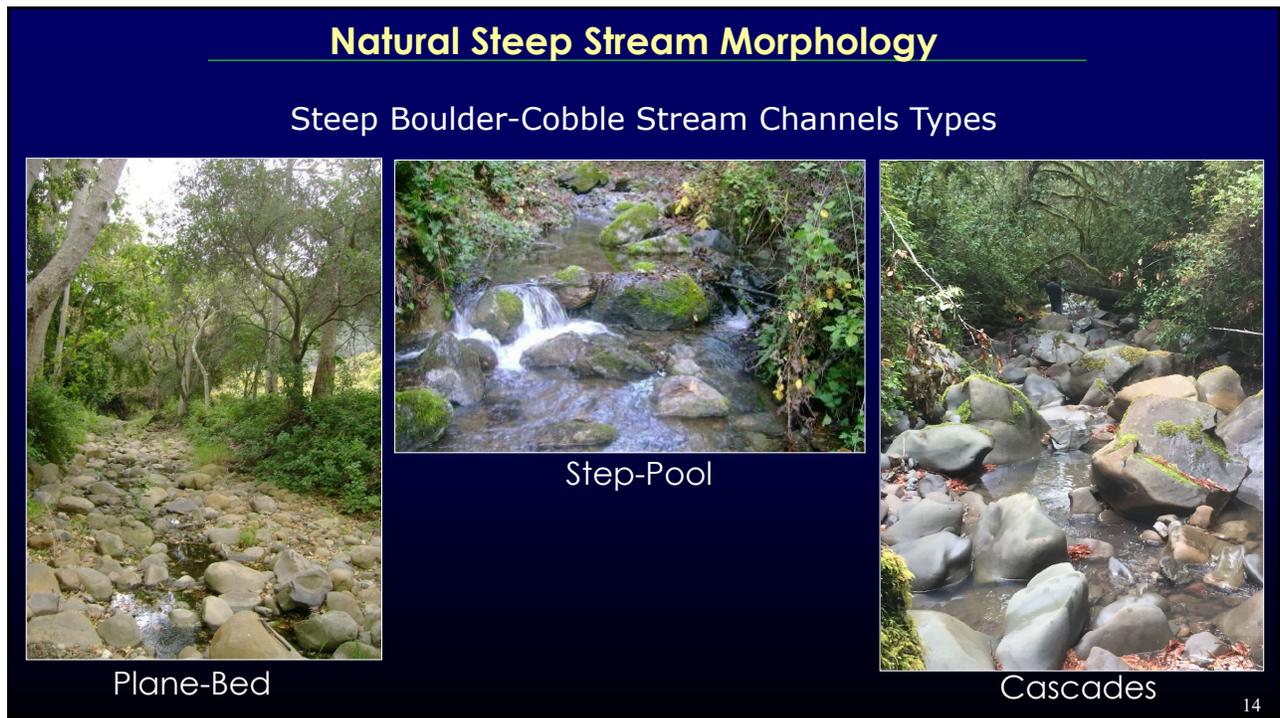

11

Examples of a Roughened Channel in Europe

12

12

Generalized Stream Classification

(from Montgomery and Buffington, 1993)

Initiation
Scour
Deposition

Large Woody Debris

Large and immobile, traps sediment

Mobile, transports with sediment

Hill Slope · Hollow · Colluvial · Cascade · Step Pool · Plane-Bed · Pool-Riffle · Regime

Slope:	>20%	30%-10%	10%- 3%	3% - 1%	2% - 0.1%	< 0.1%

Source | Transport | Response

13

13

Natural Steep Stream Morphology

Steep Boulder-Cobble Stream Channels Types

Step-Pool

Plane-Bed

Cascades

14

14

Natural Step Pool Stream Morphology

Step-Pool Stream Channels

15

15

Geomorphically-Based Roughened Channels

Common Channel Types

Increasing Slope

❖ Roughened Riffles (short ramps)

❖ Plane Bed Channel (longer rock ramps)

❖ Rapids or Chutes & Pools

❖ Step-Pools

❖ Cascades & Pool

Caution:

➢ Only use channel types & slopes that the target species/lifestage are known to ascend

➢ Risk increases further the roughened channel characteristics deviates from the natural channel (i.e. slope, bed material, entrenchment)

16

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Plane-Bed (Rock Ramp) Roughened Channels

Slope & Length Thresholds:

➢ Slope Range: $\leq$ 4%

➢ Max Head Diff.: 5 feet

➢ Use chutes and Pools for Larger Head Differentials

Bed Morphology:

➢ Random placement of rock

➢ D100 < Channel Depth

Grub Creek "Rock Ramp"   17

17

Plane-Bed (Rock Ramp) Roughened Channels

Pool

Pool

• 2006

Rock Ramp into Off-Channel Pond for Juvenile Coho Access

• **5%** Slope for 60 ft

• 3 ft of fall

• Primarily Spring Fed

•2005

• 2006   18

18

Pinole Creek Rock Ramp at I-80 Culvert Outlet

Photos: Jon Mann

- 3.5 feet of drop over 60 feet
- 4% slope
- Target Species:
  - Adult Anadromous Steelhead
  - Adult Rainbow Trout
  - Juvenile Trout

Hydraulic Diversity

High Passage flow for
Juvenile Trout (~20 cfs)

19

Pinole Creek Rock Ramp at I-80 Culvert Outlet

High Passage flow for adult Salmon and Steelhead Trout

20

20

Chutes & Pools Roughened Channels

Slope & Length Thresholds (for armored pools):

➢ Slope Range: ≤ 7% across a chute
                 ≤ 4% overall

➢ Max Head Diff.: 2 feet per chute

➢ Pools between Chutes to Dissipate Energy/Provide Fish Holding Habitat

  Bed Morphology:

  ➢ Chutes (Rapids) with both Specified and Random Rock Placement

  ➢ D100 < Channel Depth

  ➢ Pools Armored with Coarse Bed Material

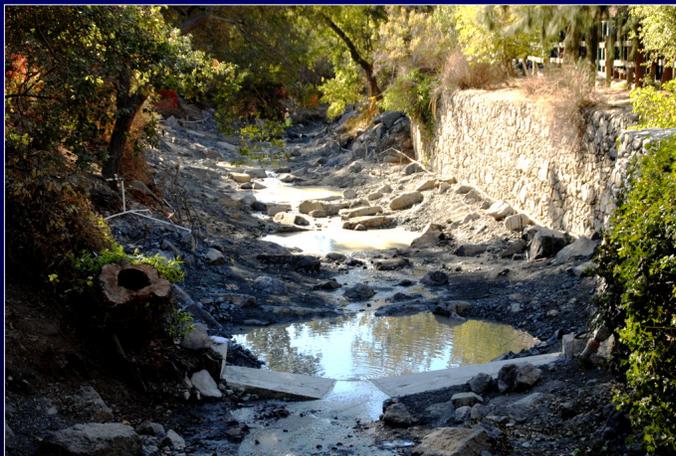Plan
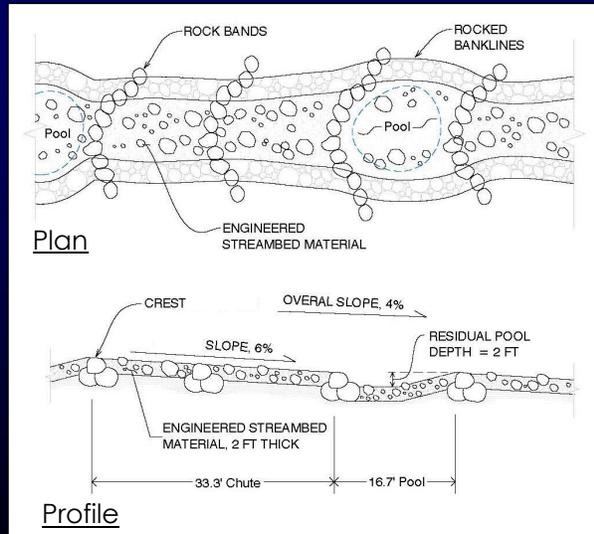
Profile

Typical Chutes and Pools Layout

21

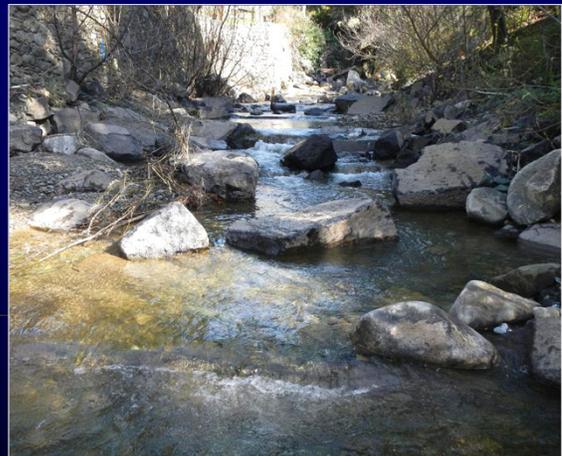## Chutes & Pools Roughened Channel

Penitencia Creek, Alum Rock Park

22

NID Measurement Weir

Concrete sills provide added
stability & control subsurface flow

23

23

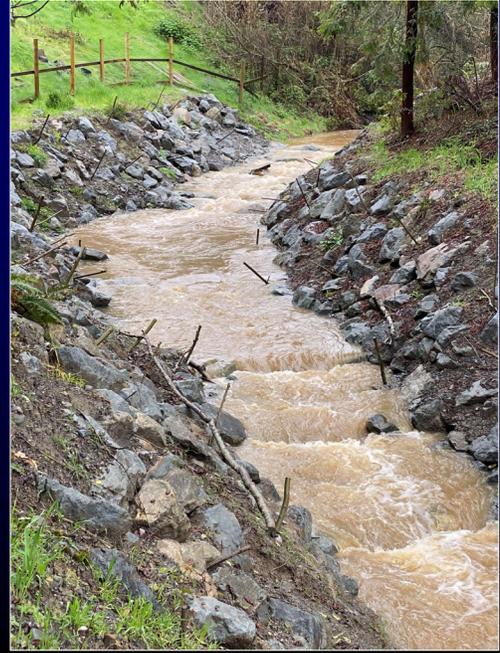## Chutes & Pools Roughened Channel

Rowdy Creek - 5 Chutes

24

24

Chutes & Pools Roughened Channel

Jameson Creek Box Culvert and Upstream Channel

10 Chutes
(5.5% Sloped)

25

Step-Pool Roughened Channels

Slope & Length Thresholds:

➤ Slope Range: 3% to 6.5% overall
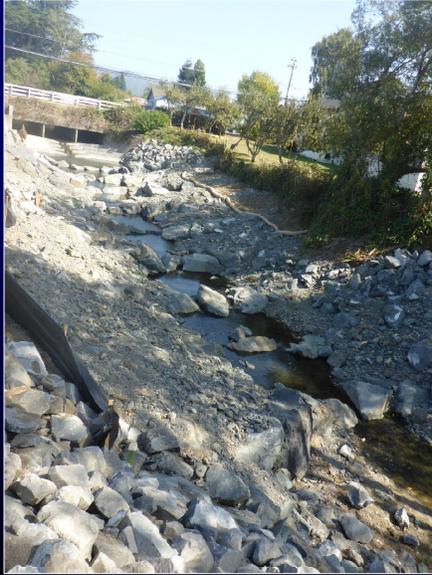
Bed Morphology:

- ➤ Rhythmic Pattern of Boulder Steps/Weirs

- ➤ Larger Rocks in Step 0.5 to 1.0 Bankfull Depth

- ➤ Oversized Pool every 3 to 5 feet of drop

- ➤ Drop Height & Pool Depth should satisfy fish passage criteria

- ➤ **Pools Armored with Coarse Bed Material**
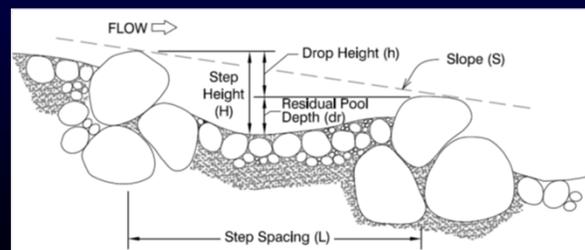
Step-pool channel slopes $\leq$4%: **2 $\leq$ H/L/S $\leq$ 5** (Chin 1998)

26

Step-Pool Roughened Channels

Rohnerville Creek at 12th St

Step-Pool Roughened Channel
Slope = 3.8%
Drop/Step = 0.5 ft
9 Boulder Steps
Spacing 13.5 ft

Steps: 36"– 48" Boulders
ESM Armored Pools
- Pool D84 = 30"
- Pool D50 = 12"

Challenging to build steps with design drop height

Use of 0.5 ft drops allowed for large vertical tolerance for step construction

27

27

Gulch 7 Step Pool
Roughened Channel-Stream Simulation Hybrid

2006

28

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Gulch 7 Step Pool
Roughened Channel-Stream Simulation Hybrid
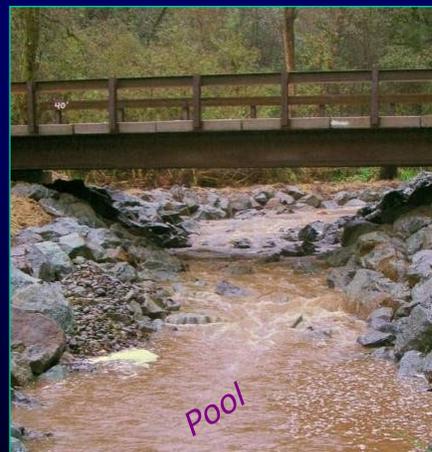

2013

29

Cascade & Pool Roughened Channels

Slope & Length Thresholds:

➤ Slope Range: > 5% cascade
                $\geq$ 4% overall

Bed Morphology:

➤ Complex series of small drops
   and pools

➤ Largest keystone
   boulders $\geq$ bankfull depth

➤ Drops and constructions form
   jet & wake hydraulics

➤ Armored pool every 3 to 5 feet
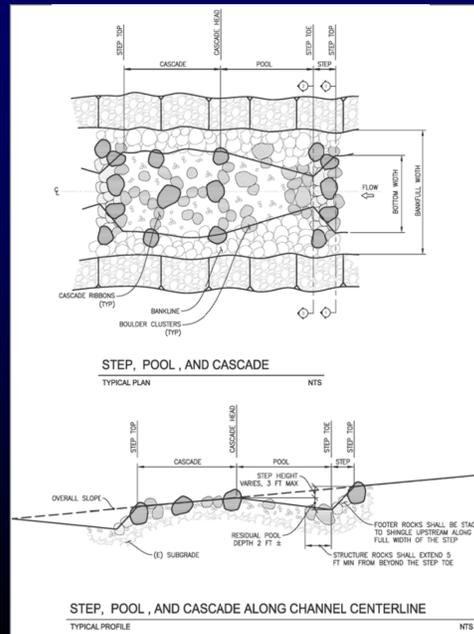   of drop to dissipate energy

Cascade Slope: 6%-7%
Overall Slope (w/pool): 4%

30

Stonybrook Canyon Step-Pool-Cascade

<u>Hybrid Design</u>:
Stream Simulation/
Roughened Channel
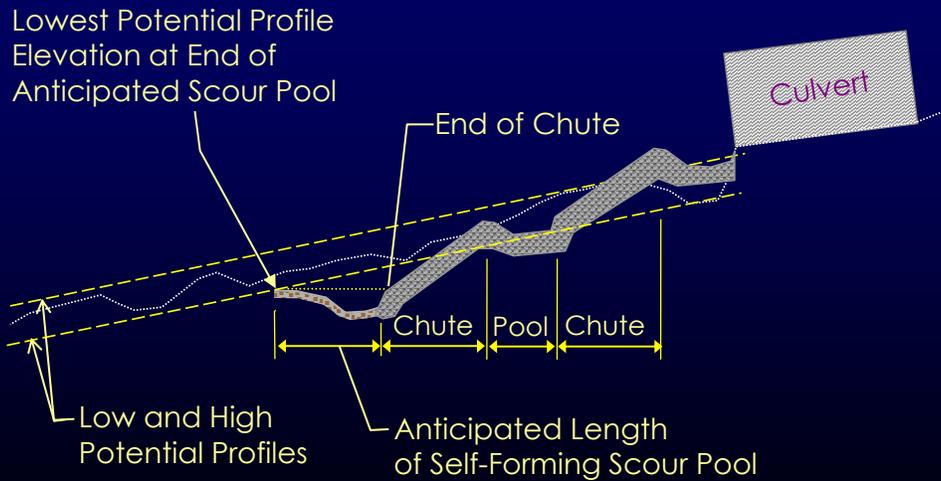
Natural Channel Slope
~8%

Cascade Overall Slope
10.6%

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Pros and Cons of Different Bed Morphologies

Roughened Channel Type	Plane Bed (aka Rock Ramps)	Chutes & Pools	Step-Pool	Cascades & Pools [Experimental]
Slope and Fall Limitations	• Max Slope 5% • Max 5 ft fall	• Max Chute Slope 7% • Max Overall Slope 4% • 2 ft drop fall between pools	• Slope 3% to 6.5% • 1 ft drop over boulder step	• Cascade Slope >5% • Overalls Slope ≥ 4% • 3-5 ft fall between pools
Low Flow Performance	Shallow Depths limit low flow passage	Shallow Depths limit low flow passage	Excellent – steps can concentrate lowest flows and pools depth	Shallow Depths limit low flow passage
Hydraulic Diversity	High – boulders create many flow paths	High – boulders create many flow paths	Moderate – boulder step has more limited flow paths	High – boulders create many flow paths
Resting/Energy Dissipation	Larger fall results in higher velocities at downstream end. Little resting habitat provided.	Good – chute roughness and pool spacing work together to dissipate energy and provide resting.	At higher flows pool can become too turbulent. Can result in streaming flow down channel. Pools provide good resting habitat.	Turbulence in steep cascades can become excessive at higher passage flows. Larger fall between pools can cause fish exhaustion
Channel Planform	Needs to be relatively straight in rock ramp and downstream channel before turn.	Channel can turn at pools – use larger pools for turning.	Not suitable for wide channels. Turns in channel shall be gentle across multiple pools	Needs to be straight with large pool at downstream end before any bends in channel.
Requires Fish to Leap	No leaping required	No leaping required	Smaller fish must leap over steps, especially at low flows	No leaping required
Construction Complexity	Standard roughened channel construction	Standard roughened channel construction	Additional attention to rock placement to achieve stability and design drop height	Additional attention to rock placement to achieve intended hydraulics

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Profile Control Transitions
Chutes & Pools Roughened Channel

Lowest Potential Profile
Elevation at End of
Anticipated Scour Pool

Culvert

End of Chute

Chute | Pool | Chute

Low and High
Potential Profiles

Anticipated Length
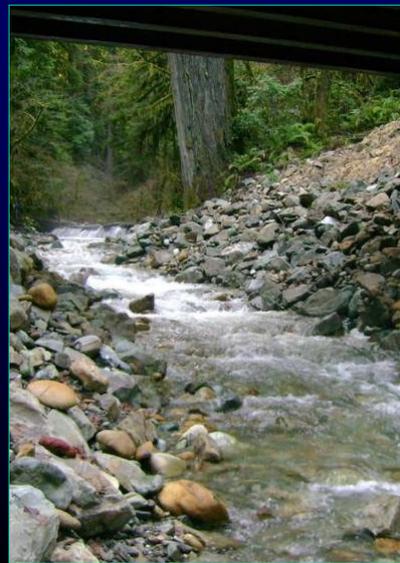of Self-Forming Scour Pool

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The Roughened Channel Design Concept

Limitation - Lack of Sediment Continuity

Engineered Bed Material is:

- Larger than bedload transported into roughened channel

- No replacement by natural bedload material

- Sized to be stable to a *bed design flow* (Q100yr)

34

34

Developing the Channel Design and Bed Mixture

The **Iterative** Design Process

1. Calculate Qbed & Qfish

2. Develop initial channel shape & slope to fit site

3. Calculate Stable D84 rock size at Qbed:
   * Initial guess for D84
   * Use hydraulic roughness relationships dependent on flow & substrate size *(Iterate)*
   * Calculate Unit Discharge for channel
   * Calculate a stable D84

5. Evaluate fish passage conditions

> If unsuitable, change channel shape/slope and repeat no. 2-5

35

35

Estimating Hydraulic Roughness

Flow resistance for steep mountain streams:

$$n = \cdot \frac{0.0926R^{1/6}}{1.16+2\log(R/D_{84})} \cdot \text{ (Limerinos, 1970)}$$

Manning's roughness

Hydraulic Radius

Water Depth

$$\sqrt{\frac{8}{f}} = 5.62 \bullet \log_{10}\left(\frac{h}{D_{84}}\right) + 4 \quad \text{(Bathurst, 1985)}$$

84% of bed material finer than D_{84}

Darcy Friction Factor
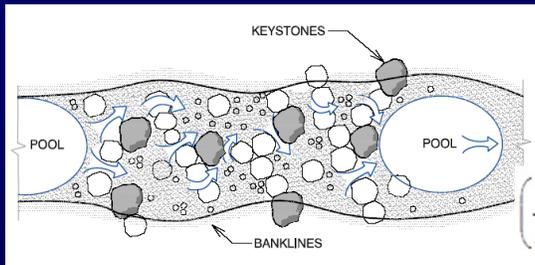
> Numerous relationships developed with varying limitations.
> See Appendix B in CDFG Part XII for more relationships.

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Importance of Depth Variable Roughened

Relative Roughness is Key to Fishway Performance

Friction Factor   Depth

$$\left(\frac{8}{f}\right)^{0.5} = 1.11 \left(\frac{d}{D_{84}}\right)^{0.46} \left(\frac{D_{84}}{D_{50}}\right)^{-0.85} S_0^{-0.39}$$

Mussetter (1989)

1:6 Model of Trabuco at Metrolink Cascade & Pool Roughened Channel

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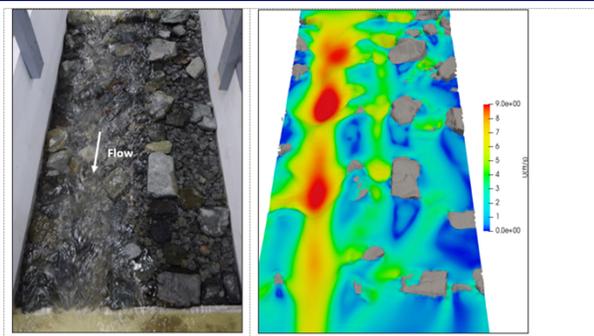37

Importance of Depth Variable Roughened

Figure 1-7. Typical fishway chute flow surface observed in the physical model (top) and modelled in OpenFOAM (bottom) for an inflow rate of 64 cfs.

64 cfs, Ave. Depth = 2.5 ft
Mannings n = 0.120

89 cfs, Ave. Depth = 2.8 ft
Mannings n = 0.110

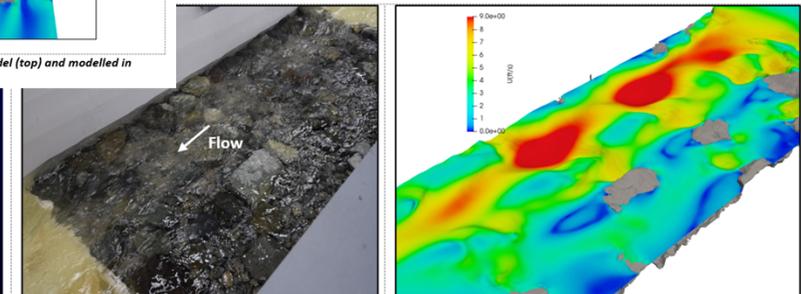*From Trabuco at I-5 Physical and CFD Modeling (NHC, 2021)*
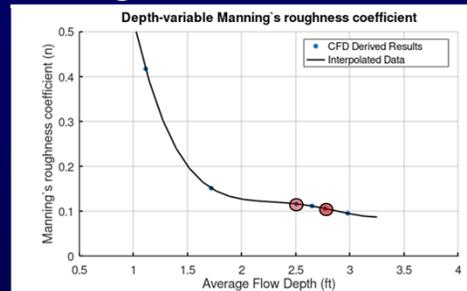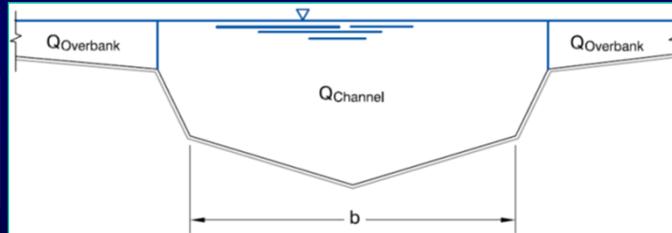
Figure 1-9. Typical fishway chute flow surface observed in the physical model (top) and modelled in OpenFOAM (bottom) for an inflow rate of 89 cfs.

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Designing a Stable Bed Using Unit Discharge Method

Unit Discharge:

$$q = \frac{Q_{channel}}{b}$$

$Q_{Overbank}$ $Q_{Channel}$ $Q_{Overbank}$ b

Water surface slope (ft/ft)

Unit discharge (cfs/ft) at *stable bed design flow* (i.e. Q100)

$$D_{30-ACOE} = \frac{1.95 S^{0.555} 1.25 q^{\frac{2}{3}}}{g^{\frac{1}{3}}}$$

from USACE EM 1110-2-1601 based on Abt et al, 1988

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Developing Gradation of Bed Material

USACE (1994) produces **porous uniform gradation** for bed material:

D84/D15 = 1.7 to 2.7

Natural channel streambed material has wide gradation:
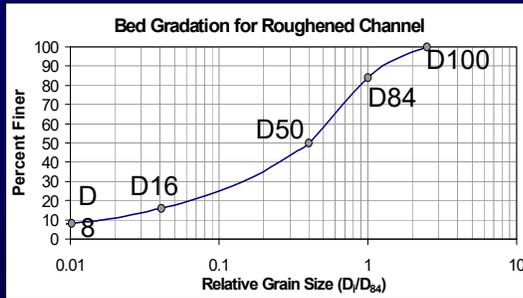
D84/D15 = 8 to 14   (typical in steeper streams)

– Larger Material ($\geq$D50) is <u>framework</u> for stability

– Smaller material (<D50) fills voids to control porosity

Porous Riffle-Pool Rock Chute

40

40

Developing Engineered Streambed Material (ESM)

Bed Gradation for Roughened Channel

Percent Finer vs Relative Grain Size (D_i/D_{84})

Labeled points: D100, D84, D50, D16, D8

<u>Gradation Shift for ESM:</u>

$$D84_{ESM} = 1.5 \, (D30_{ACOE})$$

(from WDFW, 2013)

For $D_i \geq D50_{ESM}$ use
<u>Ratios Relative to D84</u>:

$$D100_{ESM} = 2.5(D84_{ESM})$$
$$D50_{ESM} = 0.4(D84_{ESM})$$

(from WDFW, 2003)

For $D_i < D50_{ESM}$ use
<u>Fuller-Thompson Equation</u>:

$$D_i = (2 \cdot i)^{\frac{1}{n}} D_{50}$$
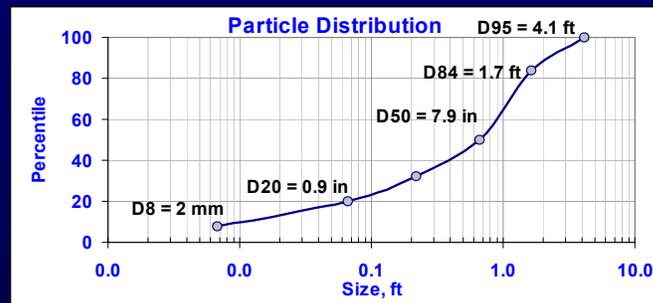
n ranged from 0.45 to 0.70
Set n to achieve D8 $\simeq$ 2mm

Sometimes produces oversized
rock, may be reduce to 1.5D84

41

Sizing and Specifying Material Gradations

Particle Distribution

Percentile vs Size, ft

Labeled points: D95 = 4.1 ft, D84 = 1.7 ft, D50 = 7.9 in, D20 = 0.9 in, D8 = 2 mm

Example Specifications for Gradation of ESM

Percent of Mix	Range of Size (Intermediate Axis)	
16	20 in	48 in
34	8 in	20 in
18	3 in	8.0 in
12	¼ in	1.0 in
8	Passes Sieve #10 **(2 mm)**	

Use largest size
class to form bed
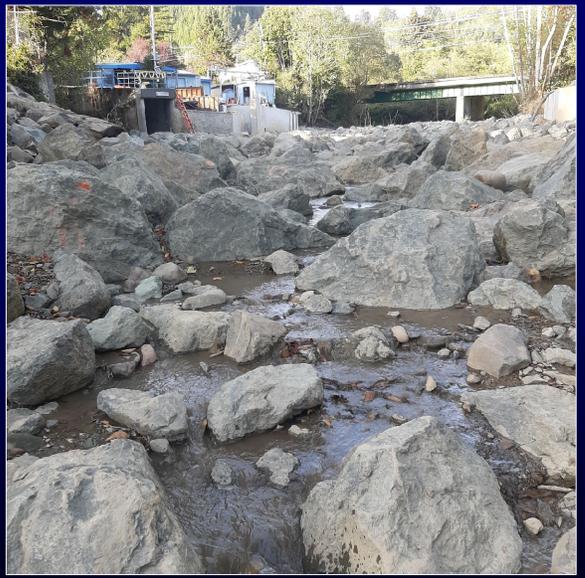structure in Rock
Placement Plan

42

Rock Placement Plan
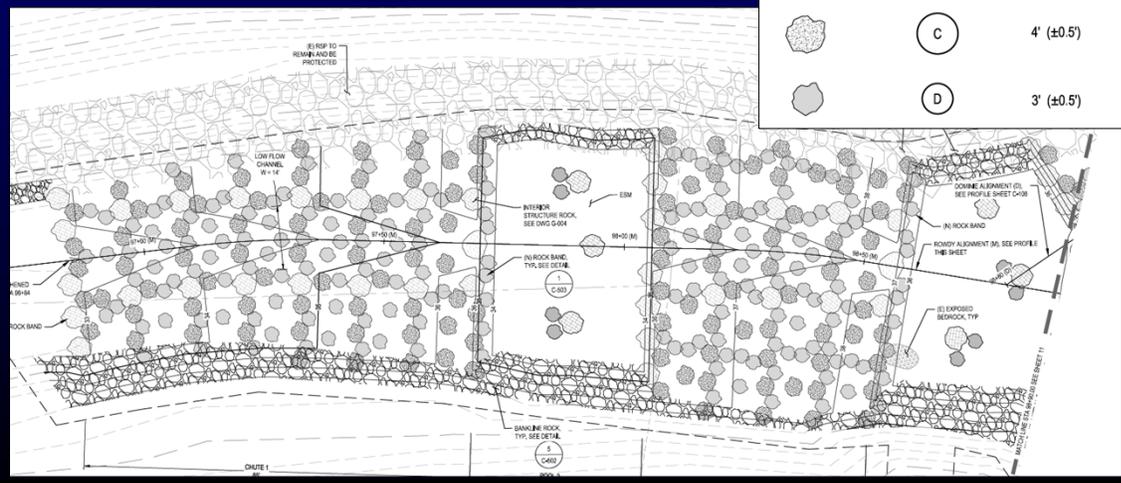
43

Rock Placement Plan Implemented

44

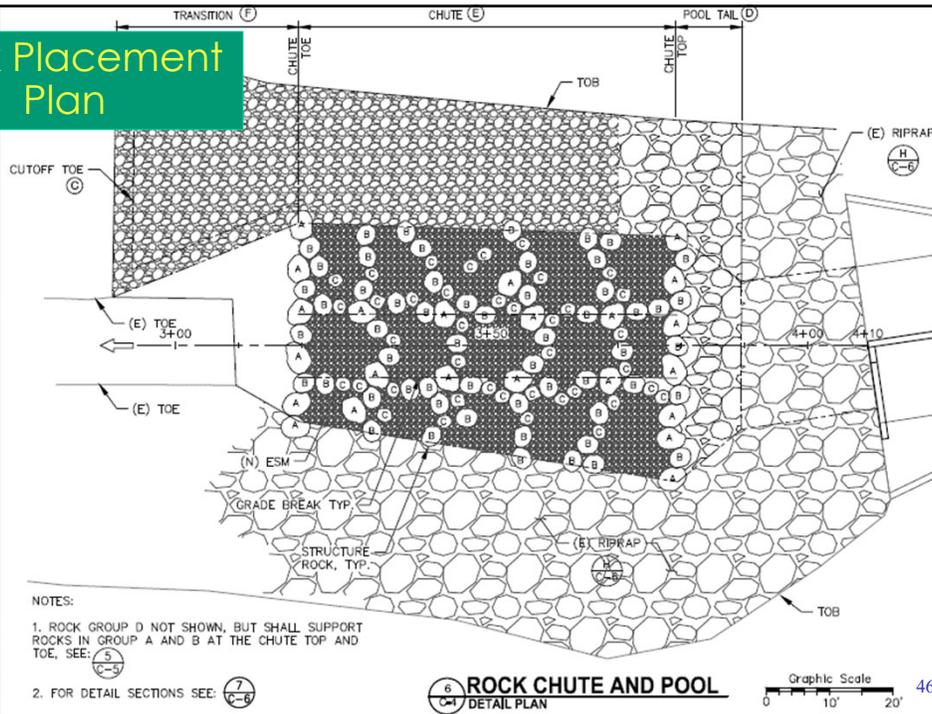Rock Placement Plan Implemented

Winter Baseflow

1,300 cfs
Close to Adult Anadromous
High Passage Design Flow
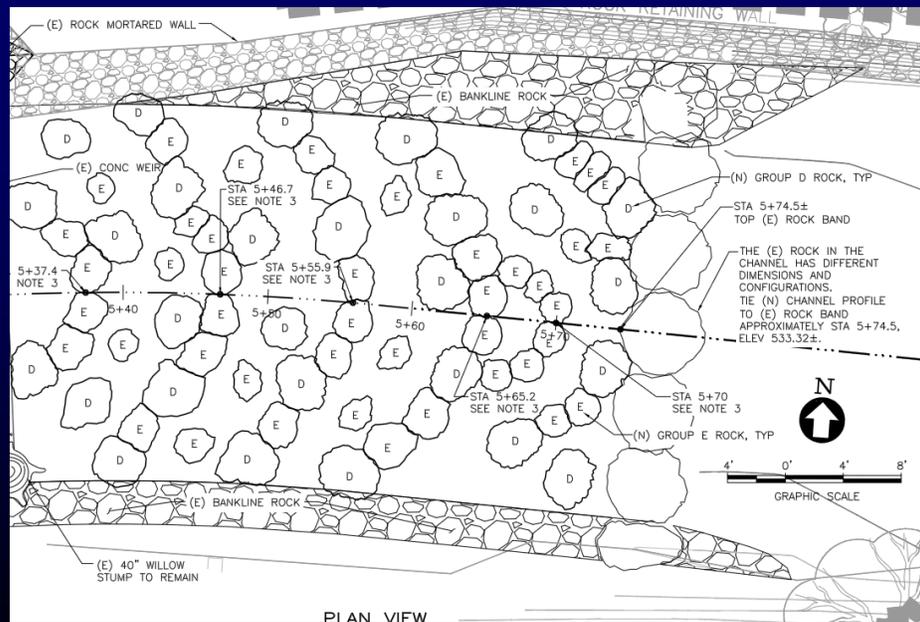
45

45

Rock Placement Plan

46

46

Rock Placement Plan Implemented

47

47

Rock Placement Plan

48

48

Rock Placement Plan Implemented

49

49

Evaluating Fish Passage Conditions in Roughened Channels

In Smaller Channels – Should evaluate passage
hydraulics using entire wetted section

In Wider Channels – Can evaluate passage through
a "Passage Corridor" with 2D or 3D model results

Applied Passage Criteria

In Ramps, Chutes & Cascades

1. Ave. Cross Sectional Water Velocity (*U*)
2. Max Cross Sectional Water Water Depth
3. Turbulence (EDF)

In Rock Armored Pools

1. Water Surface Drop
2. Pool Depth
3. Turbulence (EDF)

50

50

Adding Structure Rocks to DEM for 2D Hydraulic Modeling

DEM = Digital Elevation Model

HEC-RAS 2D model velocities using DEM from 3D Scan of constructed Rock Chutes

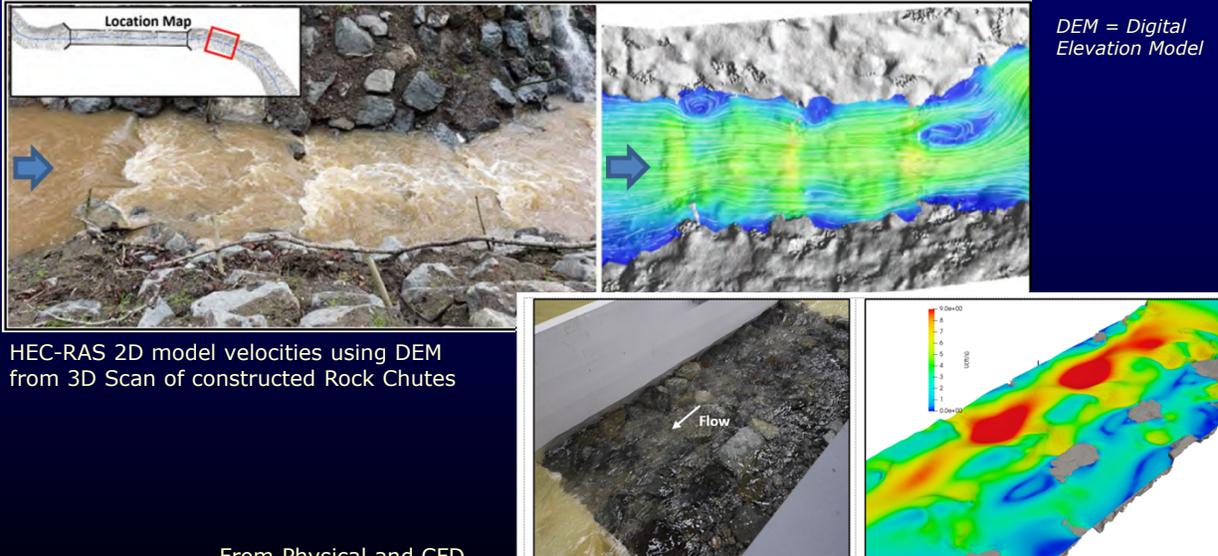From Physical and CFD Model Results (NHC, 2001)

Figure 1-9. Typical fishway chute flow surface observed in the physical model (top) and modelled in OpenFOAM (bottom) for an inflow rate of 89 cfs.

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Modeling Hydraulics with and without Boulders in DEM

Design DEM (chutes and pools with no boulders)

As-Built DEM from Scan

As-Built Fish Passage Flow

52

Adding Structure Rocks to DEM for 2D Hydraulic Modeling

Considering Analyzing Passage Hydraulics through assumed "Passage Corridors":

- Consult with CDFW/NMFS Biologist and Engineers beforehand

- Establish appropriate wetted width and minimum water depth for a passage corridor

- Establish locations/number of passage corridors at each flow (i.e. both sides of channel)
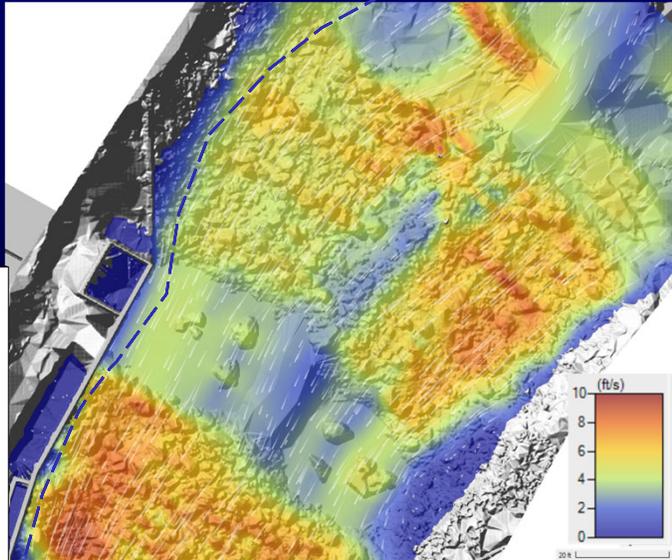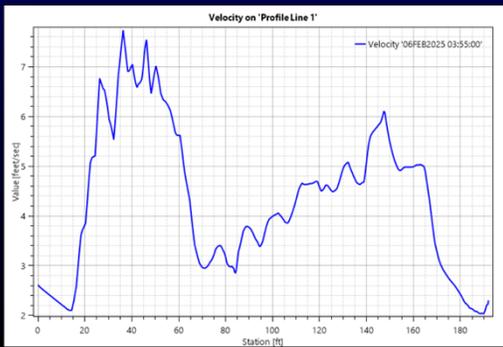
53

53

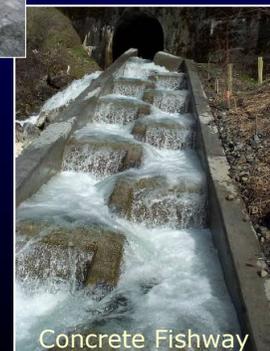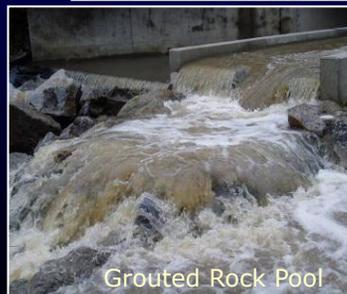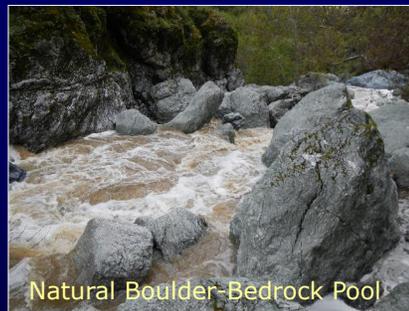## Plunging Flow & Turbulence

- Energy is dissipated in receiving pool through turbulence (heat)

- Pools with adjustable beds will scour and enlarge to dissipate energy

- Armored pools will not adjust – can become extremely turbulent

- Excessive Turbulence Creates can Block Fish Passage

Natural Boulder-Bedrock Pool

Grouted Rock Pool

Concrete Fishway

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Turbulence in Pools

Energy Dissipation Factor (EDF) for Armored Pools

Measure of Power Dissipation per Volume of Water:

$$EDF = \frac{\gamma Q h}{V}$$

h = Drop into Pool, change in EGL (ft)

Q = Flow (cfs)

V = Pool Volume (cf)

γ = Unit Weight of Water (62.4 lb/cf)

Thresholds for Pools :
Adult Salmon:
EDF > 4 ft-lb/s/ft^3

Adult Resident Trout:
EDF > 3 ft-lb/s/ft^3

Energy Dissipation Factor (EDF) for Rock Ramps/ Chutes/Cascades

$$EDF = \gamma Q S / A$$

Hydraulic Diversity in Chutes results in much higher EDF threshold

S = Water Surface Slope
A = Wetted Cross-Sectional area (sf)

55

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Turbulence in Rock Ramps/Chutes and Cascades

Check design EDF against plot to see if within reason
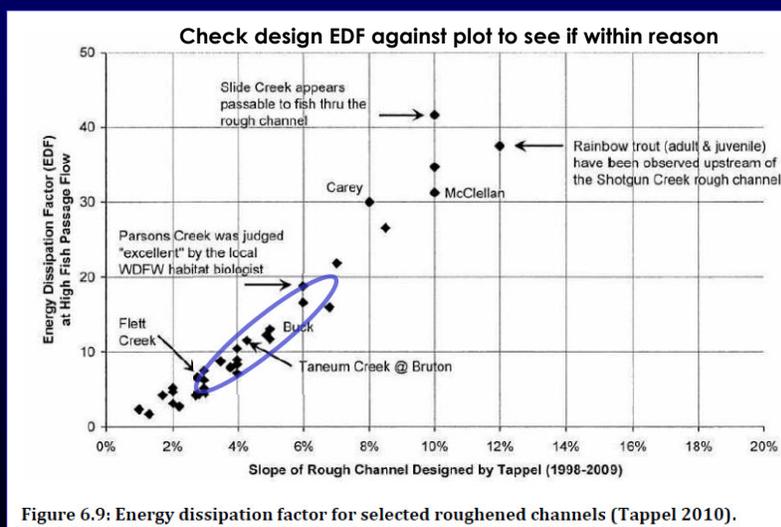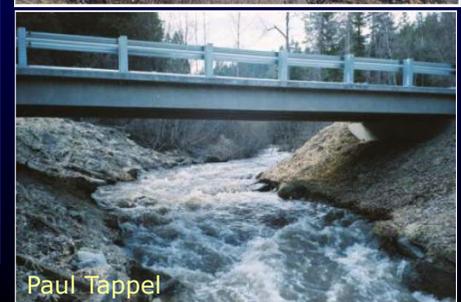
Figure 6.9: Energy dissipation factor for selected roughened channels (Tappel 2010).

From Washington State DFW Water Crossing Design Guidelines (2013)

WDFW, 2013

Paul Tappel

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Construction Sequencing and Methods

1. Grading and Compact

2. Placing Rock Structures

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Construction Sequencing and Methods

Photo by Mitch Farro

3. Keystones and Bankline Rock

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Construction Sequencing and Methods

4. Stockpile Engineered Streambed Material onsite. Within a small section of channel, place material in correct proportions and mix with excavator bucket ...

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Construction Sequencing and Methods

Delivered Premixed

4. ...If delivered premixed to site, must be remixed in channel due to settling in truck.

5. Install Engineered Streambed Material (ESM)…

60

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Construction Sequencing and Methods

5. ...Place Structure Rocks into Lifts.

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Construction Sequencing and Methods

PROTRUDE NO MORE THAN $\frac{1}{3}$ OF ROCK HEIGHT

TOP LIFT
2nd LIFT
1st LIFT

ROCKS GREATER THAN LIFT THICKNESS

GRANULAR FILTER BLANKET OR GEOTEXTILE FABRIC (IF REQUIRED)
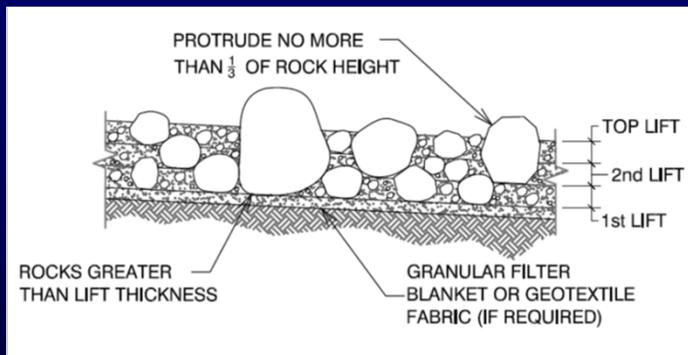
5. ..Construct channel bed in lifts. Compact each lift…
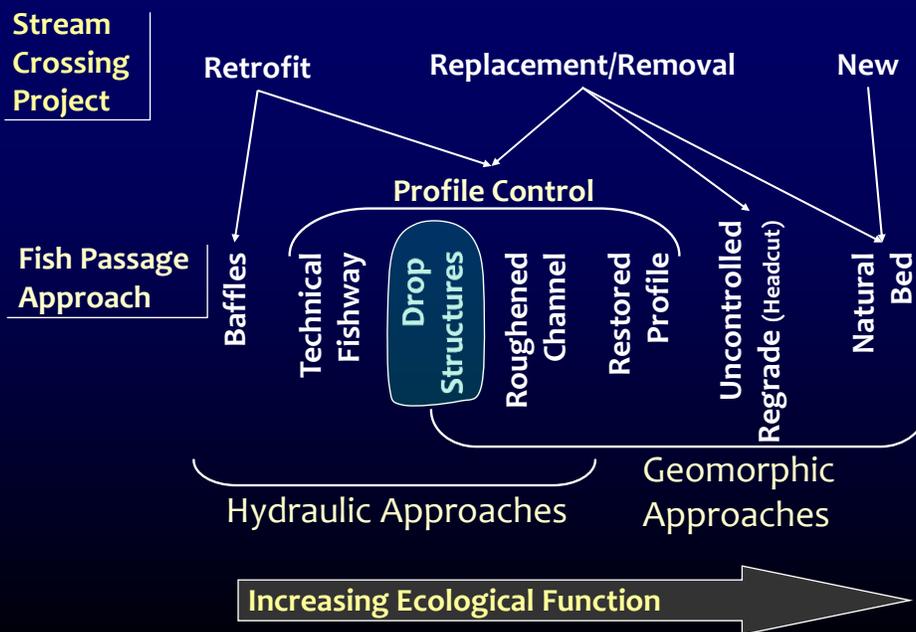
62

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Construction Sequencing and Methods

6. Flood channel bed and banklines to fill voids, compact bed, and wash fines off surface. Collect and remove fines from bottom of reach.

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Design Approaches for Aquatic Organism Passage

Stream Crossing Project

Retrofit

Replacement/Removal

New

Profile Control

Fish Passage Approach

Baffles

Technical Fishway

Drop Structures

Roughened Channel

Restored Profile

Uncontrolled Regrade (Headcut)

Natural Bed

Hydraulic Approaches

Geomorphic Approaches

Increasing Ecological Function

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Forced Profiles with Drop Structures
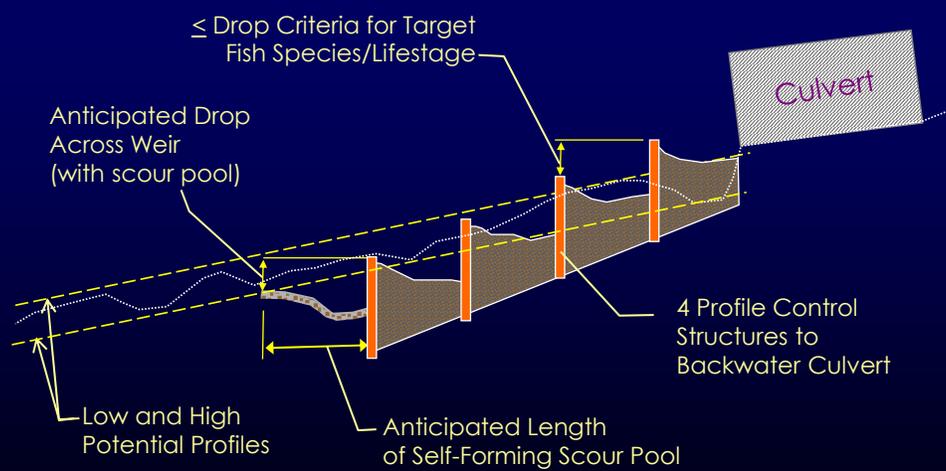
Drop Structures
(weirs, sills, chutes):

- Discrete structures
- Distinct drops in the channel
- <u>Native streambed material between</u>
- Types: Flexible vs Rigid

65

Profile Control Transitions
(Steps or Drop Structures)

≤ Drop Criteria for Target Fish Species/Lifestage

Culvert

Anticipated Drop Across Weir (with scour pool)

4 Profile Control Structures to Backwater Culvert

Low and High Potential Profiles

Anticipated Length of Self-Forming Scour Pool

❖ Place End of Profile Control based on Low Potential Profile with Anticipated Scour Pool

66
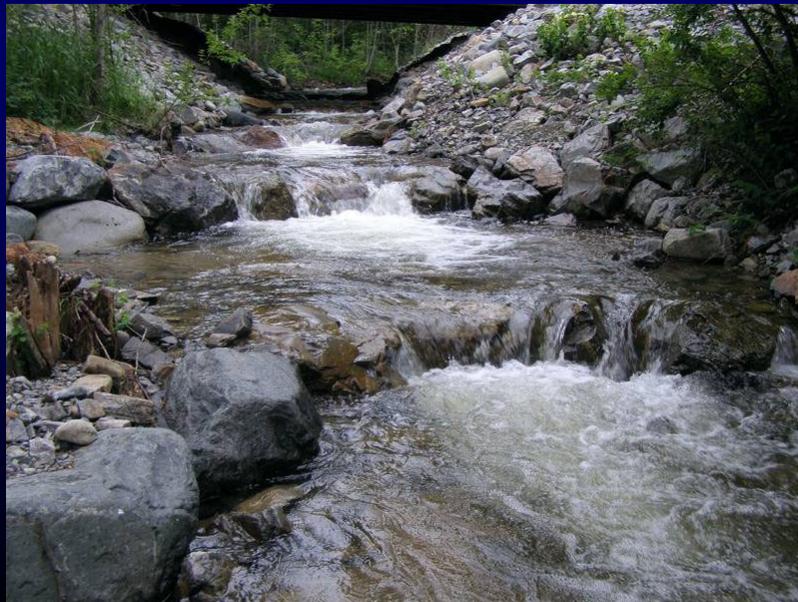
66

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Rock Weirs & Chutes

- Irregular surface provide hydraulic diversity
- Withstands small shifts, and easy to field adjust
- Maintains channel shape
- Lower cost than roughened channel

- Requires skilled operator
- Larger Vertical Tolerance
- Built at lower slopes than rigid weirs (max 4 to 5%)
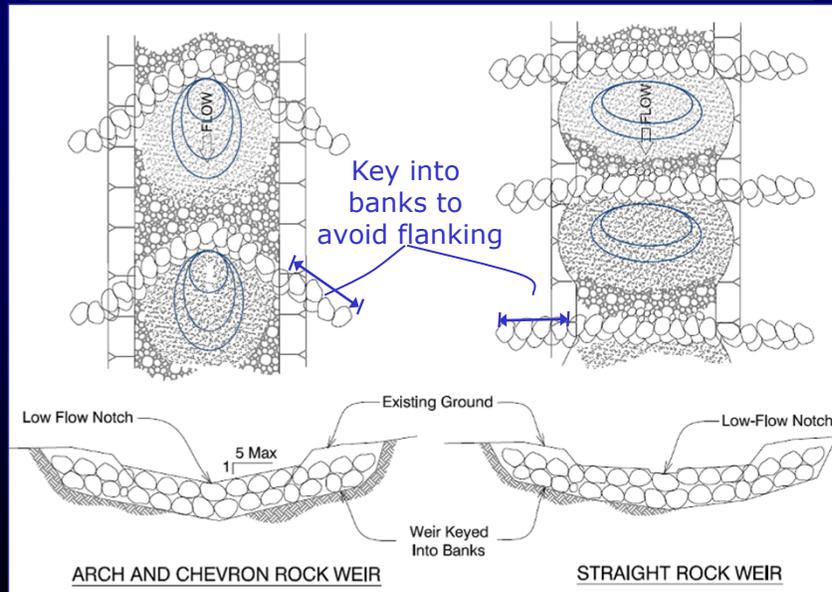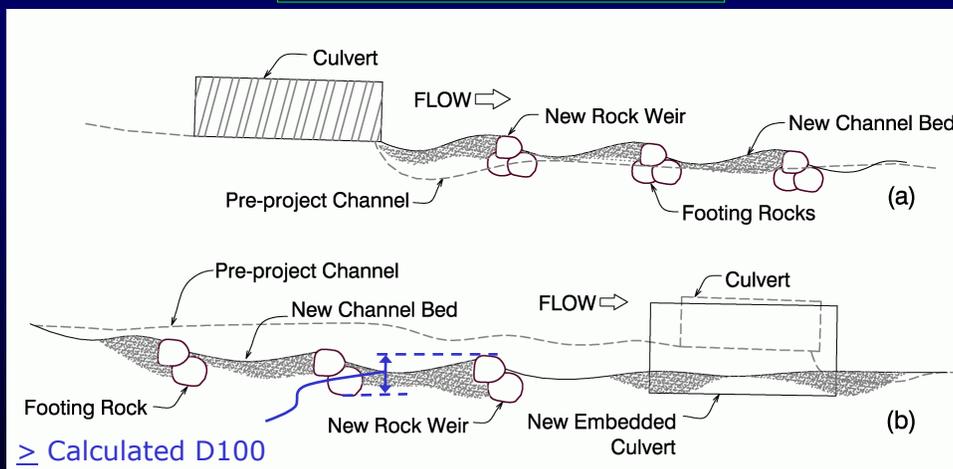- Cascading failure possible

67
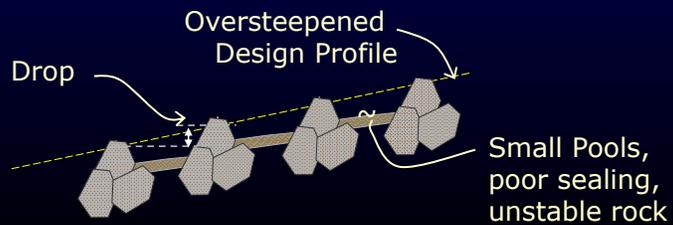
Arch Shaped Rock Weirs

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Shape of Rock Weirs

Key into banks to avoid flanking

ARCH AND CHEVRON ROCK WEIR

STRAIGHT ROCK WEIR

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Footing of Rock Weirs

> Calculated D100

(a)

(b)

70

Spacing of Rock Weirs

Drop — Design Profile — Rock Weir

Pool scoured into native streambed material

Oversteepened Design Profile — Drop

Small Pools, poor sealing, unstable rock
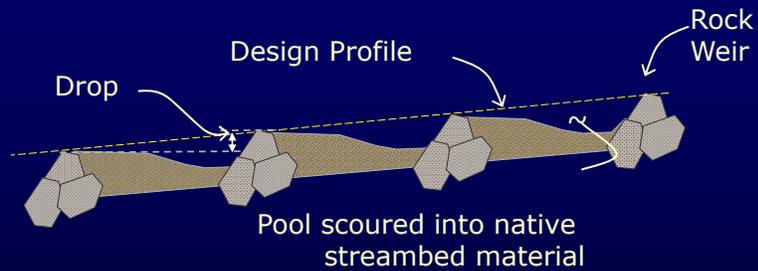
71

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Rock Sizing for Weirs

From Design of Rock Weirs (NRCS, 2000)

$$D_{50-riprap} = \frac{2.9wDS}{CK}$$

Far West States (FWS) Lane Method riprap sizing method (NRCS, 1996)

w = channel top width at the design flow (feet)

D = maximum depth of flow in channel (feet)

S = channel slope (feet/feet)

C = coefficient for channel curvature (1 for straight channels)

K = side slope coefficient. 0.53 for 1.5H:1V, 0.87 for 3H:1V,

Rock Weir Gradation

Dmin-Weir = 0.75 x (D50-Riprap)

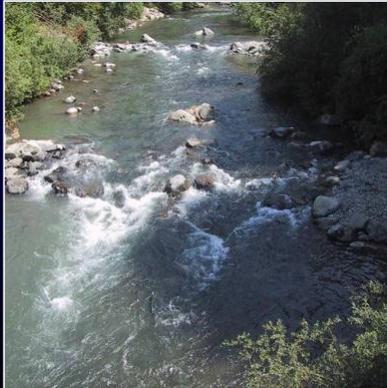D50-Weir = 2 x (D50-Riprap)

D100-Weir = 4 x (D50-Riprap)

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Rock Riffles and Chutes as Drop Structures

Individual Chutes:
- Energy dissipation
- Diversity
- Slope from crest to crest typically < 3%

Shape of Chute:
- Top width
- Head differential (typ. 2 ft max)
- Plan vee
- Cross section vee
- Low flow channel

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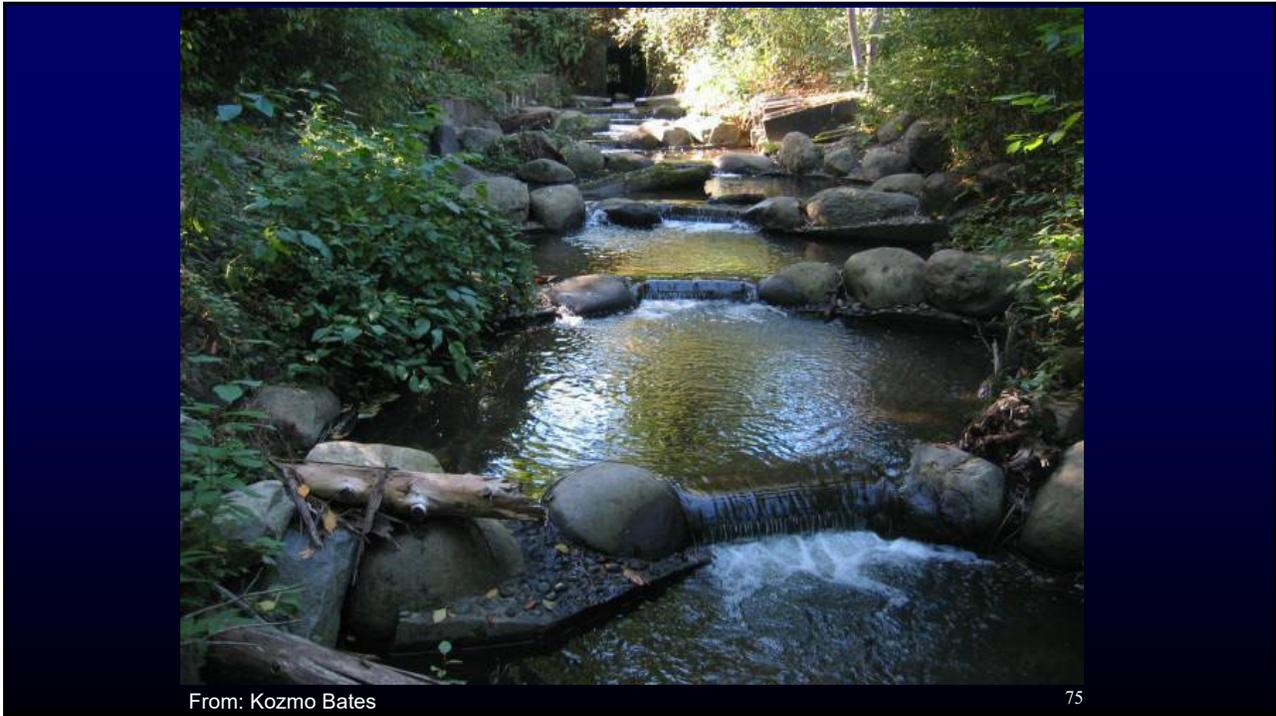## Rigid Weirs: Concrete, sheet pile, …

- Objectives:
  - Steepen grade (self sealing)
  - Rigid permanent bed control to maintain steep grade

- Max 5% grade in small streams
- Prefabricated; installation easy but demands care
- Deeper keys into bed and banks than rock weirs
- Shape to fit channel and control thalweg (v-shape)
- Can add hydraulic complexity along crest to improve passage

Prefabricated

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From: Kozmo Bates

75

3 pre-cast panels
for channels up to
12 ft

Vary arch
orientation at
channel bends

Embedded eyes
and pin to tie
panels together.

Existing Channel
cross-section

Notch to maintain
channel thalweg

Boulders keyed
loose against weir
crest boulders to
form "cascade"

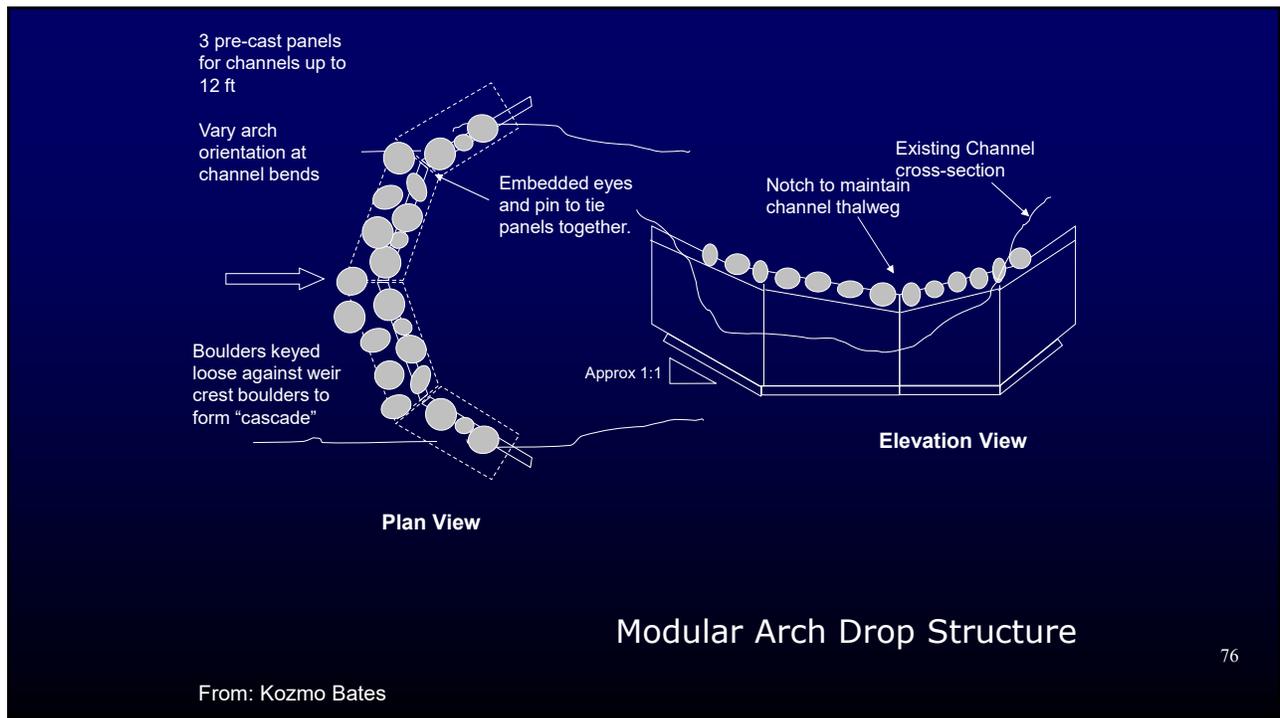Approx 1:1

Elevation View

Plan View

Modular Arch Drop Structure

From: Kozmo Bates

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Log Controls

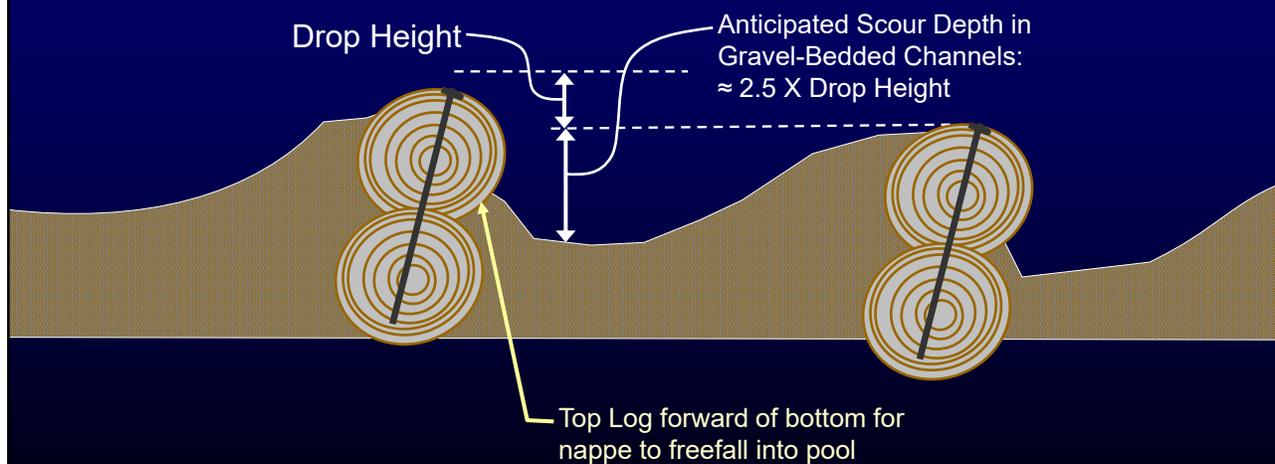**Horizontal Double Log Sills**

- Keeps log wetted to increases longevity
- Easy to construct
- Spreads out flow
  - Forms wide pools, rather than long
  - Anticipate bank erosion when keying
- Wide smooth surface/ low hydraulic complexity
  - May not be good for juvenile passage

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Log controls: Rule of Thumb for Scour

Drop Height

Anticipated Scour Depth in Gravel-Bedded Channels: ≈ 2.5 X Drop Height

Top Log forward of bottom for nappe to freefall into pool

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Three keys to stability

1. Double log, spiked
2. Ballast
   (concrete or rock)
3. Tiedown

Structure flanked

Log control remains structurally sound

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Log controls

- Logs anchored to wood posts
- Rock added to protect banks

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80

80

Natural Log Steps

Training logs along bank confine flow

Dunn Creek

81

Complex Log Steps

Notched Top Log

Guide Logs

Anchor Posts
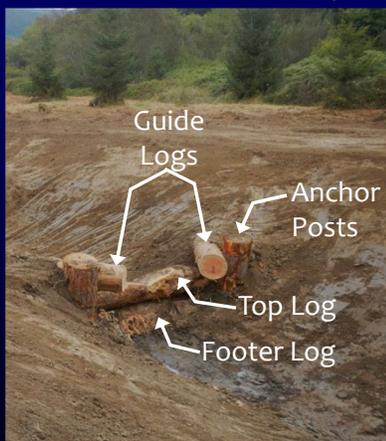
Top Log

Footer Log

o Top Log and Guide Logs Thru-Bolted to Anchor Posts
o **Top Log Anchored to Footer Log**

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Complex Log Steps

No Rock Used

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83

Log controls

- **<u>Straight</u>**
  - Objective: Steepen grade, optimize select passage, minimize cost and length, secure elevation control
  - 5% grade max as bed retention
  - Uniform channel
  - Secure designs available
- **<u>V- Shape</u>**
  - Objective: Steepen grade, deepen thalweg, narrow channel, provide select passage
  - More diverse channel
- **Can be made complex**
- **Durable**

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Design Approaches for Aquatic Organism Passage

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