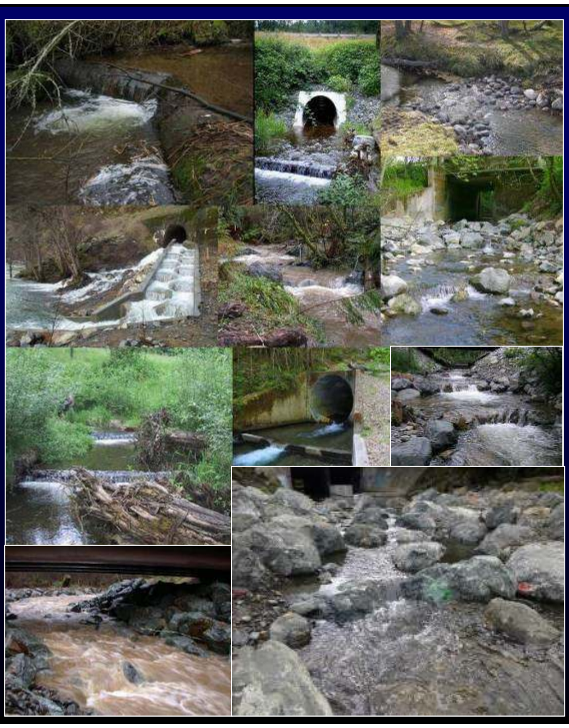
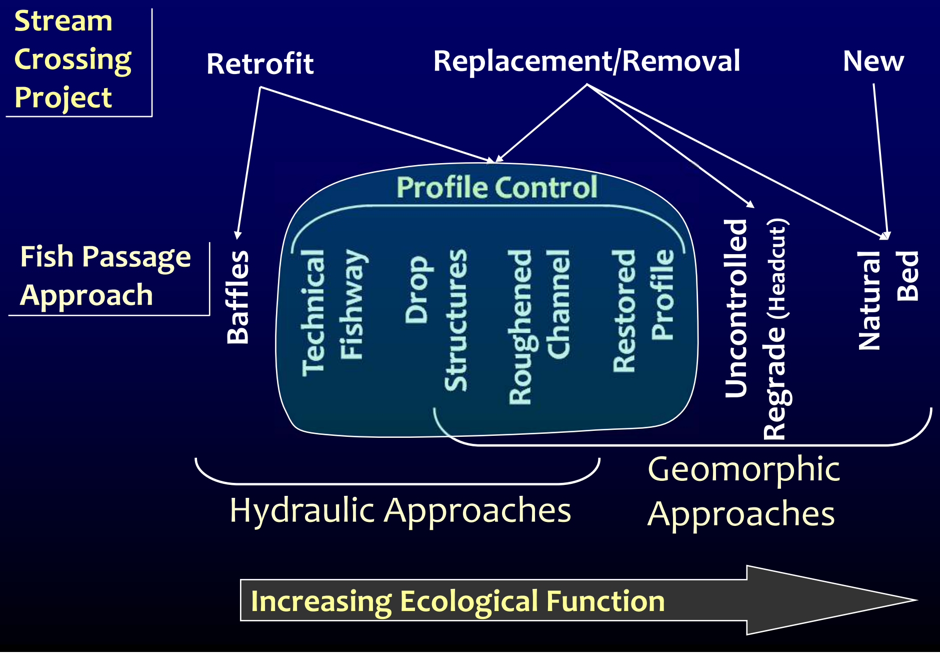
Geomorphic-Based
Profile Control Techniques



Michael Love, P.E.
mlove@h2odesigns.com

Design Approaches for Aquatic Organism Passage



Stream Crossing Project

Retrofit

Replacement/Removal

New

Fish Passage Approach

Baffles

Profile Control

Technical Fishway

Drop Structures

Roughened Channel

Restored Profile

Uncontrolled Regrade (Headcut)

Natural Bed

Hydraulic Approaches

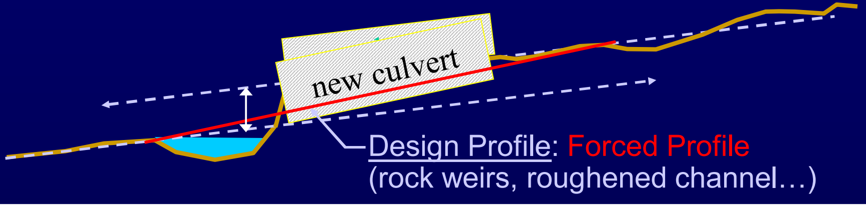
Geomorphic Approaches

Increasing Ecological Function

Profile Control Options

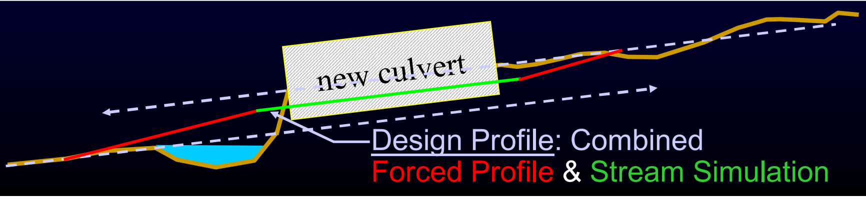
	Slope	Pros / Cons
Restored Profile	Limited by channel type	+ Passage diversity, Habitat - Scale/cost
Roughened Channel	Durability, bedload limit	+ Passage diversity - Species, failure risk
Boulder Weirs	≤5%	+ Passage diversity, Habitat - Failure risk
Rigid Weirs (log, concrete)	≤5%	+ Rigid, durable -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

Design Profiles for Incised Channels: Replacement



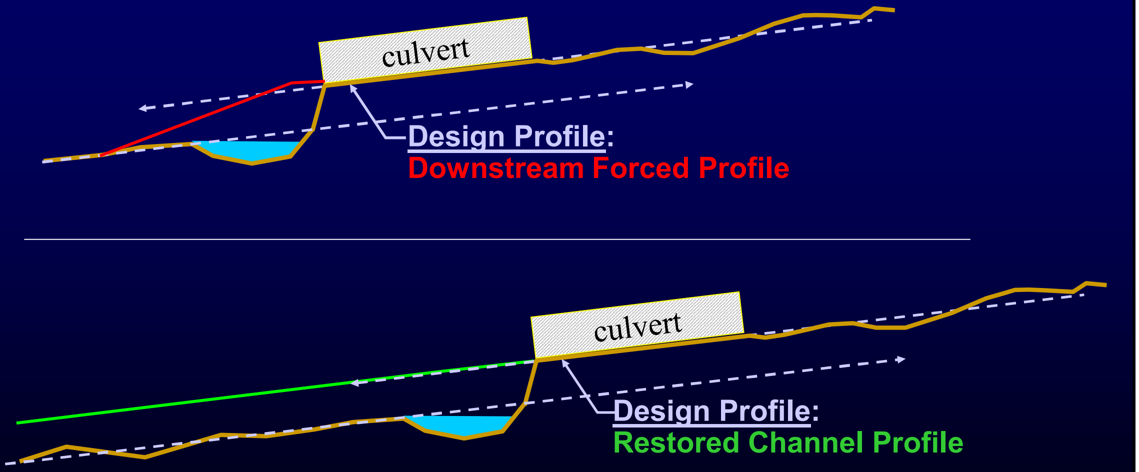
Design Profile: Forced Profile
(rock weirs, roughened channel…)

Design Profile: Stream Simulation with Uncontrolled Regarde (headcutting)



Design Profile: Combined
Forced Profile & Stream Simulation

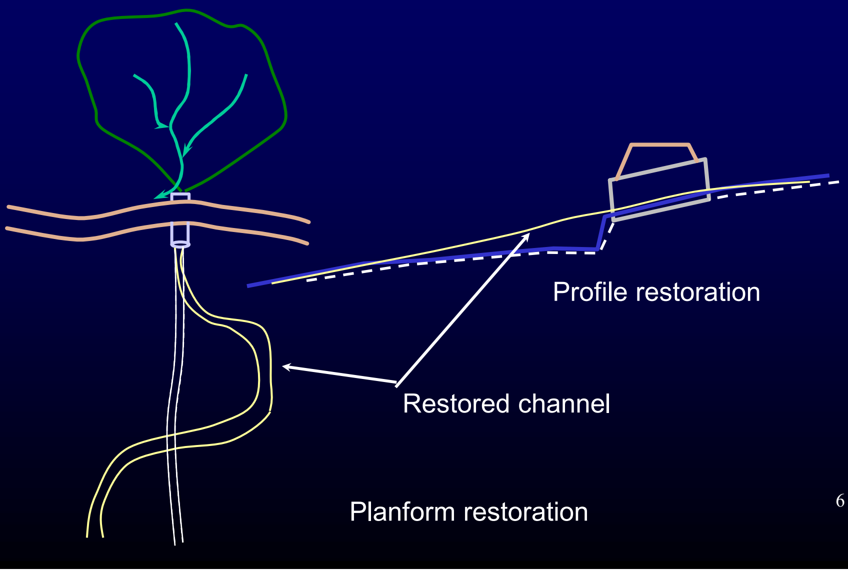
Design Profiles for Incised Channels
- Retrofit or Replacement -



Design Profile:
Downstream Forced Profile

Design Profile:
Restored Channel Profile

Channel Restoration for Passage of Aquatic Organisms



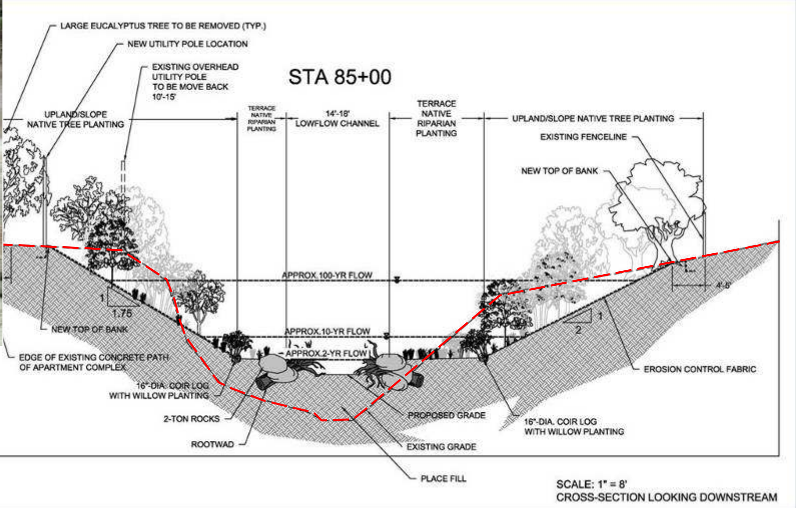
Profile restoration

Restored channel

Planform restoration

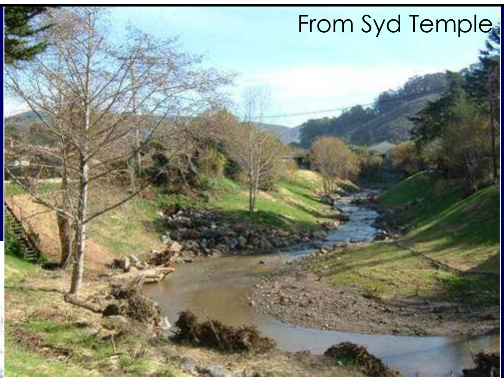
Profile Restoration

Highly Incised Channel



From Christine Chann,
San Pedro Creek
Watershed Coalition

Profile Restoration



From Syd Temple

From Christine Chann

- 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

Profile Restoration - Outlet Creek, WA

Large Wood Placed to Capture Streambed
Material and Raise Incised Channel Bed.

Eliminated Perched Culvert Outlet for Fish Passage

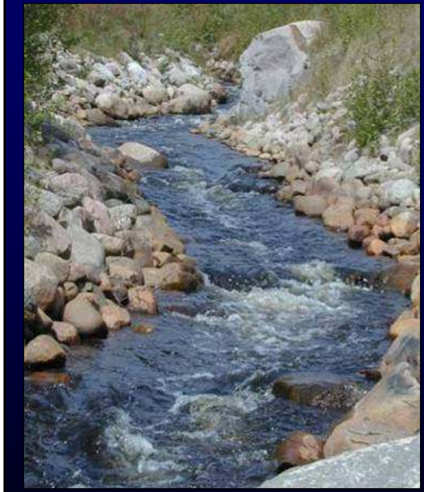
Constructed 2000 | Photos from 2005

Photos from Kozmo Bates

Geomorphically-Based Roughened Channels

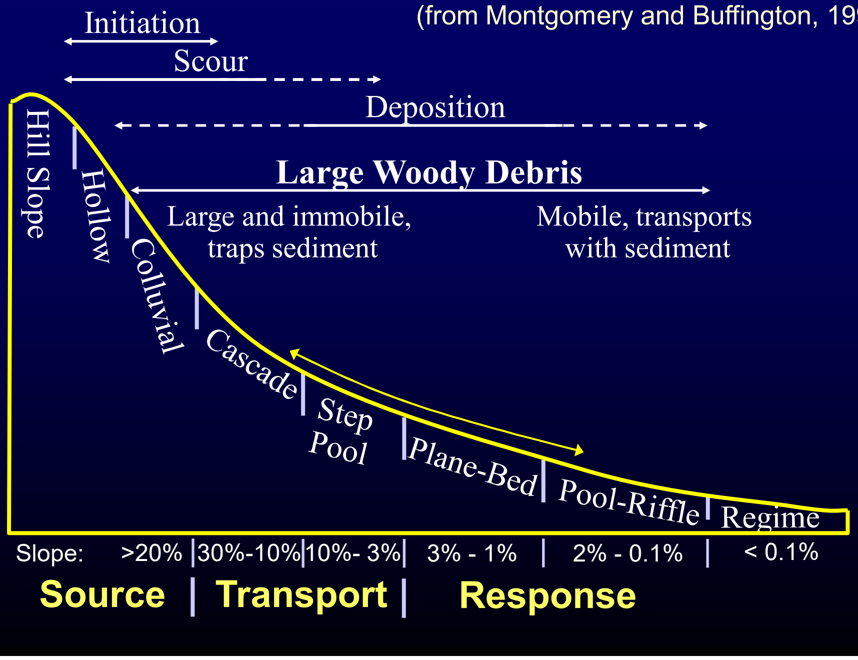
- Channel constructed **steeper** than the adjacent channel (profile control)
- Based on morphology of steeper stream channel
- Stable *engineered streambed material (ESM)* forms channel bed & banks
- Quazi-hydraulic design for target species/lifestages (velocity, depth, drop, EDF)

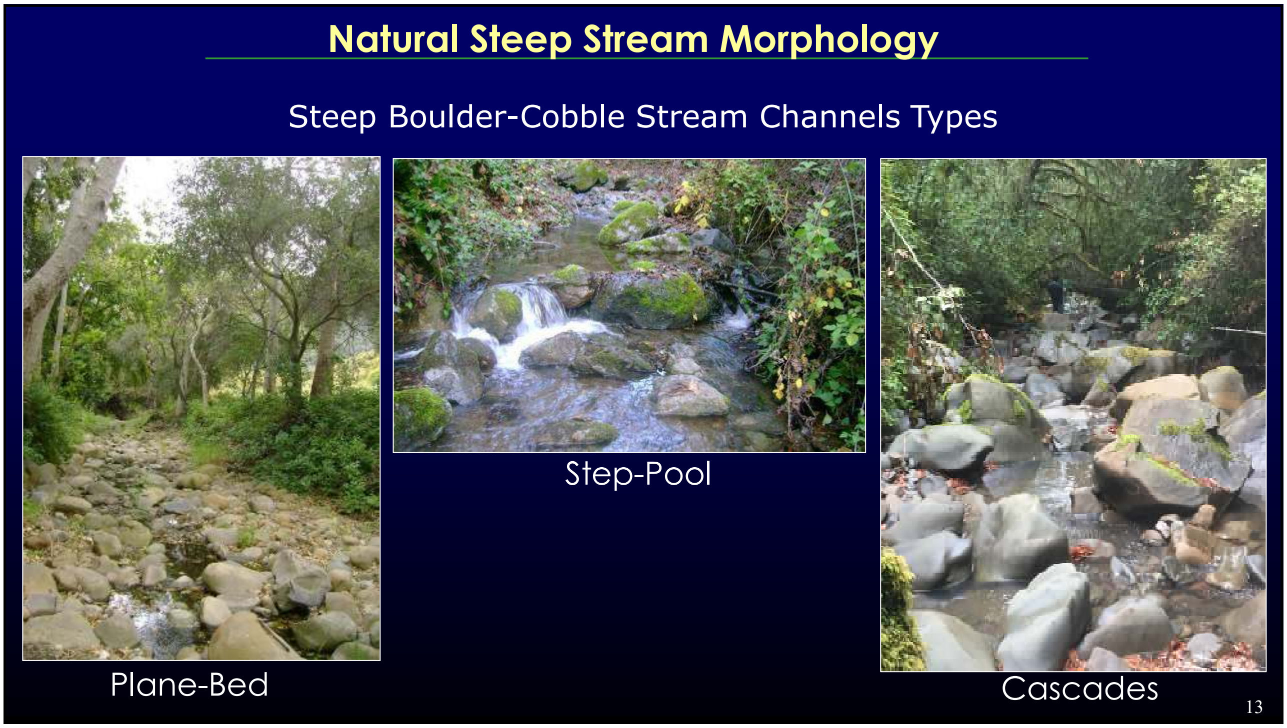
Examples of a Roughened Channel in Europe



Generalized Stream Classification

(from Montgomery and Buffington, 1993)





Natural Steep Stream Morphology

Steep Boulder-Cobble Stream Channels Types

Plane-Bed

Step-Pool

Cascades

Natural Step Pool Stream Morphology

Step-Pool Stream Channels

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)

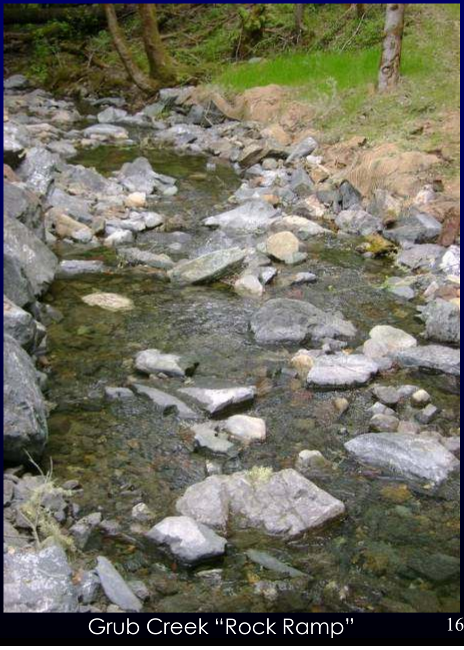
Plane-Bed (Rock Ramp) Roughened Channels

Slope & Length Thresholds:

- ➢ Slope Range: ≤ 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”

Plane-Bed (Rock Ramp) Roughened Channels

• 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

Pinole Creek Rock Ramp at I-80 Culvert Outlet

Photos: Jon Mann

- 2.5 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)

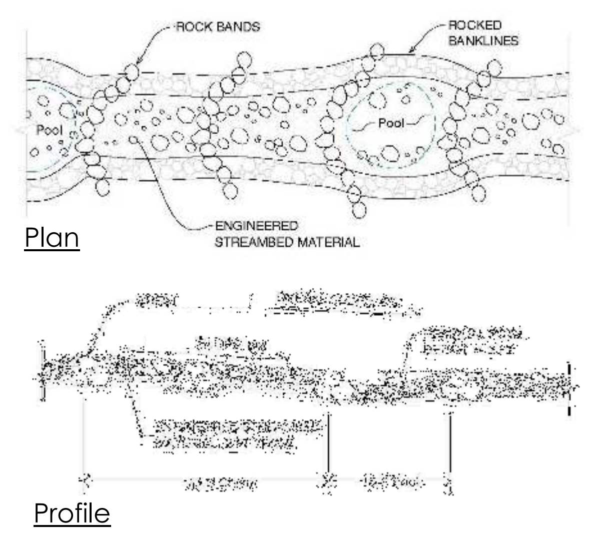
Chutes & Pools Roughened Channels

Slope & Length Thresholds (for armored pools):

- Slope Range: $\leq$ 7% across a chute
  $\leq$ 4% overall
- Max Head Diff.: 2 feet per chute
- Pools between Chutes to Dissipate Energy/Provide Fish Holding Habitat

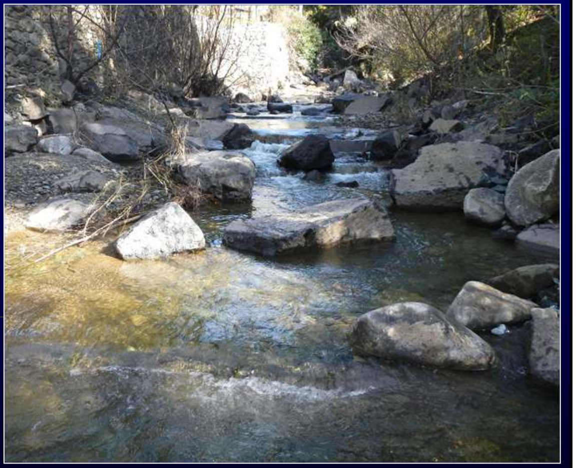
Bed Morphology:

- Chutes (Rapids) with both Specified and Random Rock Placement
- D100 < Channel Depth
- Pools Armored with Coarse Bed Material



Typical Chutes and Pools Layout

Chutes & Pools Roughened Channel



Penitencia Creek, Alum Rock Park

Profile

Chutes & Pools Roughened Channel

Rowdy Creek Fish Hatchery - Incised Channel below US101
Chutes and Pools Roughened Channel

5 Chutes and Pools | Total Fall = 10 feet

Chutes & Pools Roughened Channels

5 Chutes and Pools | Total Fall = 10 feet

Rowdy Creek Fish Hatchery
Incised Channel below US101

NID Measurement Weir

Concrete sills provide added stability & control subsurface flow

---

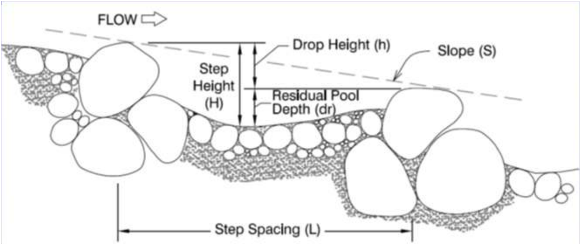
Step-Pool Roughened Channels

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 <4%: **2 < H/L/S < 5** (Chin 1998)

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

---

Gulch 7 Step Pool Roughened Channel-Stream Simulation Hybrid

2006

Gulch 7 Step Pool
Roughened Channel-Stream Simulation Hybrid

2013

Cascade & Pool Roughened Channels

Slope & Length Thresholds:

- Slope Range: > 5% cascade
  ≥ 4% overall

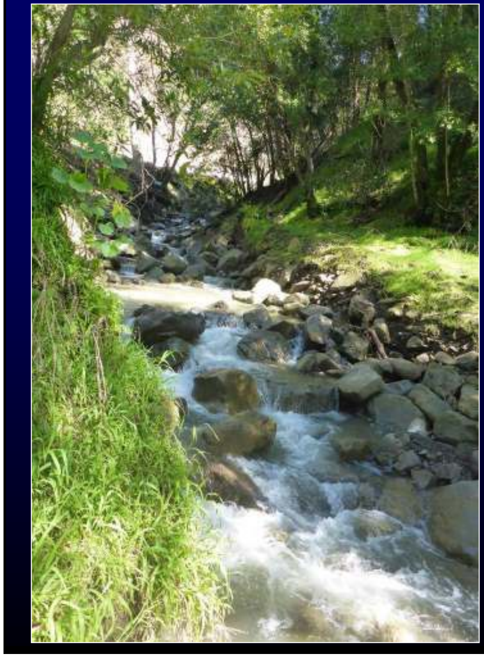
Bed Morphology:

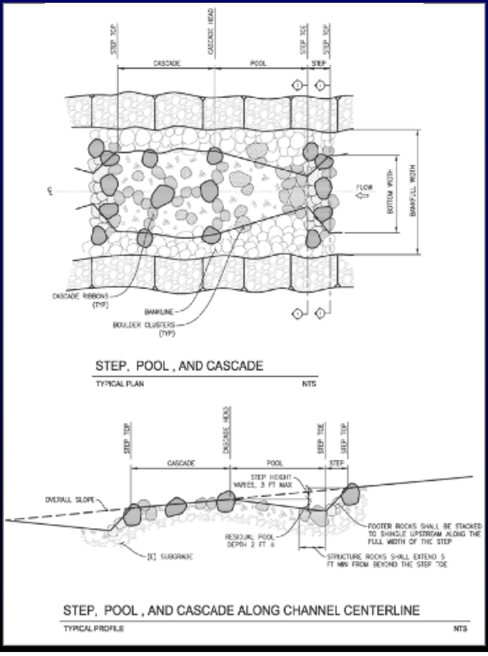
- Complex series of small drops and pools
- Largest keystone boulders ≥ bankfull depth
- Drops and constructions form jet & wake hydraulics
- Armored pool every 3 to 5 feet of drop to dissipate energy

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

Considered by CDFW as "Experimental"
May not provide suitable passage for juvenile salmonids

Stonybrook Canyon Step-Pool-Cascade





<u>Hybrid Design</u>:
Stream Simulation/
Roughened Channel

Natural Channel Slope ~8%

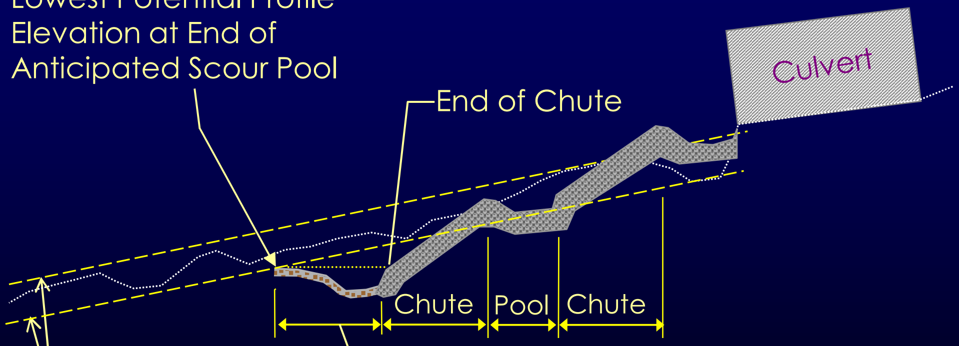
Cascade Overall Slope 10.6%

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		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

Profile Control Transitions

Chutes & Pools Roughened Channel



Lowest Potential Profile Elevation at End of Anticipated Scour Pool

End of Chute

Chute

Pool

Chute

Low and High Potential Profiles

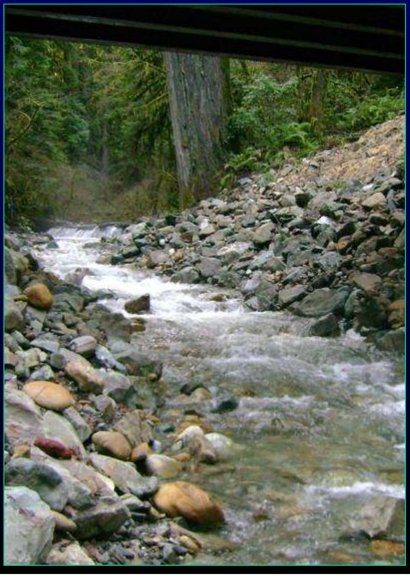
Anticipated Length of Self-Forming Scour Pool

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)



Developing the Channel Design and Bed Mixture

The **Iterative** Design Process

1. Establish stable bed flow (Qbed) & fish passage flows
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
   - Calculate Unit Discharge for channel
   - Calculate a stable D84
4. Evaluate fish passage conditions

   If unsuitable, change channel shape/slope and repeat no. 2-4
5. Develop rock placement plan
6. Model hydraulics in 1D, 2D, or 2D with rocks in DEM
7. Evaluate hydraulics for fish passage and overall stability

---

Estimating Hydraulic Roughness

Flow resistance for steep mountain streams:

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

Manning's roughness

Hydraulic Radius

Water Depth

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

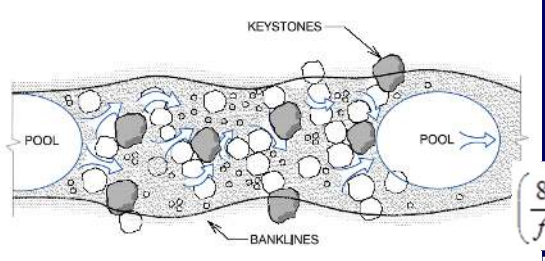
84% of bed material finer than D_{84}

Darcy Friction Factor

Numerous relationships developed with varying limitations.

See Appendix B in CDFG Part XII for more relationships.

Importance of Depth Variable Roughened



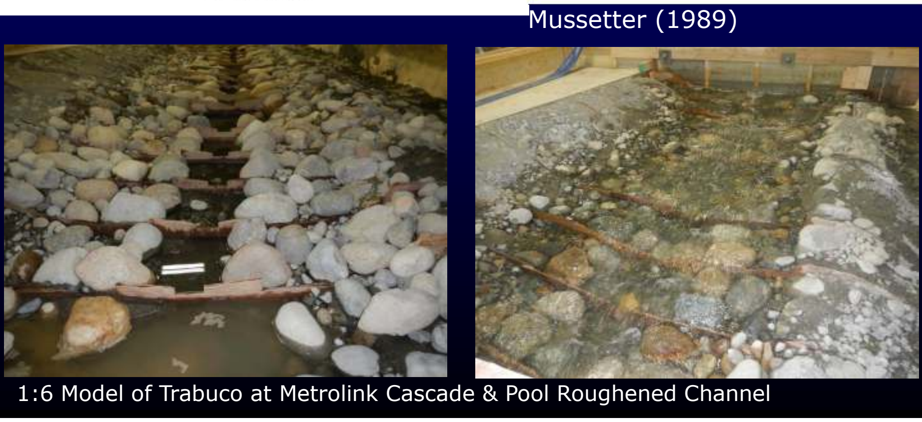
Relative Roughness is Key to Fishway Performance

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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Importance of Depth Variable Roughened

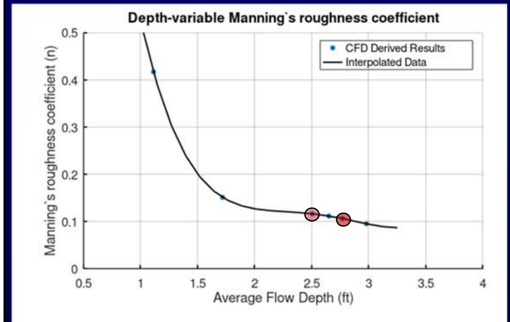
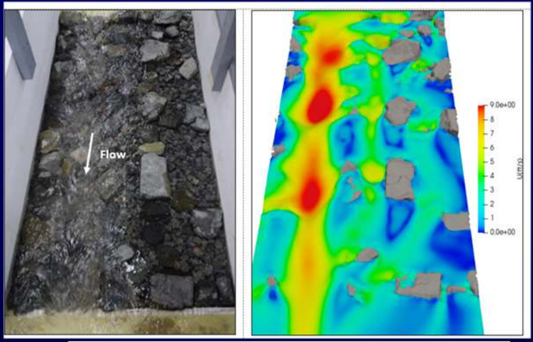
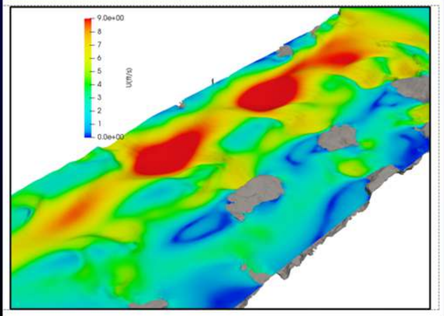


Figure 2-1. Depth-variable Manning`s roughness coefficient.

Manning's calculated using
Design Channel Section
(no protruding boulders)

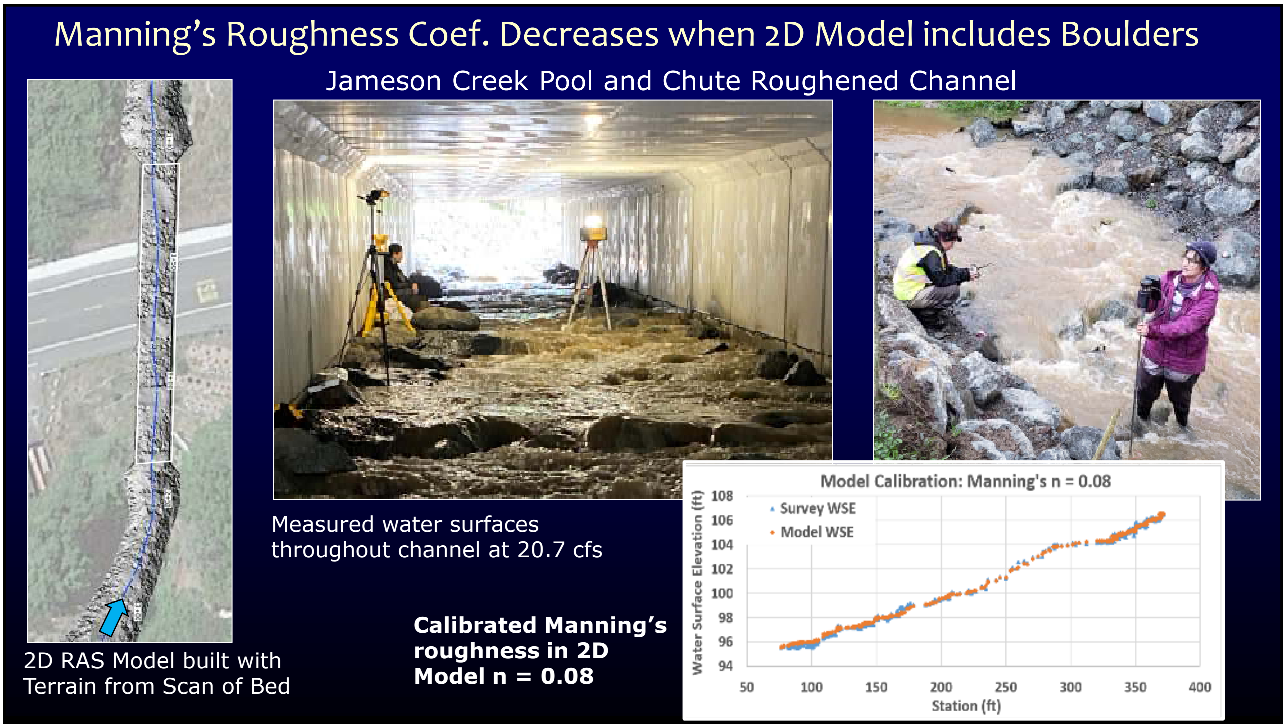


64 cfs
Ave. Depth = 2.5 ft
Mannings n = 0.120



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

*from Trabuco at I-5 Physical
and CFD Modeling (NHC, 2021)*



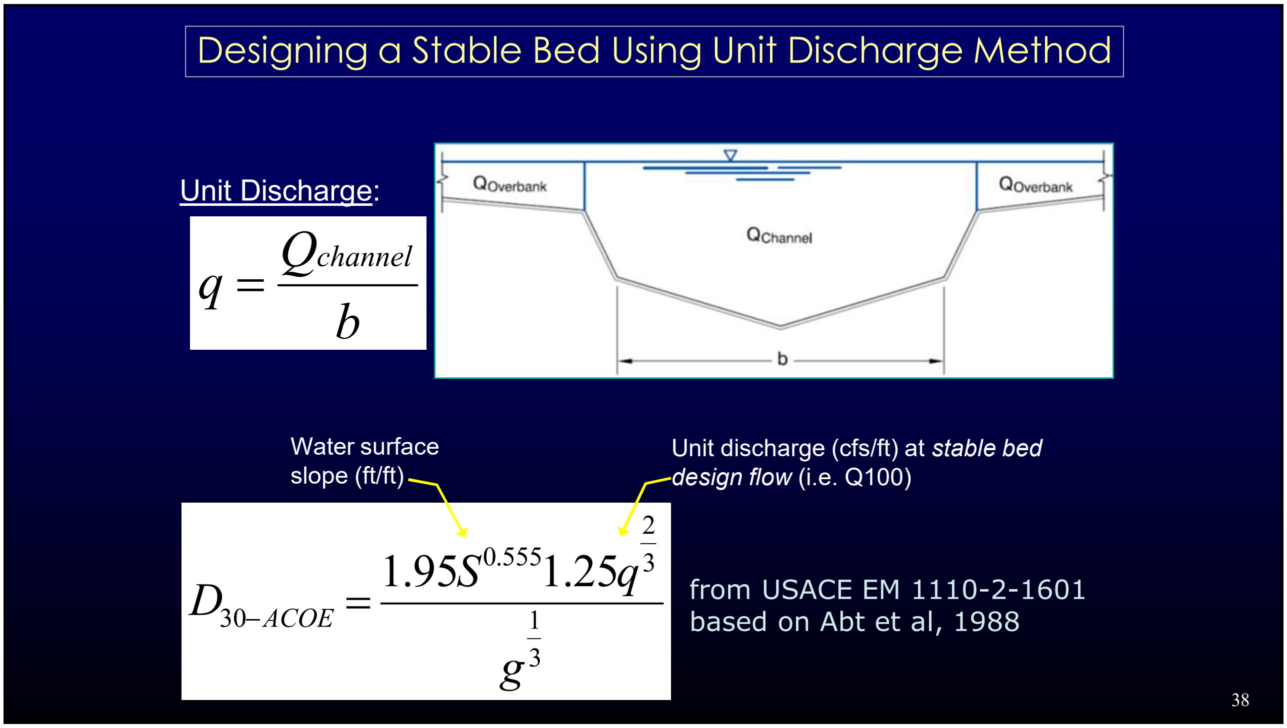
Manning's Roughness Coef. Decreases when 2D Model includes Boulders

Jameson Creek Pool and Chute Roughened Channel

2D RAS Model built with
Terrain from Scan of Bed

Measured water surfaces
throughout channel at 20.7 cfs

Calibrated Manning's roughness in 2D Model n = 0.08



Designing a Stable Bed Using Unit Discharge Method

Unit Discharge:

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

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

Developing Gradation of Bed Material

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

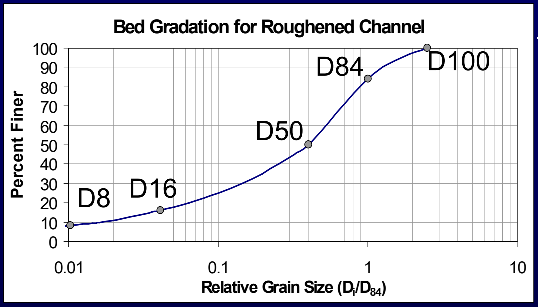
$D84/D15 = 1.7$ to 2.7

Natural channel streambed material has wide gradation:

$D84/D15 = 8$ to 14 (typical in steeper streams)

- Larger Material ($\geq$D50) is framework for stability
- Smaller material (<D50) fills voids to control porosity

Developing Engineered Streambed Material (ESM)



Gradation Shift for ESM:

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

(from WDFW, 2013)

For $D_i \geq D50_{ESM}$ use Ratios Relative to D84:

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

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

(from WDFW, 2003)

Sometimes produces oversized rock, may be reduce to 1.5D84

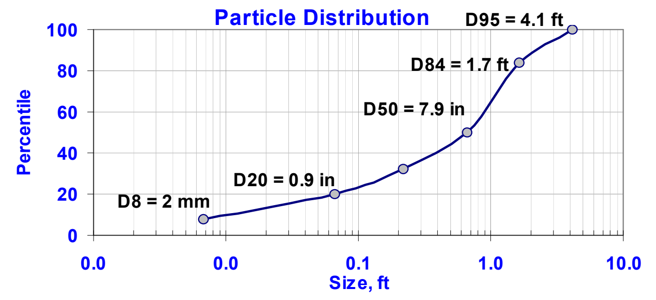
For $D_i < D50_{ESM}$ use Fuller-Thompson Equation:

$$D_i = (2 \cdot i)^{1/n} D_{50}$$

n ranged from 0.45 to 0.70

Set n to achieve D8 $\simeq$ 2mm

Sizing and Specifying Material Gradations



Example Specifications for Gradation of ESM

Percent of Mix	Range of Size (Intermediate Axis)	
16	18 in	2 in
34	6 in	23 in
18	3 in	9 in
12	1/8 in	2 in
8	Passes Sieve #10 (2 mm)	

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

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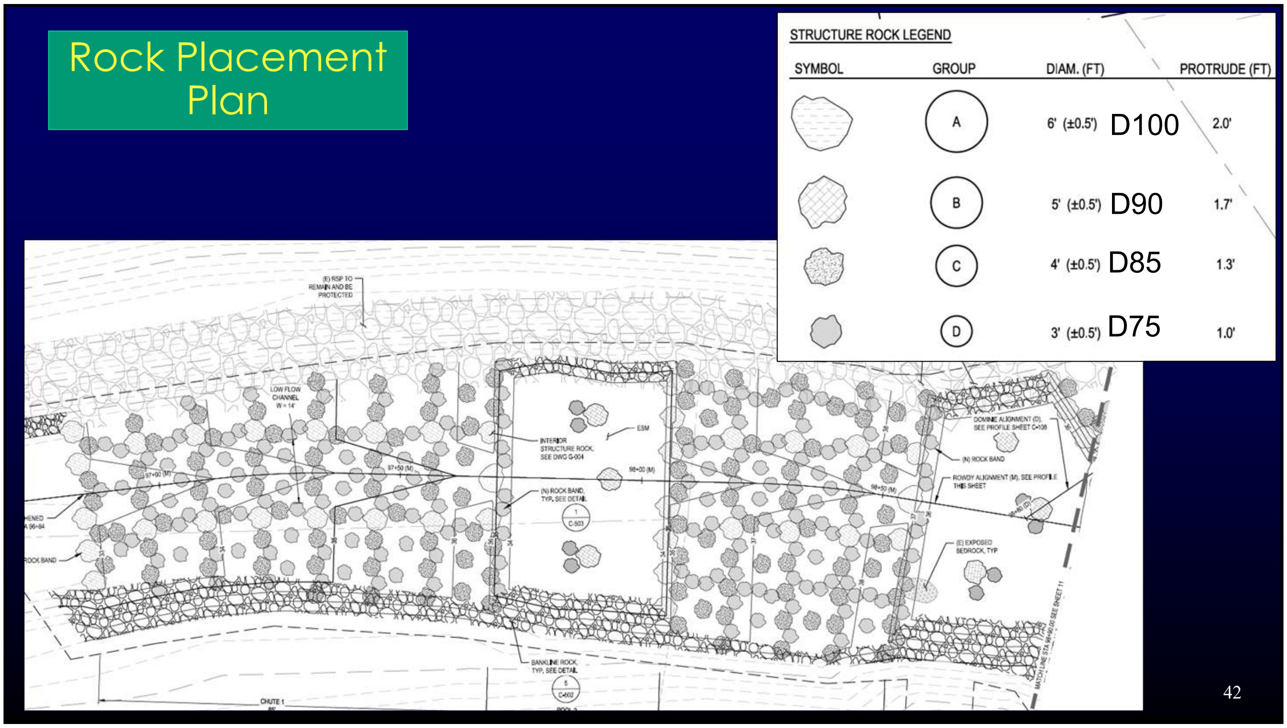
Rock Placement Plan



STRUCTURE ROCK LEGEND

SYMBOL	GROUP	DIAM. (FT)	PROTRUDE (FT)
	A	6' (±0.5') D100	2.0'
	B	5' (±0.5') D90	1.7'
	C	4' (±0.5') D85	1.3'
	D	3' (±0.5') D75	1.0'

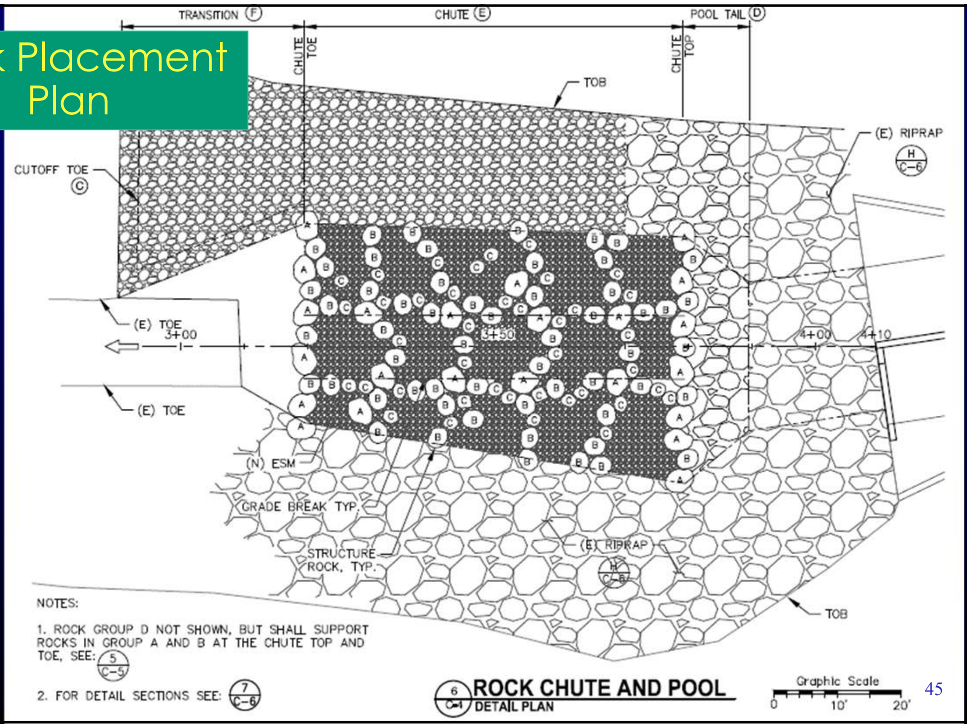
Rock Placement Plan Implemented

Rock Placement Plan Implemented

Winter Baseflow

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

Rock Placement Plan

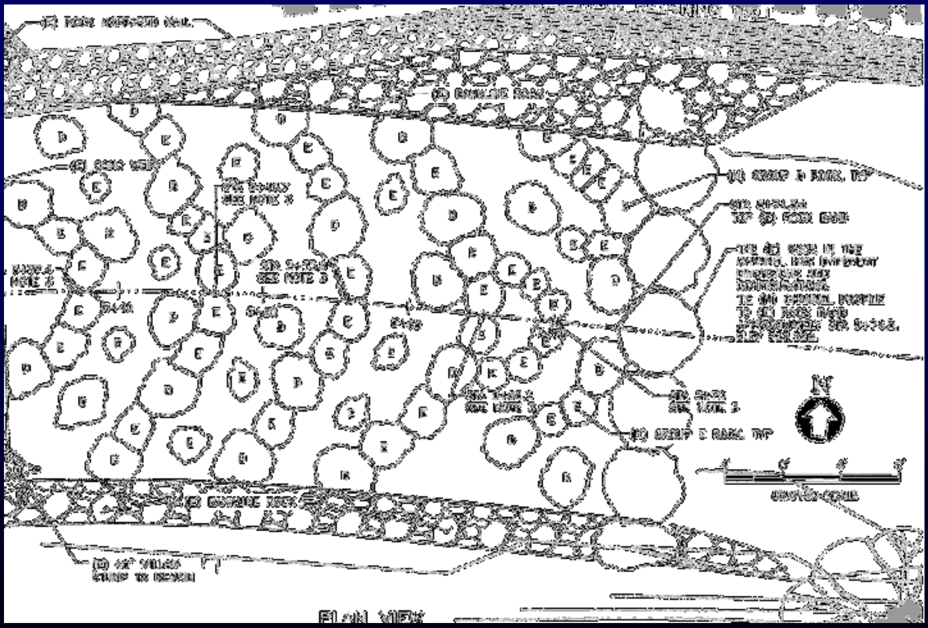


NOTES:

1. ROCK GROUP D NOT SHOWN, BUT SHALL SUPPORT ROCKS IN GROUP A AND B AT THE CHUTE TOP AND TOE, SEE: 5 C-5
2. FOR DETAIL SECTIONS SEE: 7 C-6

Rock Placement Plan Implemented

Rock Placement Plan



Rock Placement Plan Implemented

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)

Modeling Hydraulics with and without Boulders in DEM

Design DEM (chutes and pools with no boulders)

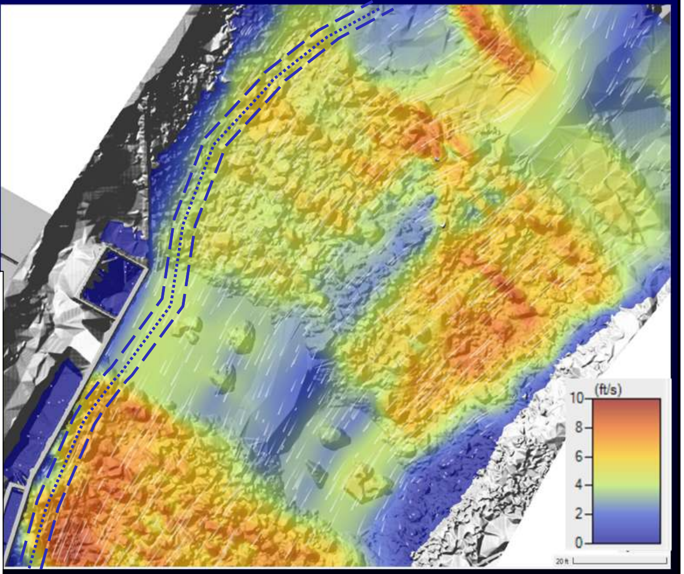
As-Built DEM from Scan

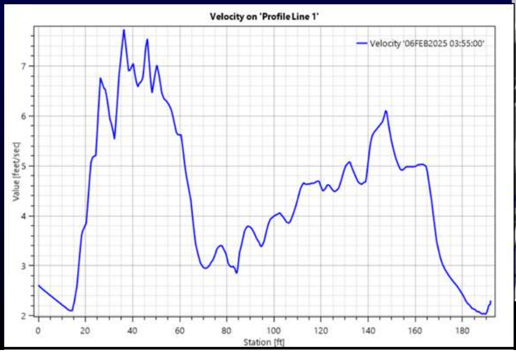
As-Built Fish Passage Flow

Adding Structure Rocks to DEM for 2D Hydraulic Modeling

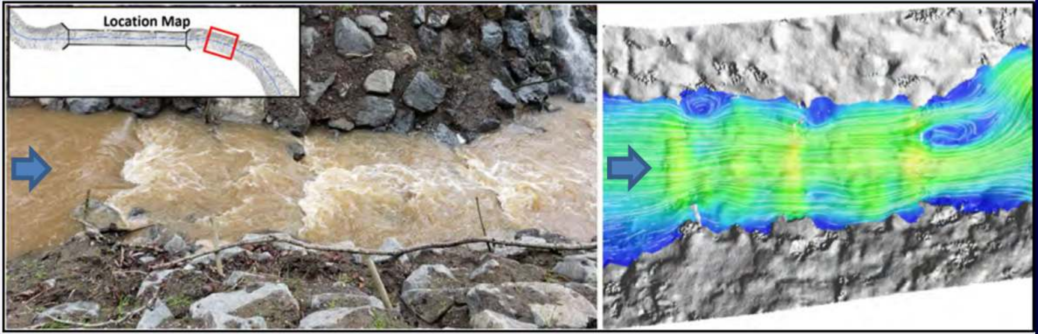
Considering Analyzing Passage Hydraulics through assumed “Passage Corridors”:

- 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)





Adding Structure Rocks to DEM for 2D Hydraulic Modeling

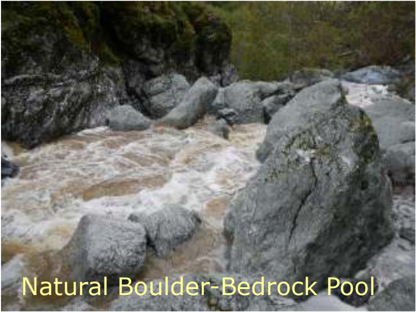


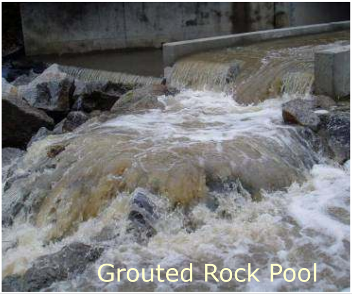
DEM = Digital Elevation Model

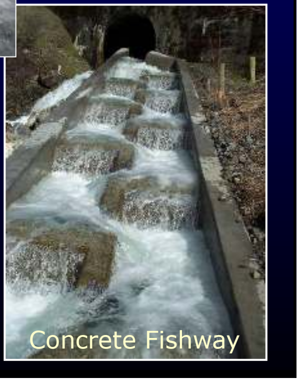
HEC-RAS 2D model velocities using DEM from 3D Scan of constructed Rock Chutes

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

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

$$EDF = \gamma QS/A$$

Hydraulic Diversity in Chutes results in much higher EDF threshold

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

Turbulence in Rock Ramps/Chutes and Cascades

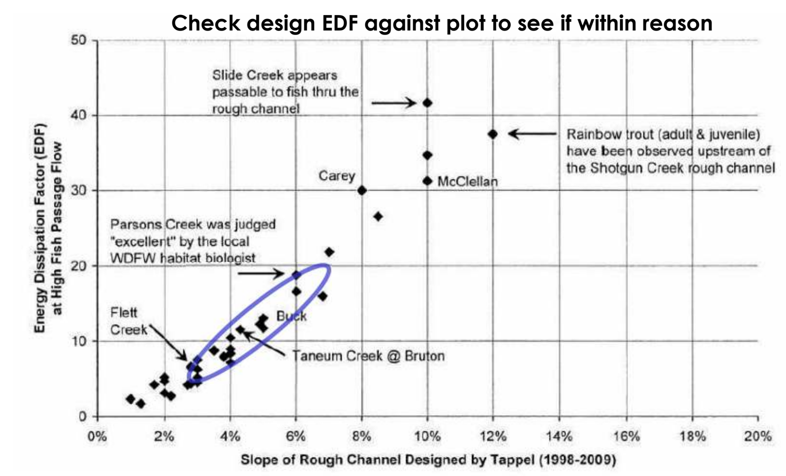

Check design EDF against plot to see if within reason

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

Construction Sequencing and Methods

2. Placing Rock Structures

Construction Sequencing and Methods

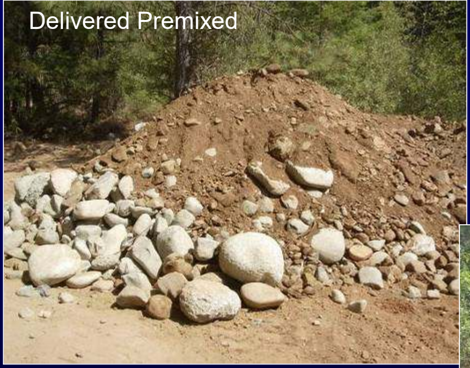
1. Grading and Compact Subgrade

2. Keystones and Bankline Rock

Construction Sequencing and Methods

3. Stockpile ESM onsite. Within a small section of channel, place material in correct proportions and mix with excavator bucket ...

Construction Sequencing and Methods



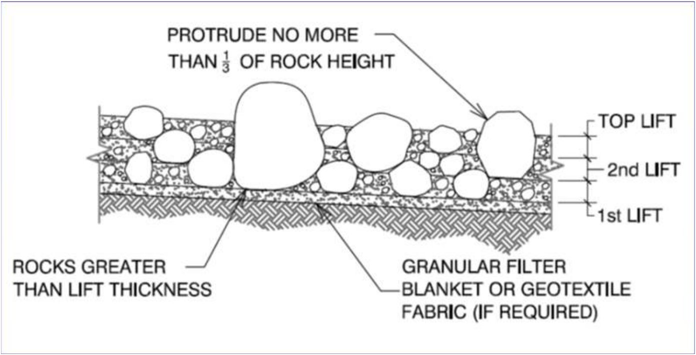
4. ...If delivered premixed to site, must be remixed in channel due to settling in truck.

5. Install Engineered Streambed Material (ESM)…

Construction Sequencing and Methods

5. ...Place Structure Rocks into Lifts.

Construction Sequencing and Methods

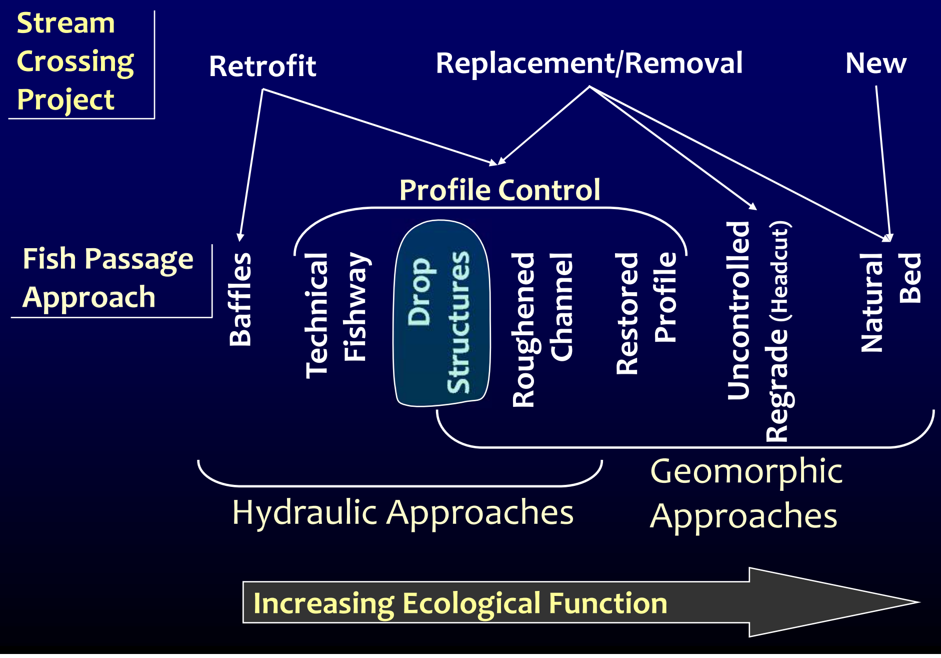


5. ..Construct channel bed in lifts. Compact each lift…

Construction Sequencing and Methods

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

Design Approaches for Aquatic Organism Passage

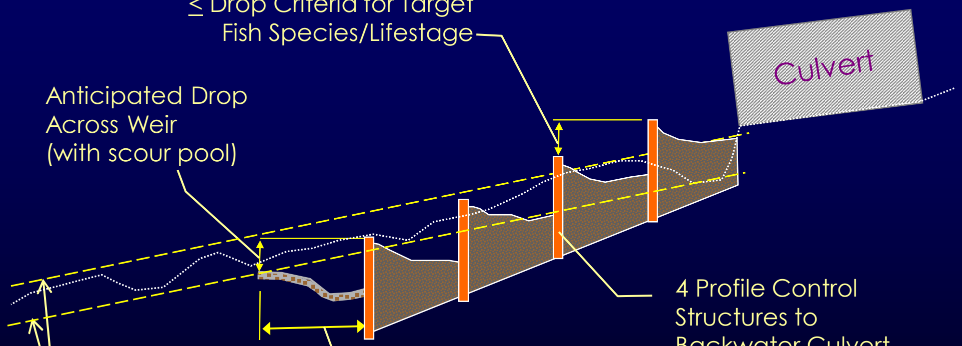


Forced Profiles with Drop Structures

Drop Structures (weirs, sills, chutes):

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

Profile Control Transitions (Steps or Drop Structures)



≤ Drop Criteria for Target Fish Species/Lifestage

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

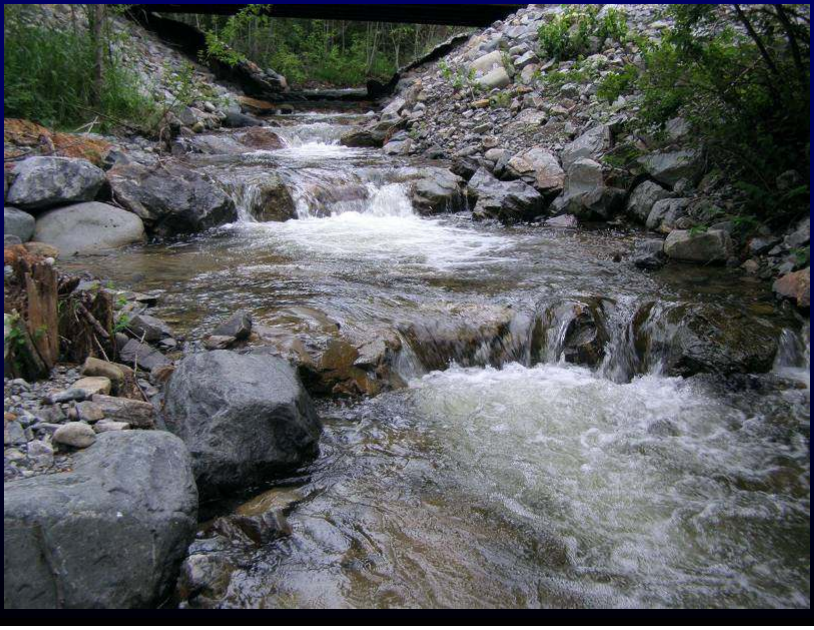
❖ Place End of Profile Control based on Low Potential Profile with Anticipated Scour Pool

---

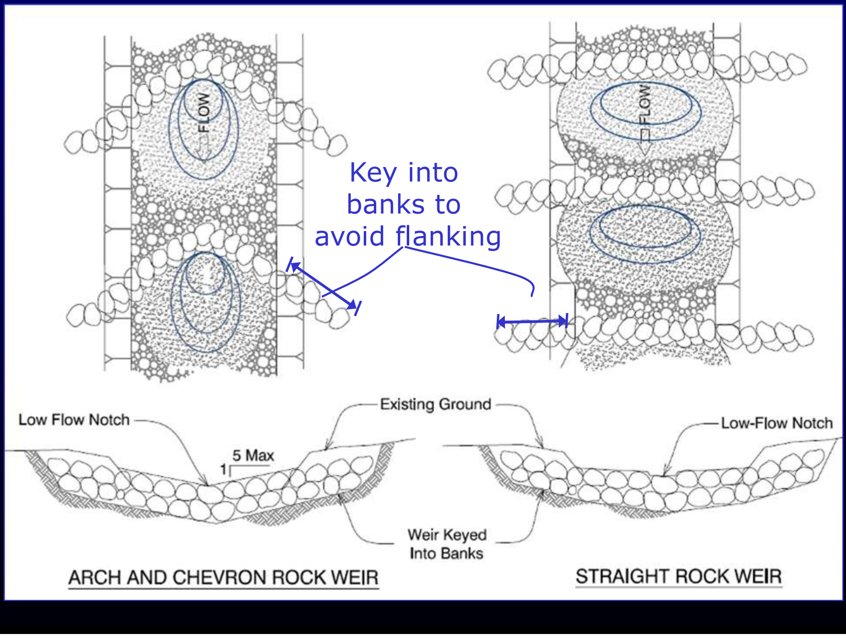
Rock Weirs & Chutes

- 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

Arch Shaped Rock Weirs

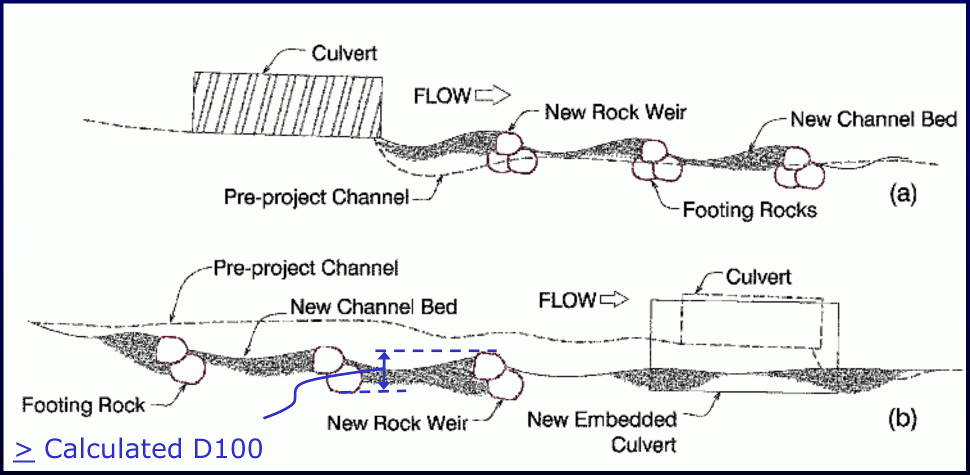


Shape of Rock Weirs



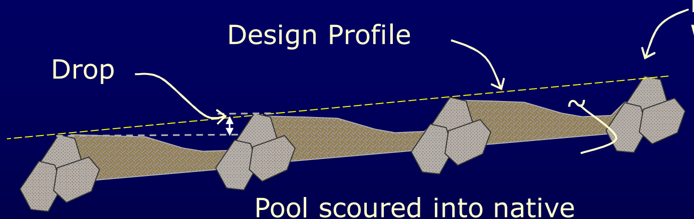
Key into banks to avoid flanking

Footing of Rock Weirs



≥ Calculated D100

Spacing of Rock Weirs

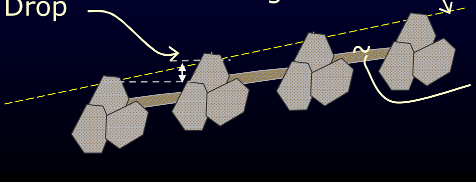


Design Profile

Rock Weir

Drop

Pool scoured into native streambed material



Oversteepened Design Profile

Drop

Small Pools, poor sealing, unstable rock

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)

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

Riffles and Chutes

Spring Prairie Cr
Cobble riffle

From Luther Aadland

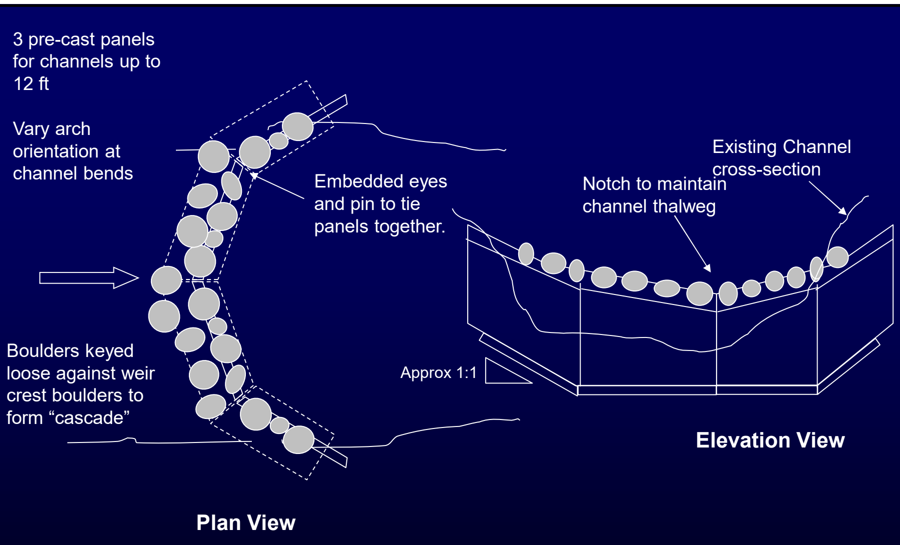
Rock Riffles and Chutes

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

From: Kozmo Bates



3 pre-cast panels for channels up to 12 ft

Vary arch orientation at channel bends

Embedded eyes and pin to tie panels together.

Boulders keyed loose against weir crest boulders to form “cascade”

Existing Channel cross-section

Notch to maintain channel thalweg

Approx 1:1

Elevation View

Plan View

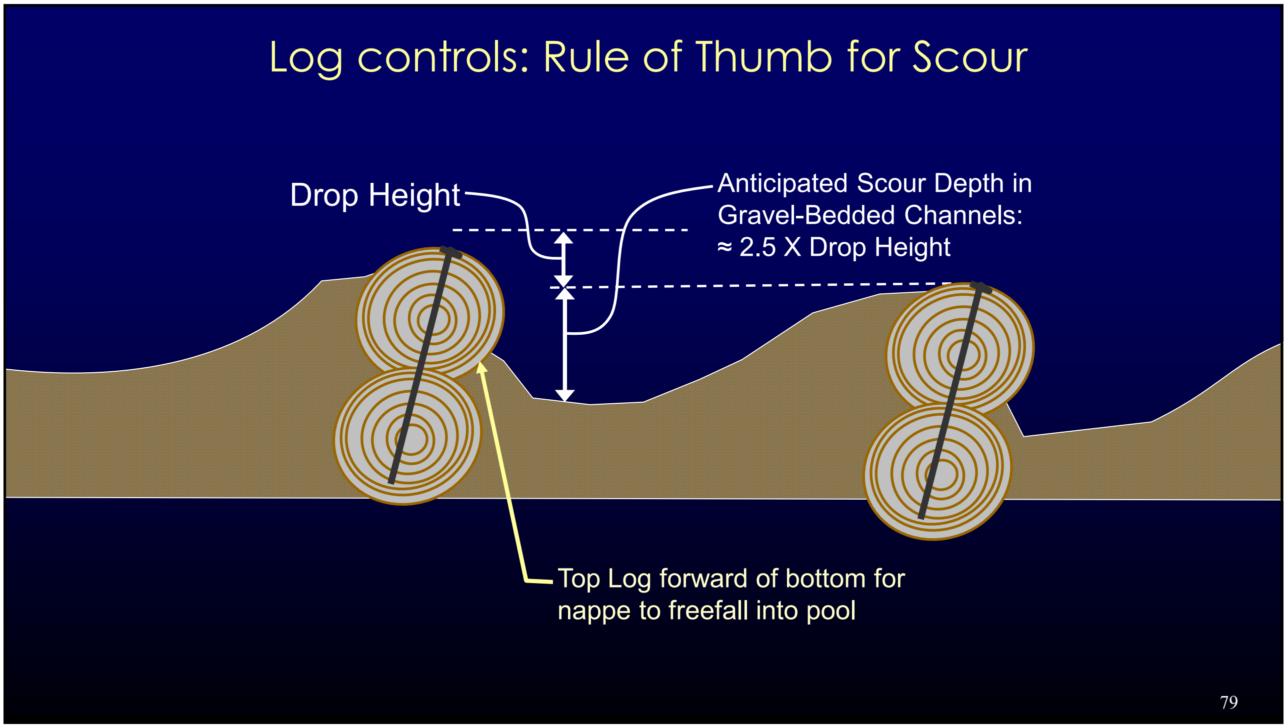
Modular Arch Drop Structure

From: Kozmo Bates

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

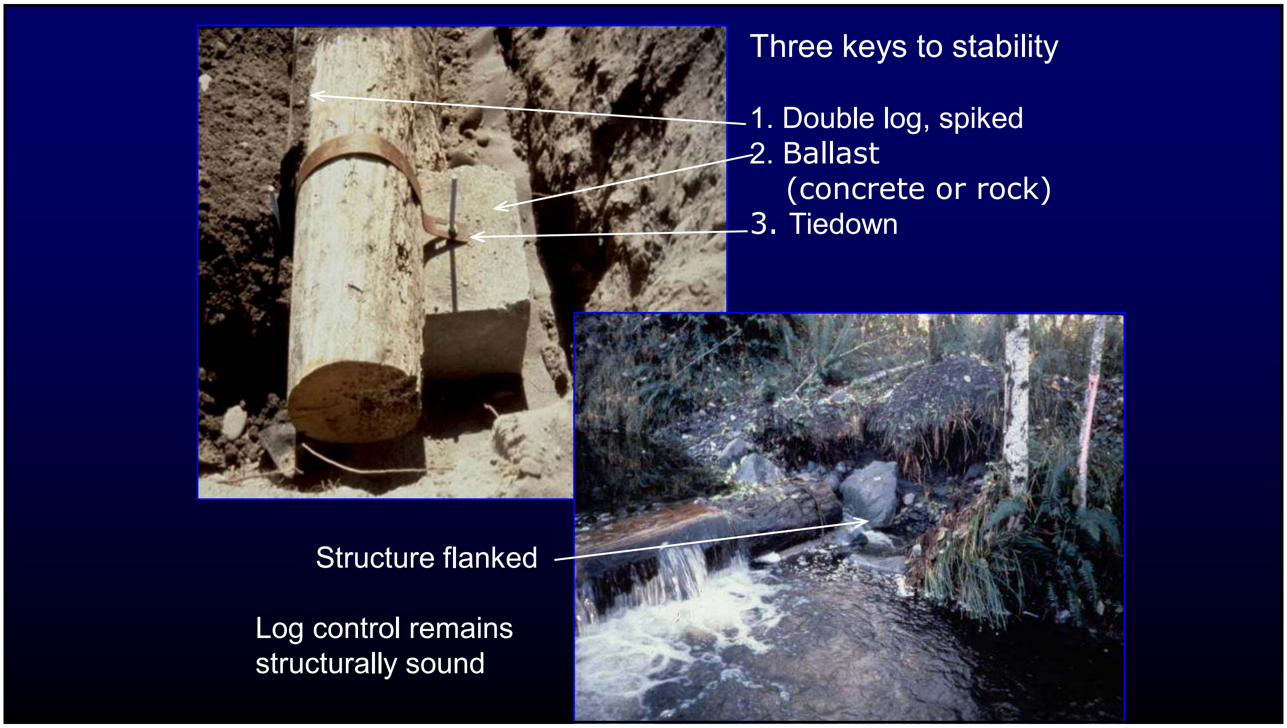


Log controls: Rule of Thumb for Scour

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



Three keys to stability

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

Structure flanked

Log control remains
structurally sound

Log controls

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

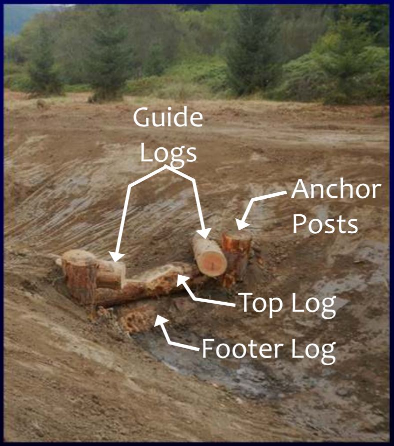
Natural Log Steps

Training logs along
bank confine flow

Complex Log Steps

Index Creek
Vee log weirs

Complex Log Steps



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

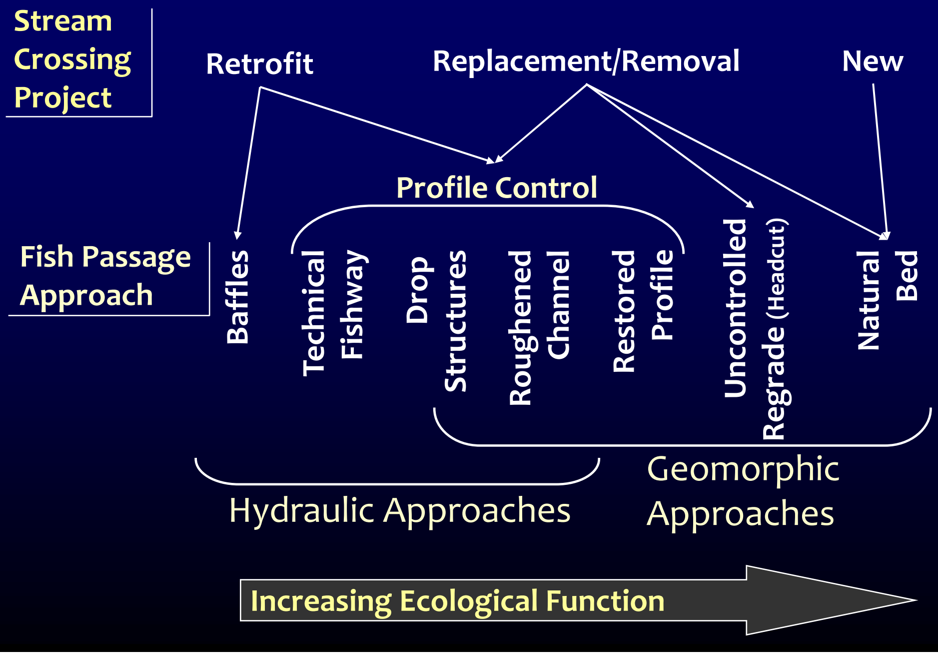
Complex Log Steps

No Rock Used

Log controls

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

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