Stream Simulation Design

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What is stream simulation?

- Geomorphic design
- Simulate natural channel reference reach
  - Bankfull cross section shape and dimensions
  - Channel slope
  - Channel structure
    - Channel type
    - Mobility – Process, not just structure.

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Stream Simulation Design Process

Assessment
Stream simulation feasibility
↓
Verify reference reach
↓
Bed shape and material
↓
Structure width, elevation, details
↓
Mobility / stability
↓
Design profile control →
↓
Final design

- Watershed, Road
- Site assessment
- Physical survey
- Continuity

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Assess >>

Some things stream simulation does not do within the culvert

- Riparian function
  - Natural bankline – cohesive soil, root structure
  - Food production
  - Flood refuge
  - Passage of terrestrial species?
- Light
- Lateral channel and floodplain processes
- Channel-scale roughness (bends, debris jams, …)

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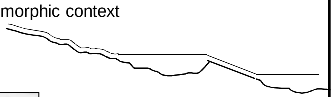
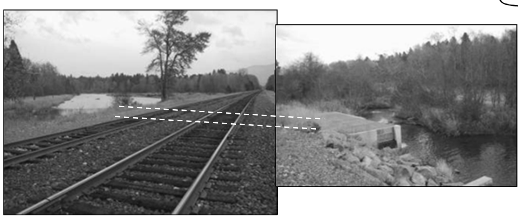
Road Impounded Wetlands

- Continuity of channel – geomorphic context
- Other culverts might apply





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Stream Simulation Design Process

Assessment
Stream simulation feasibility
↓
Verify reference reach
↓
Bed shape and material
↓
Structure width, elevation, details
↓
Mobility / stability
↓
Design profile control
↓
Final design

- Reference reach is simulated
- Template for dimensions, slope, bed, features
- Continuity with reference reach

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Selection of Reference Reach

- Represents project channel
  - Primarily selected by project gradient
  - Consider confinement of project
  - Length of project reach
- Nearby, adjacent, upstream?
  - Provides “input” to stream simulation
  - Must be “connected” to crossing reach
  - Out of the influence of existing crossing

Stream Simulation Design Process

Assessment
Stream simulation feasibility
↓
Verify reference reach
↓
Bed shape and material
↓
Structure width, elevation, details
↓
Mobility / stability
↓
Design profile control
↓
Final design

- Project objective
- Simulate reference channel bed material
- Margins, banklines, forcing features
- Bed forms, shape

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Bed Design Objectives

- Simulate natural bed
  - Bed shapes
  - Diversity
  - Roughness
  - Mobility
  - Forcing features
  - Control of permeability

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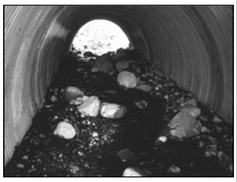
Bed Design by M&B* Channel Types

Increasing slope
Decreasing mobility

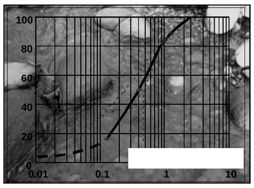
Based on channel type of reference reach
- Dune-ripple; construct or recruit
- Pool-riffle / Plane-bed; construct and let form develop
- Step-pool, forced channels; construct steps
- Cascades; construct
- Bedrock
- Clay



* Montgomery and Buffington, 1997

Bed Material Design – Alluvial

- New installations: use undisturbed channel (consider contraction)
- Replacements: use reference reach gradation.
  - Pebble count of reference channel for D_{100}, D_{84} and D_{50}
  - Include dense gradation based on D50 for smaller material and impermeability.
  - Fine-grained beds are special cases.
  - Compensate for stability of initial disturbed condition.
  - Account for large roughness and forcing features.

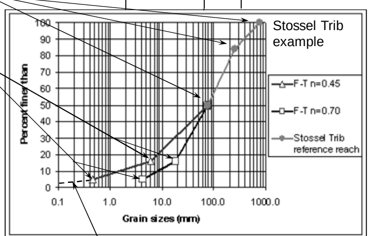


Bed Material Design – Alluvial

Larger particles sized directly from reference channel

Small grains derived by Fuller-Thompson curve based on D_{50}

sand | gravel | cbl | boulder



Verify 5% fines are included

Fuller-Thompson

$$P = \left[\frac{d}{D_{100}}\right]^n$$

P = percent finer
d = diameter of particle
n = Fuller-Thompson density; varies 0.45 to 0.70

Simplify to:
$D16 = 0.32^{1/n} \times D50$
$D5 = 0.10^{1/n} \times D50$

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Bed Material Example
W Fk Stossel Cr

	Reference	Strm Sim	Fuller-Thompson n=0.7	
D100	30”	30”		
D84	10”	10”		
D50	3”	3”	3”	
D16			0.59”	= $0.32^{1/n}$ x D50
D5			0.11”	= $0.10^{1/n}$ x D50
Fines		5-10%		

Which is:
50% cobble and boulder
34% gravel
16% medium gravel and fines

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Bed Material Example

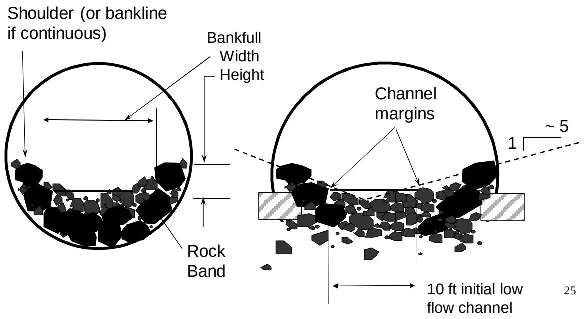
W Fk Stossel Cr – 6.4% slope

- 1 scoop bank run dirt
- 4 scoops 4” minus pit run
- 4 scoops 8” minus cobbles (or quarry spalls)
- 2 scoops 1.5’ minus rock
- 1.5 to 2.5 foot rock added during installation

Special Considerations

- Bedform diversity
- Bed permeability
- Channel cross-section
- Banklines
- Key features
- Small-grain beds

Stream Simulation Bed
Channel cross-section



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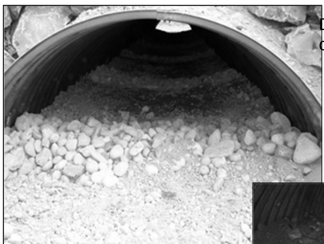
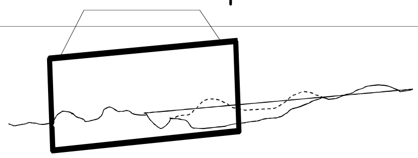


Darby Ck. rock bands just after construction

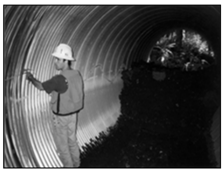
Darby Ck. rock band during first flood. Band has altered; flow is centered.

Steps



Step pool channel

“Set up” step pools and forcing features



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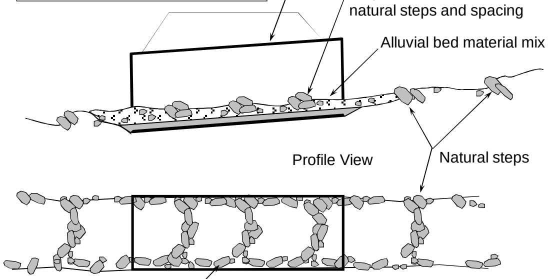
Steps



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Hydraulic, Bank diversity

Ore Creek, Oregon

From USFS, 2006

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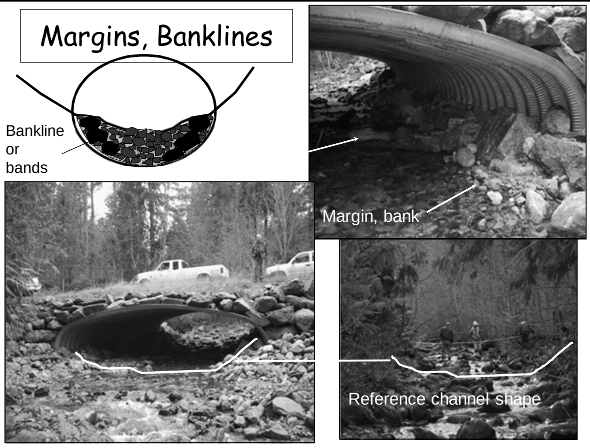
Margins, Banklines



Banks and key pieces

- Key pieces are likely permanent
  - Stability analysis
    - Particle entrainment equations
    - Or bank protection design

Blue Creek
Lolo Nat'l Forest

Bed material example design and spec
W Fk Stossel Cr

	Reference	Design
D95	30”	30”
D84	10”	10”
D50	3”	3”
D16	?	0.6”
D5	sand	0.1”
Fines		5-10%
Colluvium, debris	Spanning 6-12” debris at 50’ spacing	24” rock scattered at 15’ oc throughout
Banklines	Bankline root structure protrudes 3’ at 25’ spacing	36” bankline rock at 25’ spacing or continuous each bank

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Last thoughts on bed material

- Mobility is a key to design of bed
- No good spec or source for fine-grained bed other than the channel itself
- Carefully select and supervise source, mixing, and placement
- Mitigate the mess
- Round vs angular rock?
- Does it meet project objective?

Stream Simulation Design Process

Assessment
Stream simulation feasibility
↓
Verify reference reach
↓
Bed shape and material
↓
Structure width, elevation, details
↓
Mobility / stability
↓
Design profile control →

- Profile range
- Sustainability
- Floodplain function, connectivity
- Safety factor

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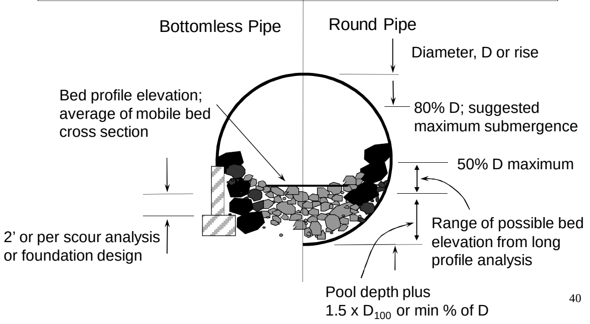
Culvert Rise, Elevation



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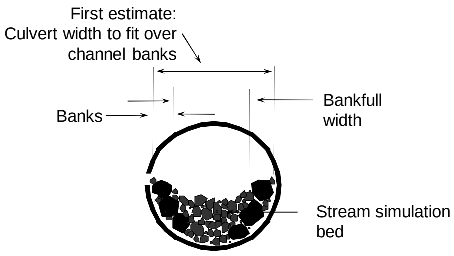
Stream Simulation
First estimate of culvert width



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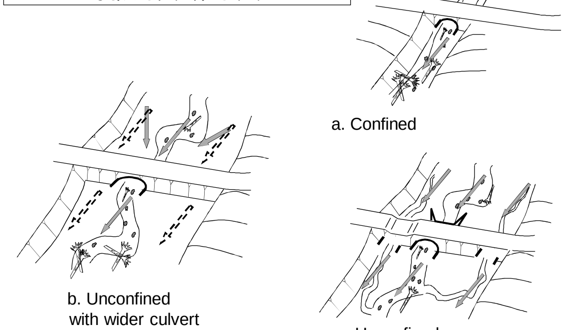
Culvert Size
1. Based on Project Objectives:

- Passage of aquatic, non-aquatic species
- Bed sustainability and stability
- Hydraulic capacity of the culvert
- Risk of blockage by floating debris or beaver activity
- Construction, repair, and maintenance needs
- Meandering channel pattern part of project objectives
- Protection of floodplain habitats

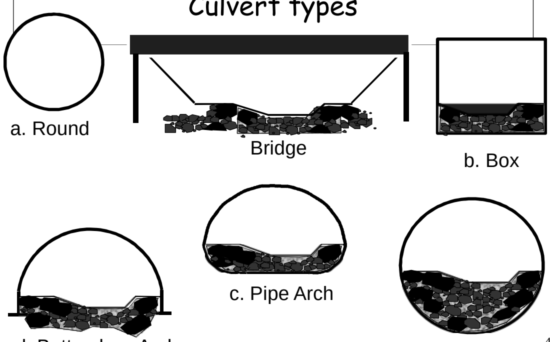
Culvert Size
2. Based on Site Conditions:

- Expected future channel width, location
- Channel skew with road crossing
- Ice plugging in severe cold climate
- Large bed material relative to culvert width

Stream Simulation culvert width

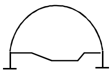


Culvert types



Bottomless compared to pipe

Bottomless



- + Can be placed over existing streambed or top loaded
- + Can be placed over bedrock
- + Footings can be shaped to bedrock.
- + Concrete stemwall provides durability against abrasion, corrosion, construction damage
- - Construction duration increased by cast-in-place concrete
- + High shear strength of bed reduces risk of bed failure
- + Compaction easier without round shape

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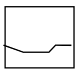
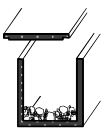
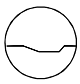
Pipe compared to bottomless

Pipe





- + Pre-assembled pipe greatly reduces time for construction
- + Structure not vulnerable to scour and headcut
- + No measures needed to protect stream from fresh concrete
- + Less costly and complex construction and less risk of error because no concrete footing
- + Shape may allow narrower excavation
- + Higher load capacity in poor foundation soils



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Yikes!

Not necessarily better just because it's a bridge.

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Stream Simulation Design Process

Assessment
Stream simulation feasibility
↓
Verify reference reach
↓
Bed shape
and material
↓
Structure width,
elevation, details
↓
Mobility / stability
↓
Design profile control
↓
Final design

- Failure modes
- Sustainability of stream simulation (mobility)
- Stability of key pieces
- Culvert capacity (regardless of design method)

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Mobility / Stability Analysis
Three purposes

Mobility
1. Is channel shape and bed material stream simulation? – project objective
   – Project objectives still satisfied?
   – Driven by moderate flood - bankfull to 50-yr flood?

Stability
2. Does bed stay in place?
   – Banklines, key pieces stable?
   – Might fail at high flows
   – Gradual chronic failure
3. Is culvert stable?
   – Extreme flows
   – Headwater, pressurized pipe
   – Debris might be a greater risk than flow
   – Diversion

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Bed Failure

Stimson Ck.
Width ratio = 1.0
Slope = 2.2% (5%)

Note regrade

Original profile

Resulting profile

Culvert too narrow, bed material too small.

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Mobility / Stability Analysis - Process

- Compare design reach to reference reach
- Establish design assumptions
  - Design of D_{84} mobility the same in both channels
    - D84 is important – roughness, form, mobility
    - One possible design assumption
- Calibrates analysis; therefore not sensitive to hydrology
- Analyze key pieces at high stability design flow
- Is it real?
  - Test sensitivity of parameters and compare alternatives.
  - Compare results to reference channel.
  - Is it a natural conclusion or are you forcing the channel?
  - Stream simulation? ⟷ Roughened channel?

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Risks and Design/construction strategies

Risk	Design/construction strategy
All culverts	
Debris blockage, flows	• Limit headwater depth • Efficient upstream transition
Stream diversion	• Build sag in road • Design for plugging, failure
Stream simulation culverts	
Steeper than reference reach	• Minimize slope increase • Increase bed material size * • Increase bed culvert width *
Floodplain contraction	• Larger culvert, Additional culverts * • Increase bed material size *
Lack of initial bed structure	• Compact bed • Consolidate bed • Increase bed material size
Downstream channel instability	• Verify potential profiles
Pressurized pipe	• Limit headwater depth * • Larger culvert, additional culverts *
Long culvert	Minimize length Add safety factor to stability analysis *

* = bed mobility / stability analysis required

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Unit discharge – Bathurst (1987)

- Developed in:
  - steep channels; 0.23 < S < 9.0%,
  - Course bed material; 9 < D_{84} < 280 mm
- Lab and field data
- relative submergence (water depth/D_{50}) less than 10 or less than 4 (water depth/D_{84}).

$$q_{ci} = q_{cD50}\left(\frac{D_i}{D_{50}}\right)^b$$

$$q_{cD50} = \frac{0.15 g^{0.5} D_{50}^{1.5}}{S^{1.12}}$$

Critical unit discharge for D_{50}

$$b = 1.5\left(\frac{D_{16}}{D_{84}}\right)$$

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Procedure using Bathurst

Reference channel | Stream simulation channel

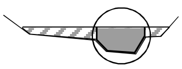
$$Q_{c84} = \left[\frac{0.15 g^{0.5} D_{50}^{1.5}}{S^{1.12}} \left(\frac{D_{84}}{D_{50}}\right)^b\right] w + Q_{FP}$$

equals

$$Q_{c84} = \left[\frac{0.15 g^{0.5} D_{50}^{1.5}}{S^{1.12}} \left(\frac{D_{84}}{D_{50}}\right)^b\right] w + Q_{FP}$$

$$b = 1.5\left(\frac{D_{16}}{D_{84}}\right) \qquad b = 1.5\left(\frac{D_{16}}{D_{84}}\right)$$

Q_{c84} is flow in the active channel



>> Exmpl H

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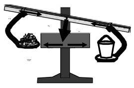
Schafer Cr trib

Stream Simulation bed by Bathurst critical unit discharge



Reference channel | **Stream sim channel**

$$Q_{c84} = \left[\frac{0.15 g^{0.5} D_{50}^{1.5}}{S^{1.12}} \left(\frac{D_{84}}{D_{50}}\right)^b\right] w + Q_{FP} \quad \textbf{equals} \quad Q_{c84} = \left[\frac{0.15 g^{0.5} D_{50}^{1.5}}{S^{1.12}} \left(\frac{D_{84}}{D_{50}}\right)^b\right] w + Q_{FP}$$

$$b = 1.5\left[\frac{D_{16}}{D_{84}}\right] \qquad b = 1.5\left[\frac{D_{16}}{D_{84}}\right]$$

Reference channel:

Given	D95	200	mm
	D84	160	mm
	D50	85	mm
	D16	10	mm
	S	1.3	%
	w	6.1	m active channel width
	Qfp	0	cms active floodplain flow
	g	9.8	m/s/s
Compare	Q	9.76	cms

Stream sim channel:

	Initial est		Multiplier	Resulting	
D95	200	mm	1.25	250	mm
D84	160	mm		200	mm
D50	85	mm		106	mm
D16	10	mm		13	mm
S	1.9	%			
w	6.4	m active channel width			
Qfp	0	cms active floodplain flow			
g	9.8	m/s/s			
Q	9.35	cms			

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ScAnalysis >>

Key Pieces - Stability Analysis

- Key pieces are permanent (up to stability design flow)
- What is stability design flow?
- Stability models - analytical
  - Bathurst
  - Corps bank riprap
  - Corps rock chute

Culvert Capacity

- Review range of project profiles.
- Analyze capacity with the high profile.
- Consider headroom and elbow room for debris.
- Review risk of diversion.
- With debris, alignment might be more important than culvert size.
- What are consequences of failure?

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Risk consideration

Calculated design flow for specific project durations

$$P_n = 1 - \left[\frac{T_r - 1}{T_r}\right]^n$$

n = years
T_r = return interval
P = probability

Probability of occurrence (failure?)	Life of project, T_r		
	10 years	20 years	50 years
1.0%	1,000 yr	2,000 yr	5,000 yr
5.0%	200 yr	400 yr	1,000 yr
10%	100 yr	200 yr	500 yr
20%	45 yr	90 yr	225 yr
40%	20 yr	40 yr	100 yr

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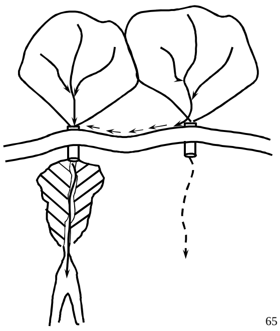
The point is …

Design conservatively.

Design for failure.



Ayers Cr trib VT

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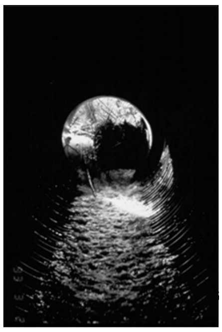
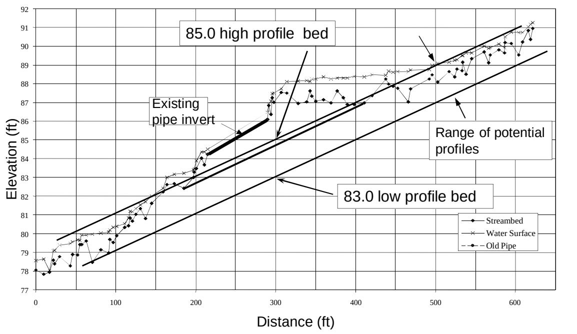
Debris

In forested watersheds, debris is often the most prevalent cause of culvert failure. Culvert alignment is a major contributor to debris-caused failures.

Solutions: Culvert width, alignment, and transition.



Culvert elevations, capacity



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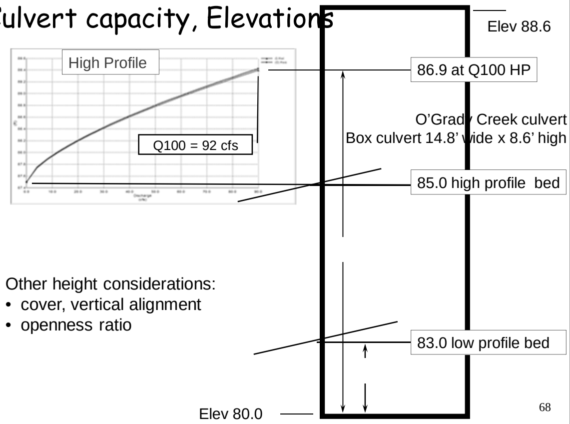
Culvert capacity, Elevations



Other height considerations:
- cover, vertical alignment
- openness ratio

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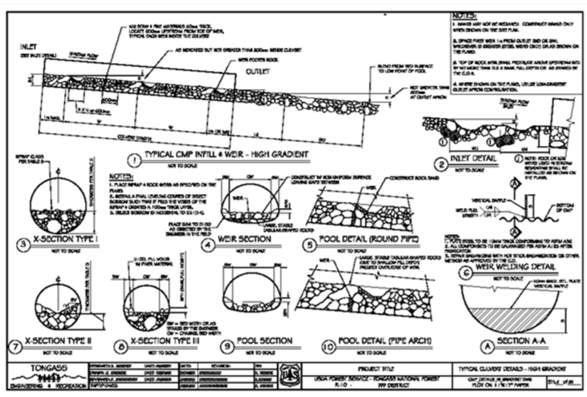
O'Grady Cr – 2002

Reference Channel
D_{84} = 52 mm
BFW = 11 ft

Stream simulation solution
- Culvert 14.8 ft w x 8.6' h
- D84 = 50 mm
- D100 = 130 mm (or by key pieces)

Is it real?

Does bed design satisfy project objective?



Bob Gubernick

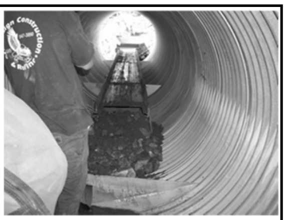
Stream Sim Construction

Standard const equip

Any problems here?

Kim Johansen, USFS

Bed Material Placement



- Dingo Loader
- Manually
- Trail equip
- Special equip

Some last thoughts on stream simulation

- It isn't this complicated. Use the tools that are appropriate.
- Check your conclusions with reality
- Might lead to roughened channel design

Bankfull width structure after 16 years

Low-Slope Design
AKA "active channel"

Pre-design → Low Slope Design → FINAL DESIGN Or other option

Low Slope Design: Intent: Cost effective design for low risk sites. Culvert width by criteria. Countersink.

Three design options - Premises

- Low-slope: The design of an oversized culvert in a low risk site can be simplified and built with little risk
- Hydraulic: A structure with appropriate hydraulic conditions will allow target species to swim through it.
- Stream Simulation: A channel that simulates characteristics of the adjacent natural channel, will present no more of a challenge to movement of organisms than the natural channel.

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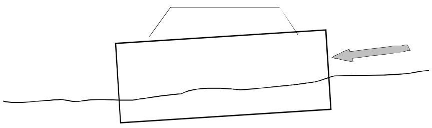
What is "low risk?"



- Low slope channel; Max slope: 1.0%
- Short culvert; Max length: 75 ft.

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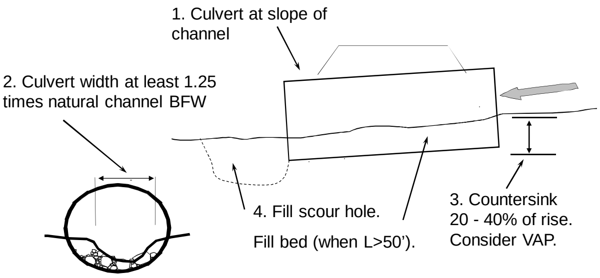
Low-slope Definition



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Low-slope option; general application

- Purpose: small, low-risk sites
- New and replacement culverts
- Simple installations; low to moderate channel slope and culvert length, moderately confined channel
- No special design expertise or survey information required for fish passage design.
- Pre-design and slope must be well understood.

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