Culvert Design for Fish and Other Aquatic Organisms

Southeast Fish and Aquatic Species
Barrier Assessment Workshop

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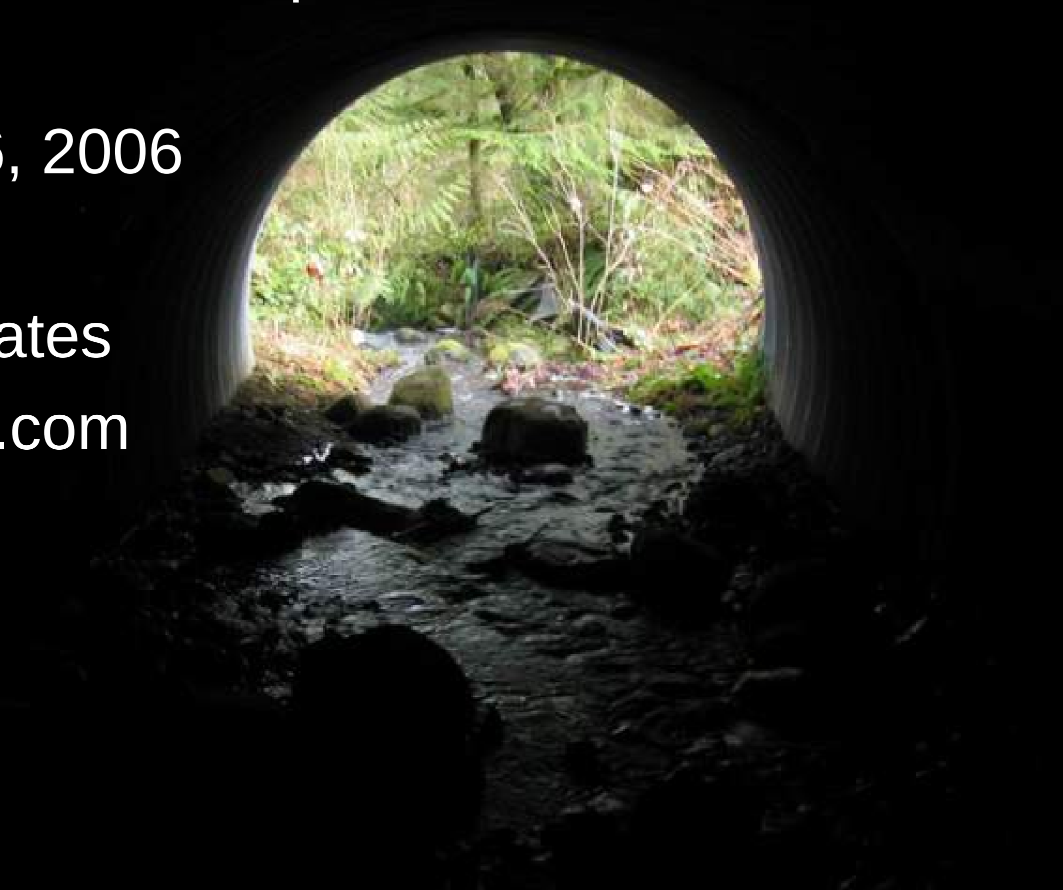
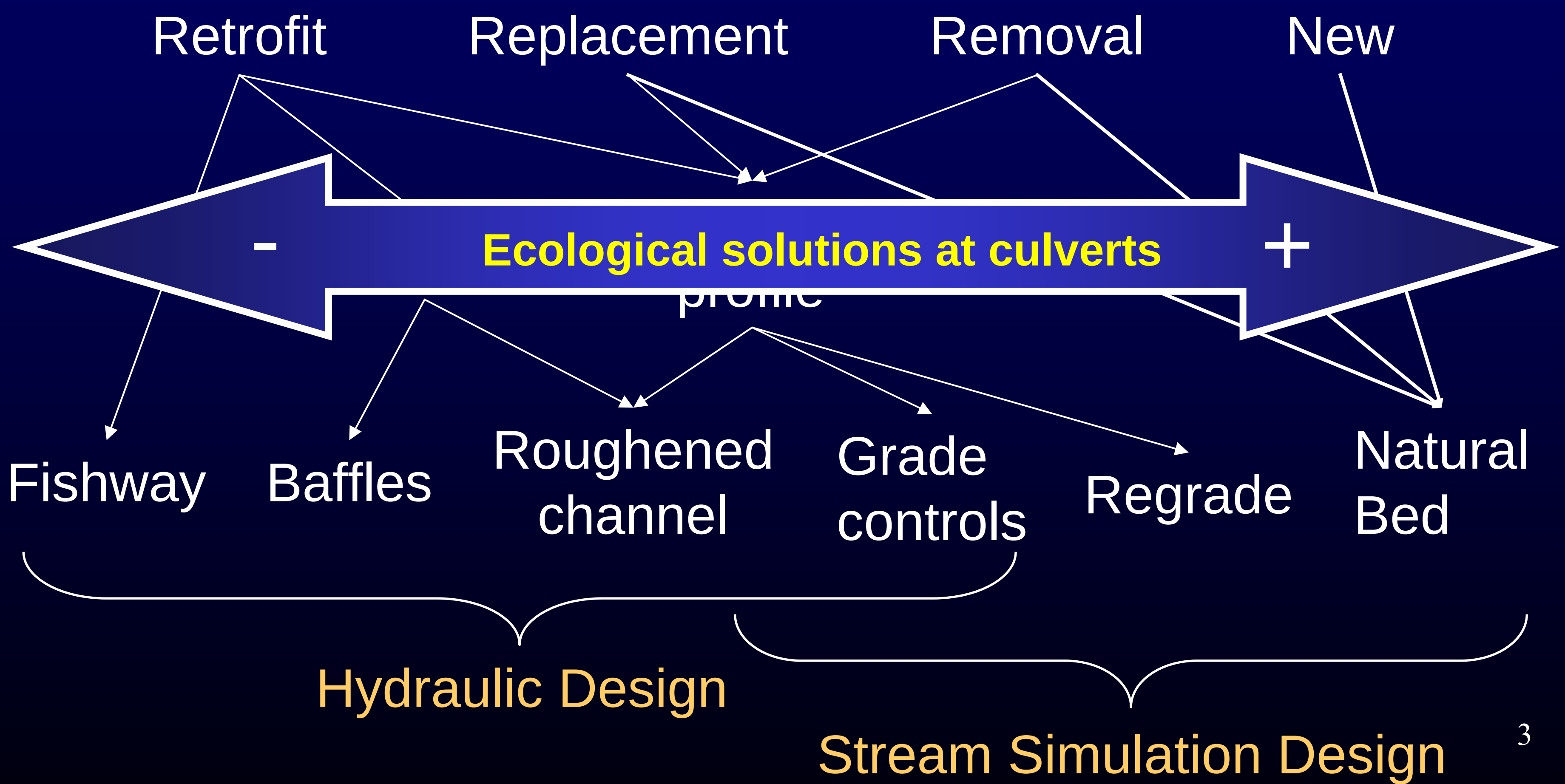


Culvert Design for ~~Fish~~ AOP Passage

- Hydraulic and Stream Simulation designs
  - Definitions, applications
- Design
  - Pre-design
    - Site context
    - Design method
  - Bed
  - Culvert
- Some examples
- How this relates to culvert assessments

Types of Culvert Design Projects and Tools



Design method determined by project objectives

- Passage of fish
- Passage of other aquatic organisms
- Habitat protection, restoration
- River and stream continuity
- Wildlife passage
- Traffic, road, safety
- Funding limits and requirements
- Regulatory

Design methods

- Hydraulic
- Stream Simulation
- No slope
- Others

Hydraulic Design

- Premise: A structure with appropriate hydraulic conditions will allow target species to swim through it.

Hydraulic Design Option

Pre-Design

Hydraulic Design

FINAL DESIGN

Or other option

Channel or Culvert length

Hydrology; fish passage design flow

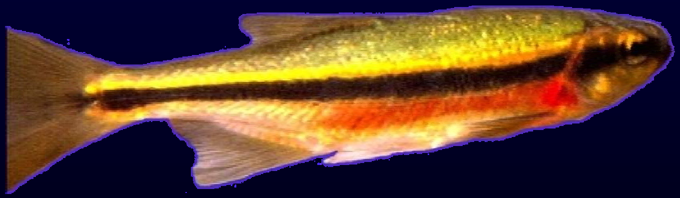
Fish; timing, ability, behavior

Maximum velocity;
Culvert size, slope, roughness

Set elevation
Countersink

Hydraulic Design Biological Parameters

- Target species; what are they?
  - Weakest fish and species of community? (Other species my limit due to timing.)
  - Migration timing?
  - Swimming ability?, behavior?
  - Default?



Hydraulic Design Biological Parameters

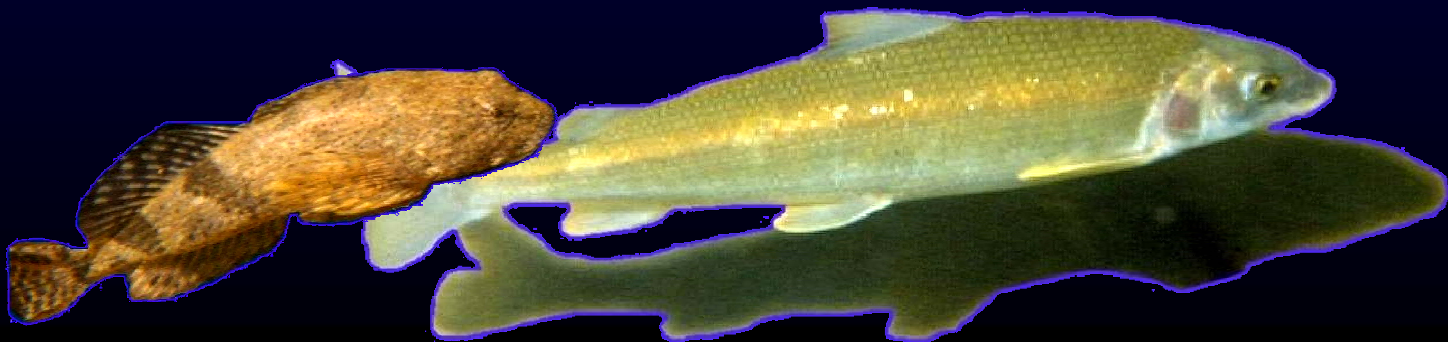
- What hydraulic conditions?
  - Velocity
  - Flow condition
    - Surface, submerged
    - Streaming, plunging
    - Turbulence
  - Occupied zone
- Minimum water depth
- Length of culvert

Example criteria:

Culvert Length, ft	Adult Trout >6in. Maximum velocity, fps
10 - 60	4
60 - 100	4
100 - 200	3
>200	2

Maximum hydraulic drop in fishway 0.8 ft

Minimum water depth 0.8 ft



Example: Maine DOT Criteria

- Rehabilitated culverts
  - Max Velocity based on species - Species table
    - Boundary layer acceptable
  - Depth
    - 1.5 times body depth
  - Hydrology: median flow during migration season
  - Design guide: default criteria
- New culverts
  - Reproduce hydraulic geometry of stream at BFW.

2004 Draft
http://www.maine.gov/mdot/community-programs/csd/waterbodies.php

MAINEDOT
Maine Department of Transportation

Example: Maine DOT Criteria

Species, life stage

Body thickness

Timing

Swimming speed

Basis of swim speed

Table 2. Maine Fish Species: Times of Impact and Related Data.[1]

Months / Stage/species	Body Length (inches)	Body Thickness (inches) (% body length)	Direction	Feb 1	Feb 2	Mar 1	Mar 2	Apr 1	Apr 2	May 1	May 2	Jun 1	Jun 2	Jul 1	Jul 2	Aug 1	Aug 2	Sep 1	Sep 2	Oct 1	Oct 2	Nov 1	Nov 2	Sustained Swim Speed (feet per second)	Basis of Swim Speed
adult smelt-landlocked	5.5 - 9.7*	0.9 - 1.5 (16%)#	U	S	S	S	S	S	S	S	S													1.8 - 3.2	L
[illegible]	[illegible]	[illegible] #)	U			S	S	S	S	S														1.8 - 3.2	L
[illegible]	[illegible]	[illegible] #)	D			F	F	F	F	F														1.8 - 3.2	L
[illegible]	[illegible]	[illegible] #)	D			F	F	F	F	F														0.2 - 0.4	L
juvenile eel (glass/elvers)	2.5 - 5*	1/8 - 1/2	U				F	F	F	F	F	F	F											0.8 - 2.6	L
adult eel	7.8 - 26	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]											S	S	S	S	S			5.2 - 9.1	L
adult alewife	2.6 - 9.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]				S	S	S	S											3 - 5	Pb
adult alewife	2.6 - 9.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					F	F	F	F										3 - 5	Pb
juvenile alewife	1.7-4.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]									F	F	F	F	F	F	F			0.6 - 1.0	L
adult shad	12-17*	2 - 3 (18%) +	U								S	S	S	S										2.3-7.2	Pb
adult shad	12-17*	2 - 3 (18%) +	D			[illegible]	[illegible]	[illegible]	[illegible]		F	F	F	F										2.3-7.2	Pb
juvenile shad	3*	0.6 (18%) +	D			[illegible]	[illegible]	[illegible]	[illegible]						F	F	F	F	F	F	F			1.0 - 1.8	L/Pb
adult blueback herring	9.4 +	2.2 (23%)	U			[illegible]	[illegible]	[illegible]	[illegible]		S	S	S	S										3 - 5	Pb
adult blueback herring	9.4 +	2.2 (23%)	D			[illegible]	[illegible]	[illegible]	[illegible]		F	F	F	F										3 - 5	Pb
juvenile blueback herring	1.4 - 2.8*	0.3 - 0.7 (23%)	D										[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		0.4 - 0.8	L
adult salmon (searun/landlock)	15 - 36*	3 - 7.2 (20%)	U										[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	S	5.0 - 8.8	L
juvenile salmon	4.5 - 6.8*	1 - 1.4 (20%)	Both					F	F	F	F	F	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	F	1.6 - 2.6	L
smolt salmon	7.8 - 15*	1.4- 5 (20%)	D					F	F	F	F	F	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		2.5 - 4.4	L
adult white sucker	4 - 14 +#	0.7 - 2.6 (18%)	U					S	S	S	S													1.2 - 2.1	L
brown trout	6-16*+	1.6 - 3 (18%)+	Both					F	F	F	F	F	F	F	F	F	F	S	S	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
brook trout	6-16#	1.5 - 4 (25%)	Both					F	F	F	F	F	F	F	F	F	F	S	S	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
sea-run brown trout	9-16*+	1.6 - 3 (18%)+	U															S	S	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
sea-run brook trout	6-12#	1.5 - 4 (25%)	U															S	S	S	S	S	S	2.0 - 3.5	L
rainbow trout	6-18 +*	1 - 3 (17%)	Both			S	S	S	S	S	S													2.0 - 3.5	L/P+
resident fish movement	3 - 10#	Varies	Both				F	F	F	F	F	S	S	S	S	S	S	F	F	F	F	F	F	1.0 - 1.8	L

Turbulence

- Measured by Energy Dissipation Factor (EDF)
- Limits fish passage – Roughness might just convert a velocity barrier into a turbulence barrier.

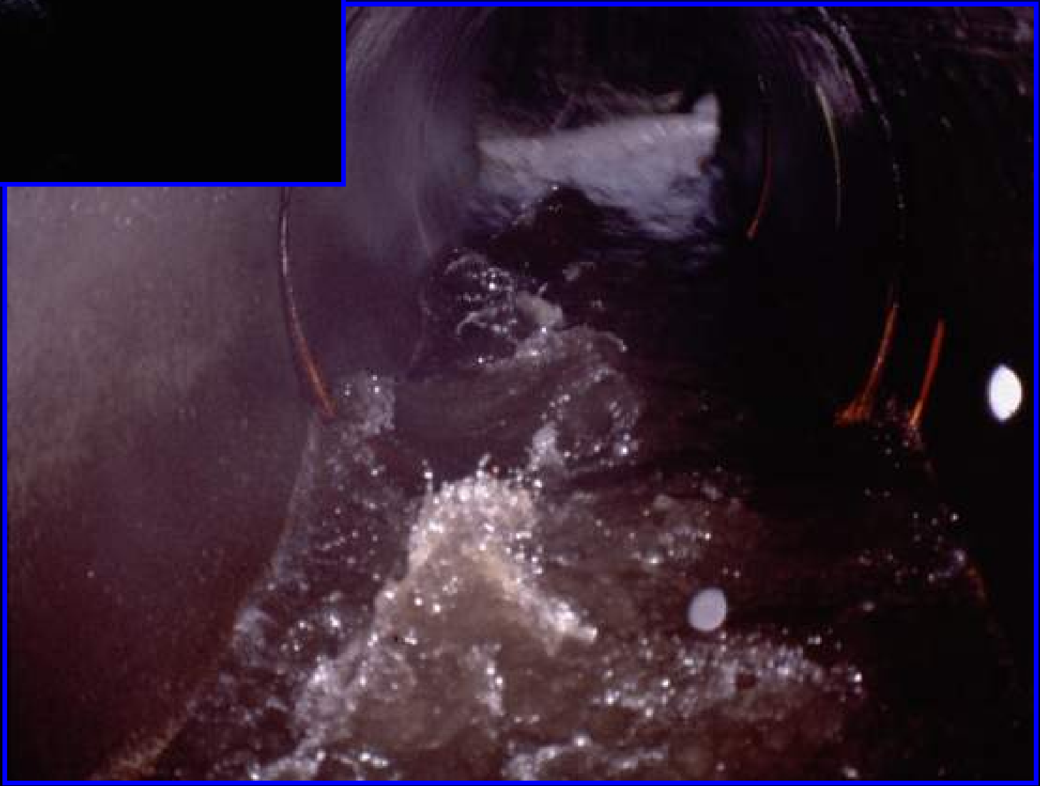
Examples of EDF

Low Flow

Adult salmon design flow
EDF = 4 ft-lb/sec/ft3

Two times design flow
EDF = 8 ft-lb/sec/ft3

Low Flow
Baffles as weirs



Moderate Flow
Baffles as roughness

Energy Dissipation Factor (EDF)

- Energy dissipation factor
  - A measure of turbulence
  - Energy dissipated per unit volume of water
  - Culvert EDF = (γ)(velocity)(slope)

- Recommended maximum EDF for adult salmon
  - Fishways: 4.0 ft-lb/sec/ft^3
  - Baffled culverts: min: 3.0, max: 5.0 ft-lb/sec/ft^3 (estimated)
  - Roughened channels: 7.0 ft-lb/sec/ft^3 (estimated)

Example: Calculate EDF in a 3.0% channel with velocity of 2.7 fps

$62.4 \text{ lb/ ft}^3 \times 2.7 \text{ fps} \times 0.03 = 5 \text{ ft-lb/sec/ft}^3$

Roughened Channel is Hydraulic Design

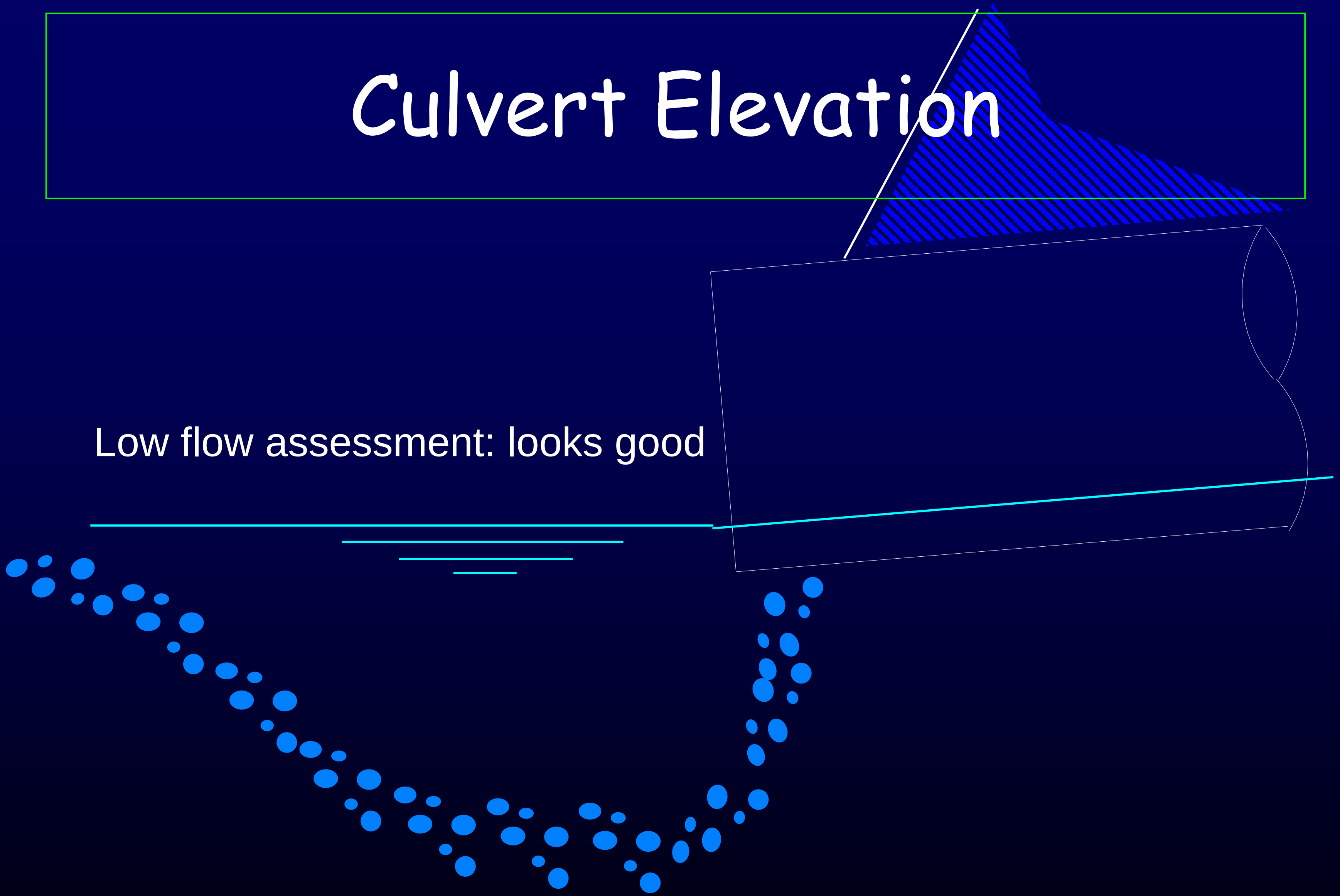
- Roughen channel with rock
- Use hydraulic culvert design
- Rigid structure

Fish passage hydrology
At what flows must velocity criteria be applied?

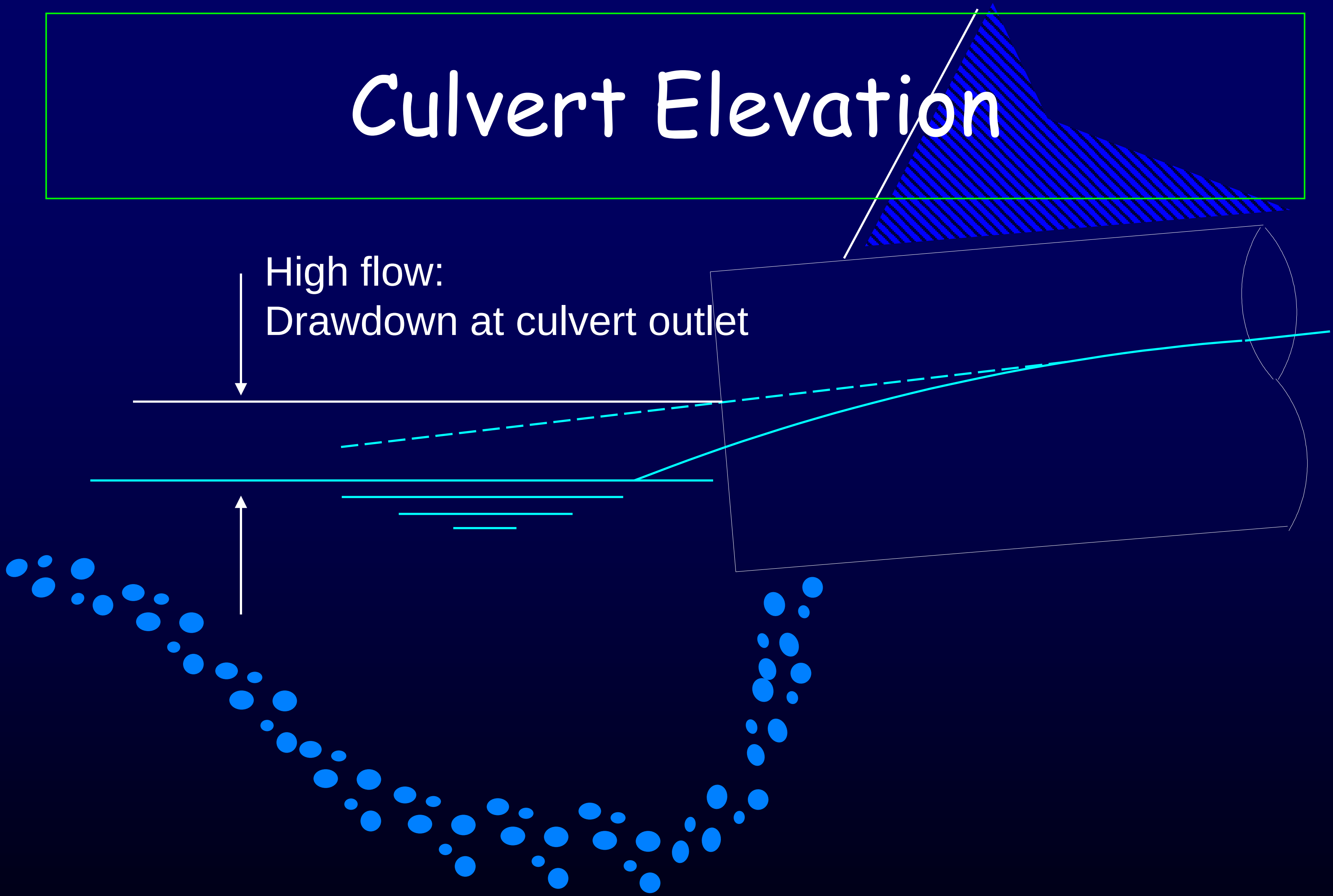
- Adult salmonid fish passage design flow
  - Alaska, Canada DFO: Q2D2 during migration season.
  - Washington, Oregon: Satisfy fish passage criteria 90% of the time during fish passage season
  - Idaho: none defined
  - NOAA Fisheries SW Region and California Fish & Game:
    - 1% annual exceedance (preferred)
    - 50% of 2-year flood
    - Flow that fills the active channel
    - CF&G has criteria also for non-anadromous salmonids, juvenile salmonids, native non-salmonids, and non-native species.
  - Maine, Vermont: median flow during migration season.

Culvert Elevation

Low flow assessment: looks good



Culvert Elevation



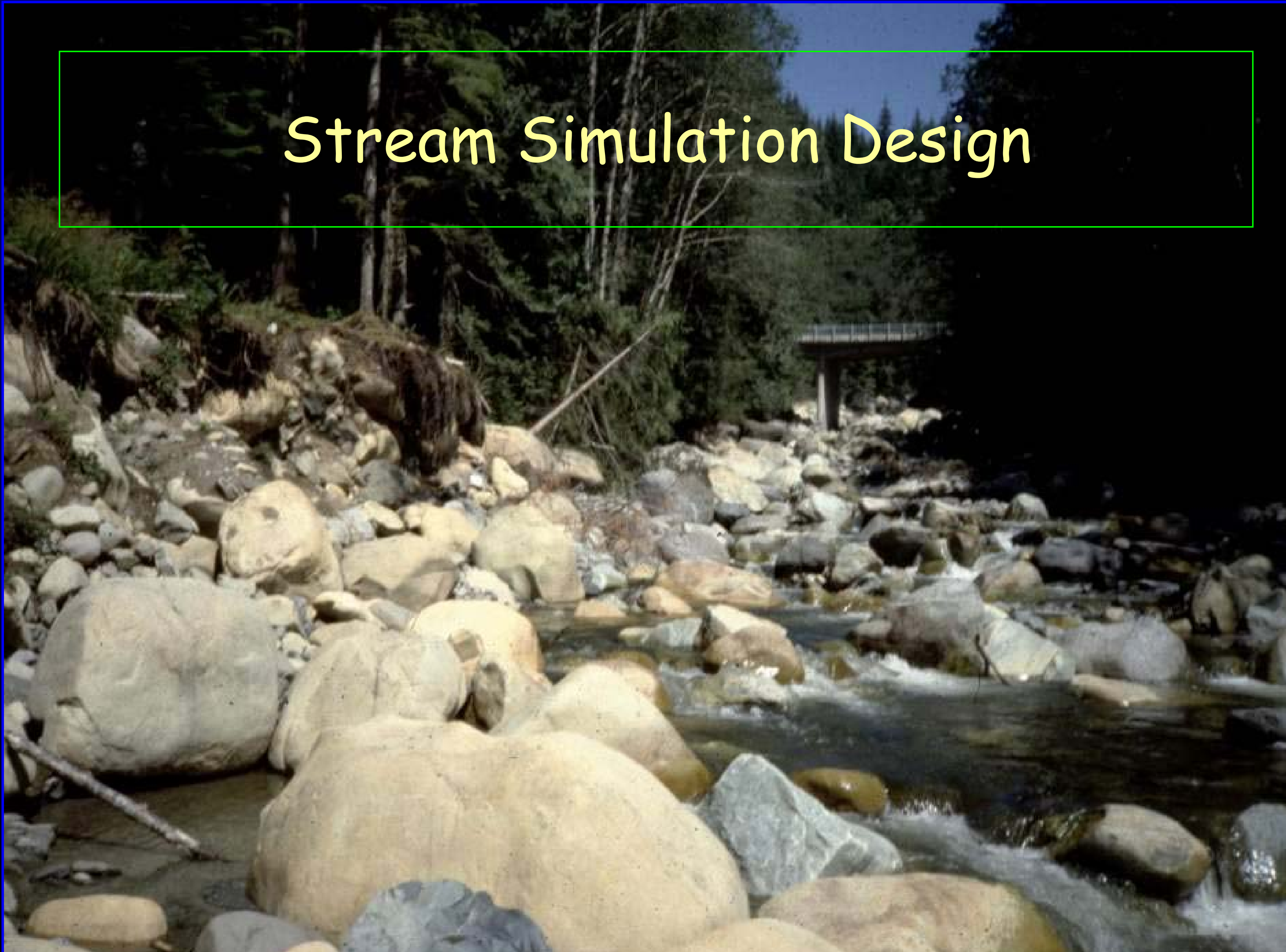
Some Last Thoughts on Hydraulic Method

- Uncertainties
  - Target species? Other species present and their ecological roles?
  - Swimming ability, behavior, and migration timing of target species?
  - Hydrology; models have standard errors of 25 -100%?
  - Small scale hydraulics? Turbulence a barrier?
- Application:
  - Trend is to use for retrofits only. May be the “best reasonable” as retrofit in some situations with low to moderate slopes

Then biologists reminded us to observe and understand fish behavior.

And that organisms and processes other than fish must be considered in culvert design.

Stream Simulation Design



Premise of Stream Simulation

- 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.

What is stream simulation?

- Geomorphic design
- Simulate natural channel reference reach
  - Bankfull cross section shape and dimensions
  - Channel slope
  - Channel structure
    - Channel type
    - Mobility
- "Mobile bed in stable channel"

Stream Simulation Design Process

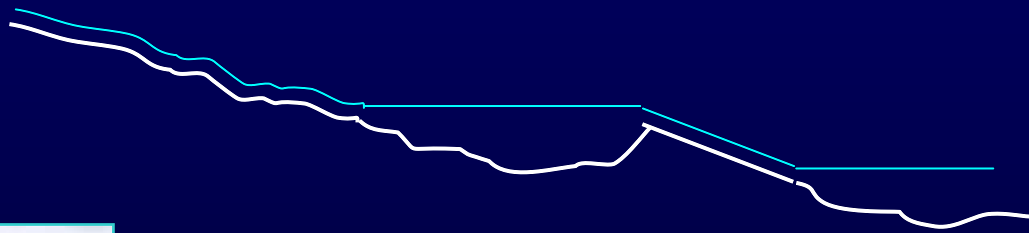
Assessment
Stream simulation feasibility
↓
Project alignment and profile
↓
Verify reference reach
↓
Bed shape
and material
↓
Structure width,
elevation, details
↓
Mobility / stability
↓
Design profile control →

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

Assess >>

Road Impounded Wetlands

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



Suitable for Stream Simulation

- Rock, sediment dominated
- Equilibrium

Stream Simulation Design Process

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

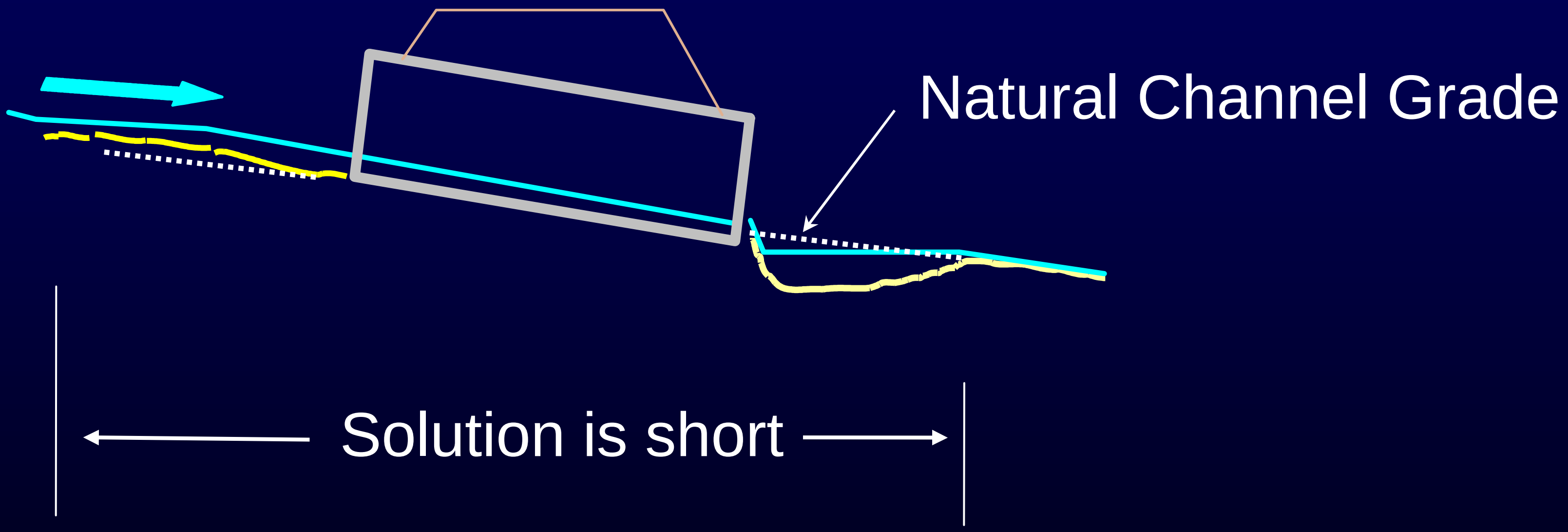
- Scour or incision, scale of the problem
- Variability over time and distance
- Sensitivity
- Headcut issues

This applies to any in-stream design!

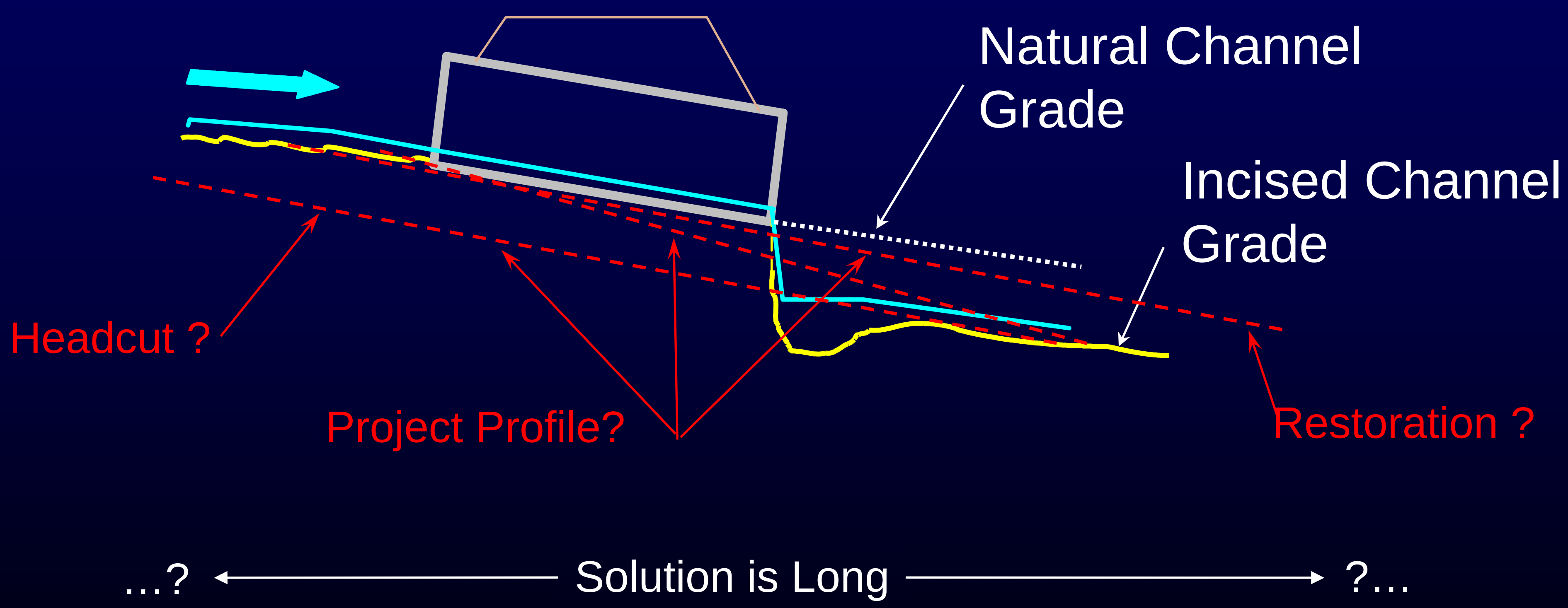
Project Profile

- Project profile is what is actually constructed
- Start with initial vertical adjustment potential from site assessment
- Consider profile and alignment issues concurrently
- A forced profile might be necessary

Case #1: Scour Pool



Case #2: Incised Channel



Channel regrade considerations

- Extent of regrade expected
- Adjacent channel
  - Upstream banks – stability, riparian, impounded wetlands?
  - Is there value of culvert as nick point? Habitat, infrastructure
- Bed material
  - Backwater wedge?
  - Potential bedrock exposure?
- Culvert and channel capacity with sediment slug
- Potential passage barriers created upstream
- Construction access to build regrade
- Opportunities for downstream habitat restoration

Outlet Creek – 2005

Upstream channel

Downstream channel incised

Headcut issues
Bed material

Wynoochee trib - 1983

Culvert replaced

Headcut issues
Bed material

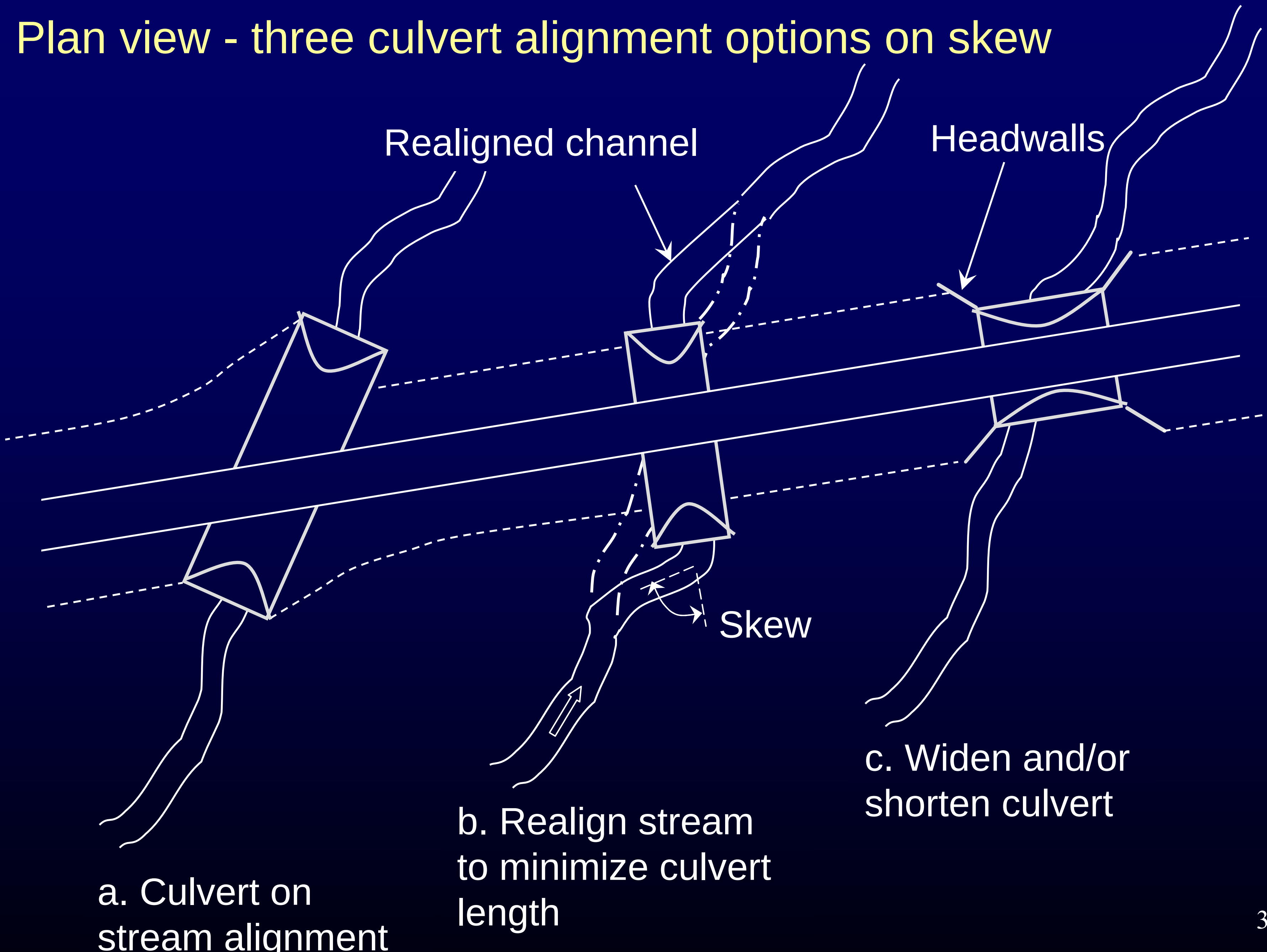
Wynoochee trib – 2002

Channel regraded to bedrock

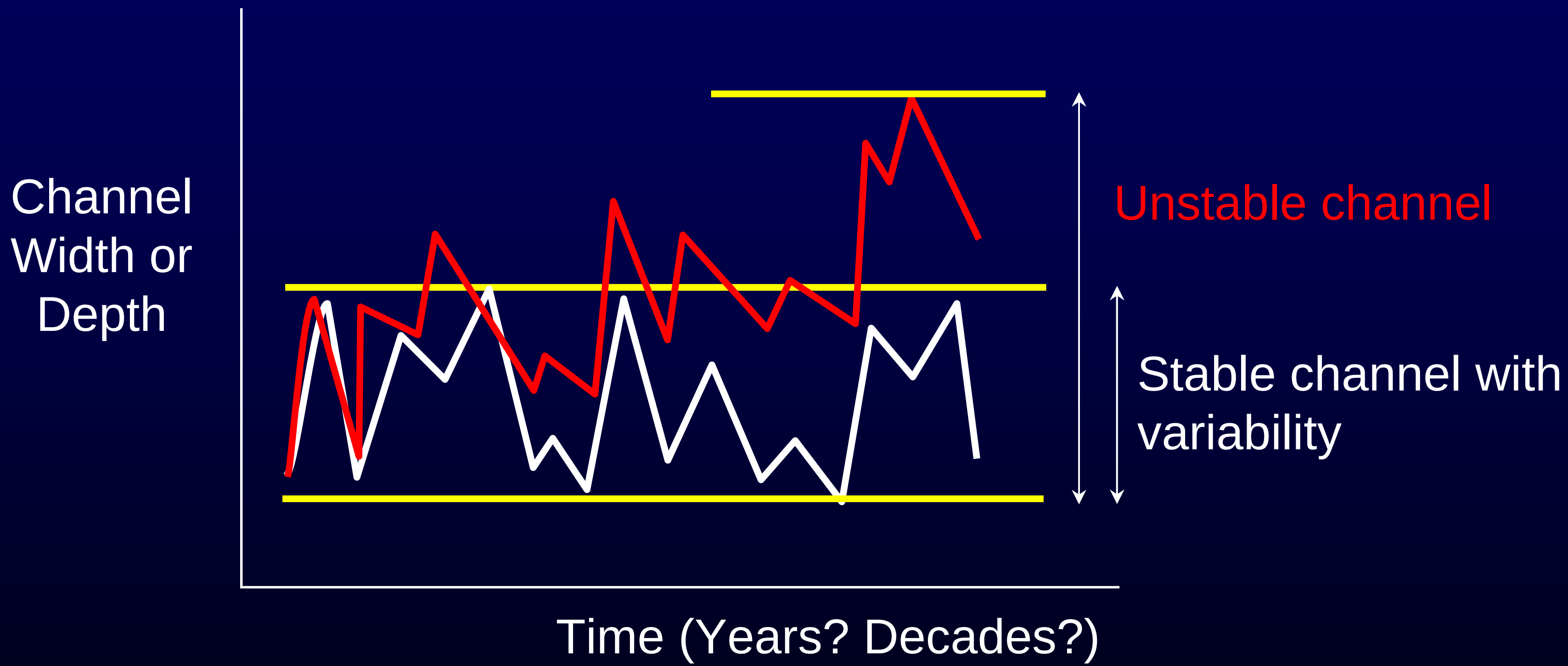
Alignment

- Design concurrently with profile
- Important factor for debris blockage and failure
- Choose reasonable alignment for existing and future stream channel.
- Disturbance, stability, length, cost are often a compromise.
- Consider: shorten culvert using headwall, change road alignment, or switch to bridge option.

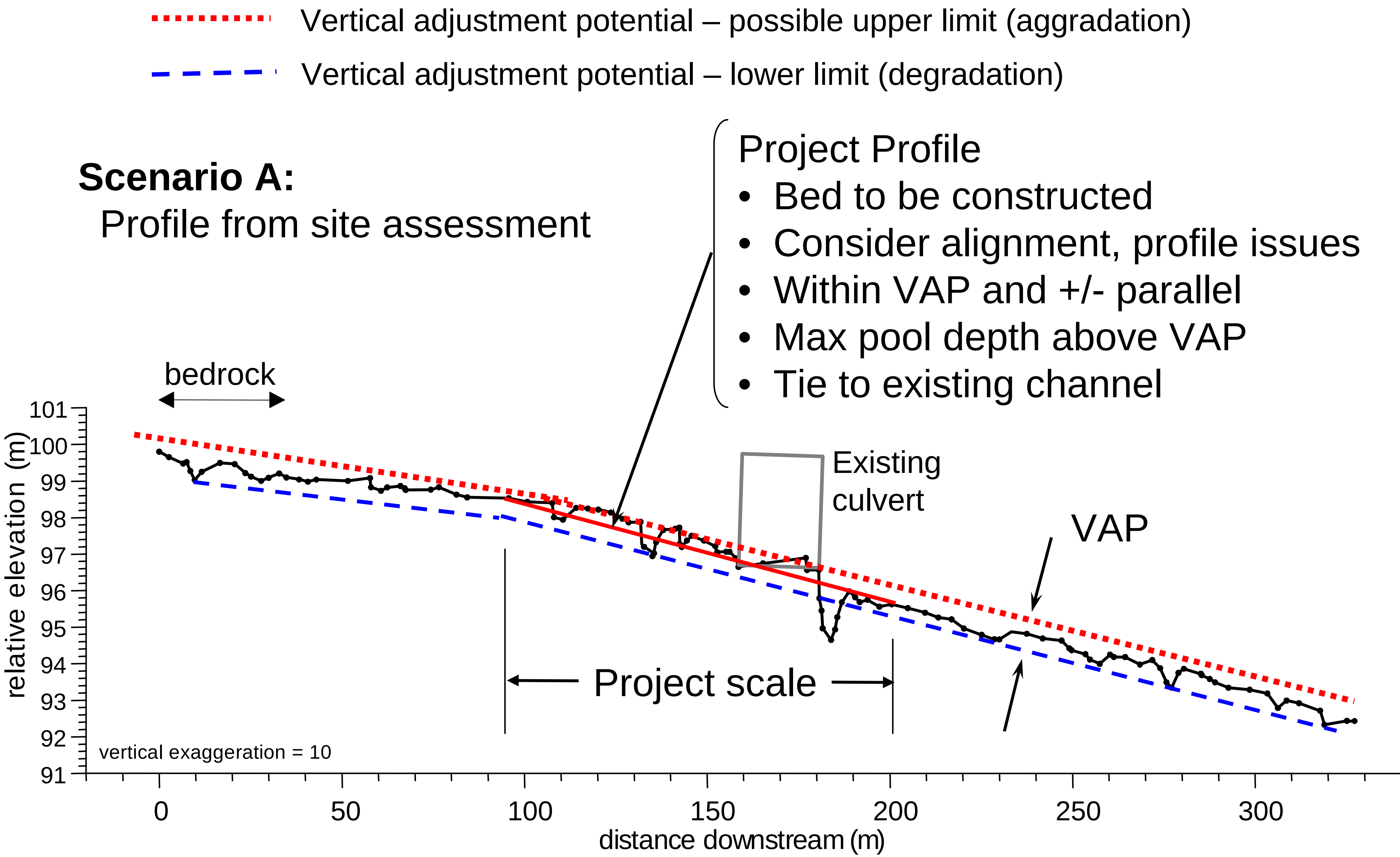
Plan view - three culvert alignment options on skew



Estimate channel adjustments for life of project



Newbury Creek Project Profile

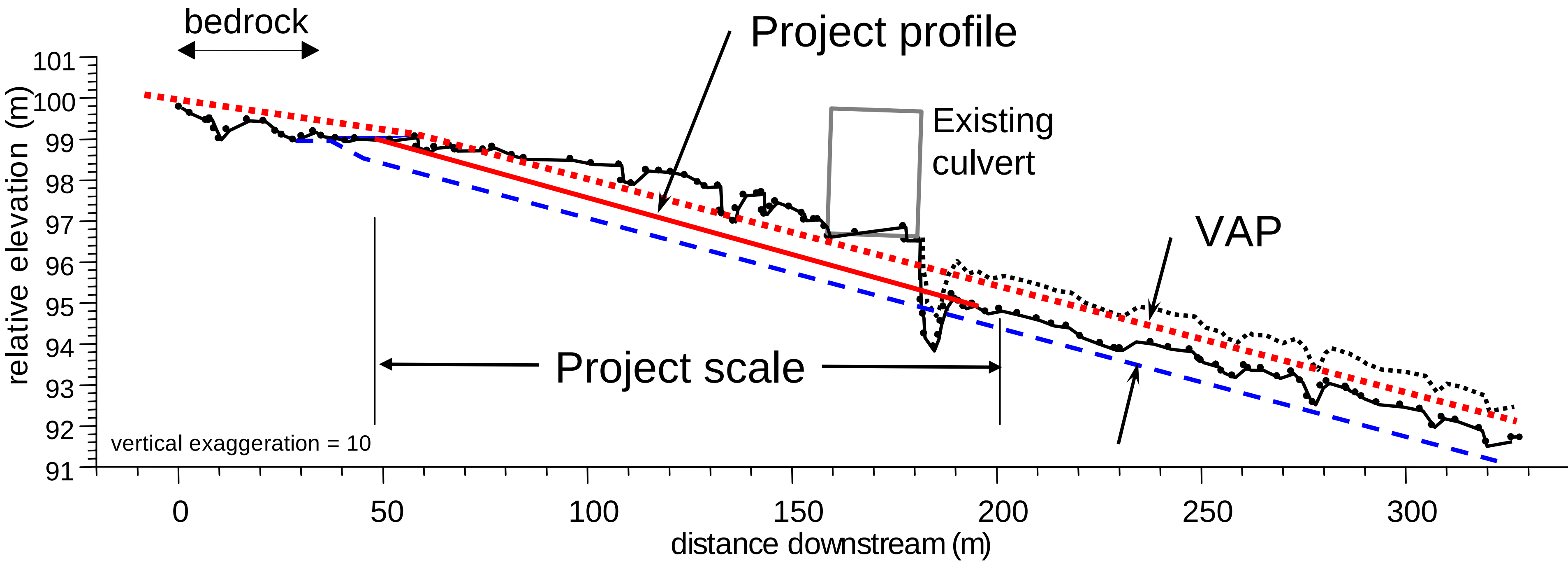


Newbury Creek Project Profile
With incised channel

Scenario B:

Regional incision.

Vertical adjustment potential assumes no culvert.

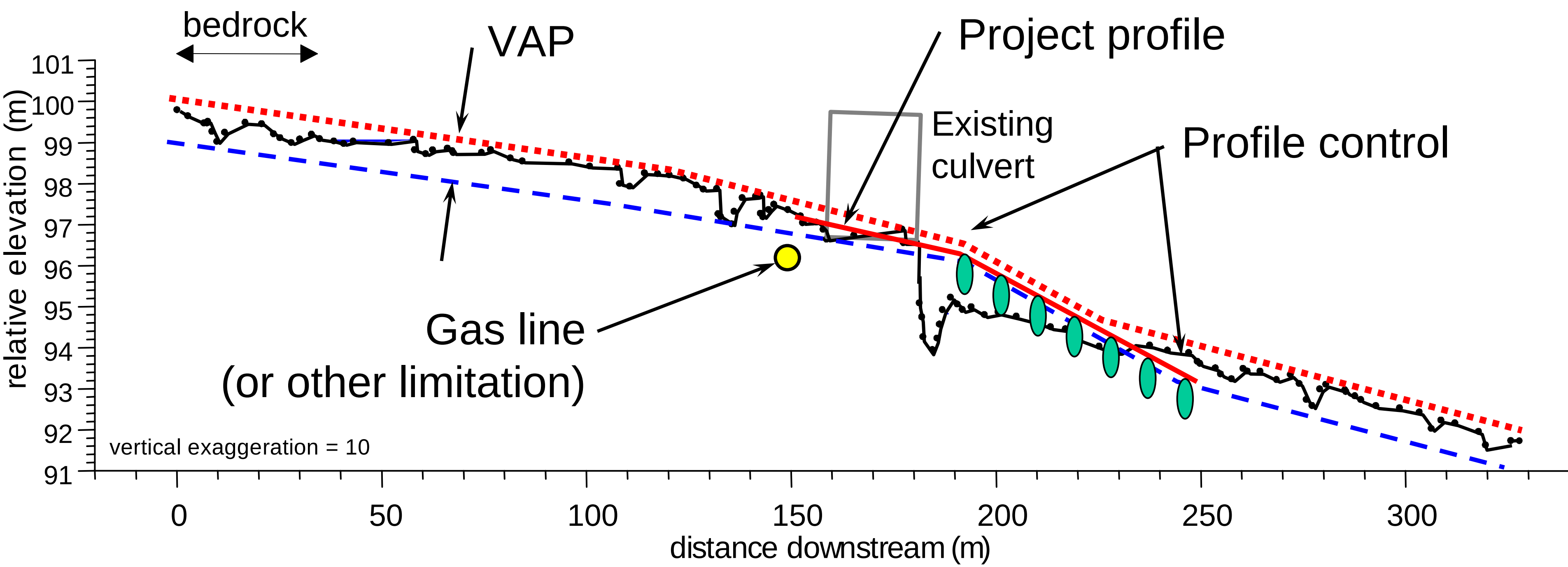


Newbury Creek Project Profile
With a forced profile

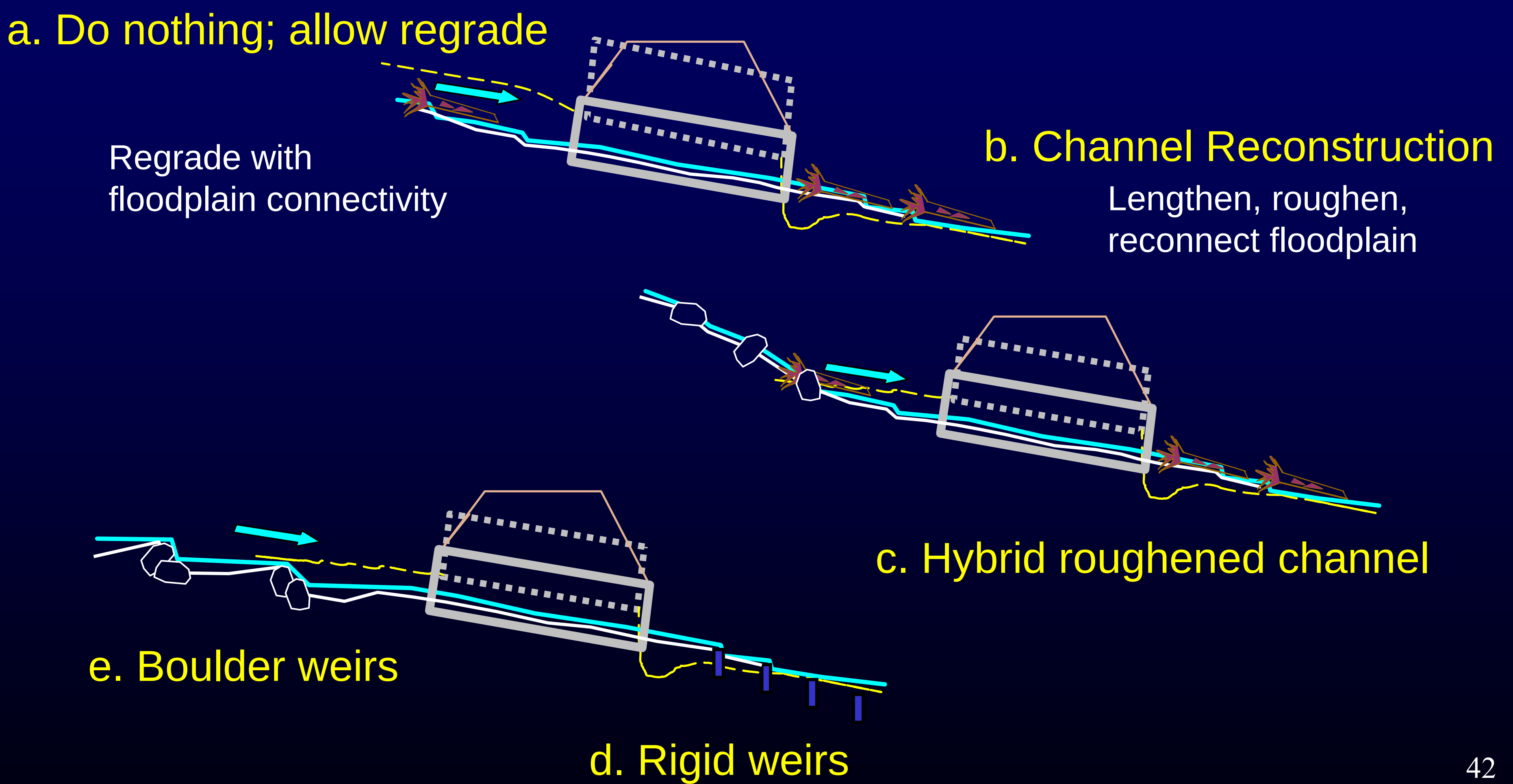
Scenario C:

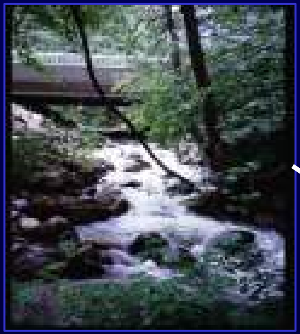
Regional incision.

Forced profile necessary.



Profile control options

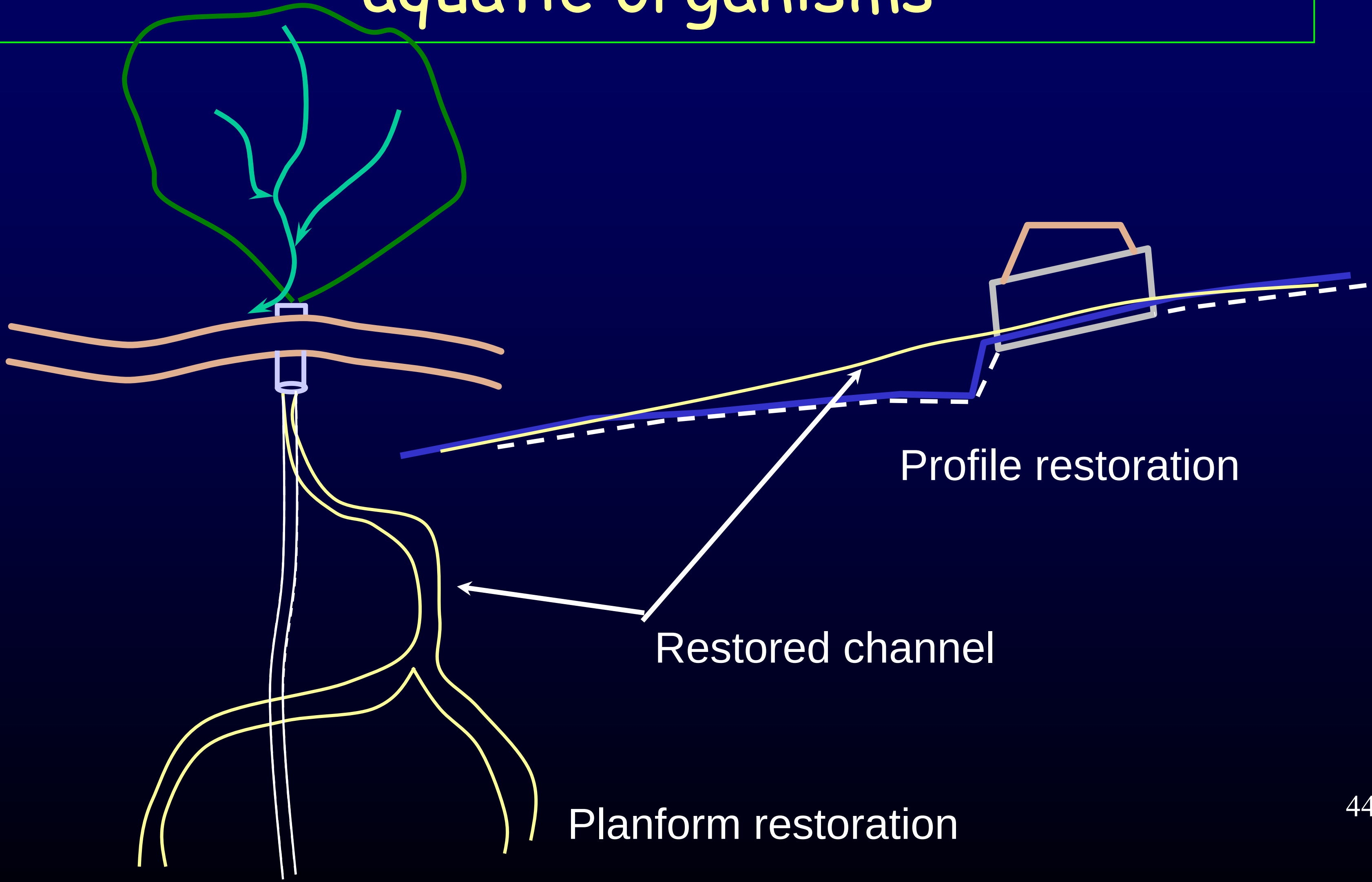




Profile control options

	Slope	Advantages	Limitations
Fishway	10% or "vertical"	Small footprint	Species, Flow, Sediment, Debris
Log sills	5%	Rigid, durable	Species, habitat
Hybrid Roughened channel	Limited by durability, bedload	Passage diversity	Species, Failure risk
Boulder weirs	5% (+)	Passage diversity, Habitat	Failure risk
Channel restoration	Limited by channel type	Passage diversity, Habitat	Scale
Regrade	?		Regrade risk, Time to restore

Channel restoration for passage of aquatic organisms



K Caromile

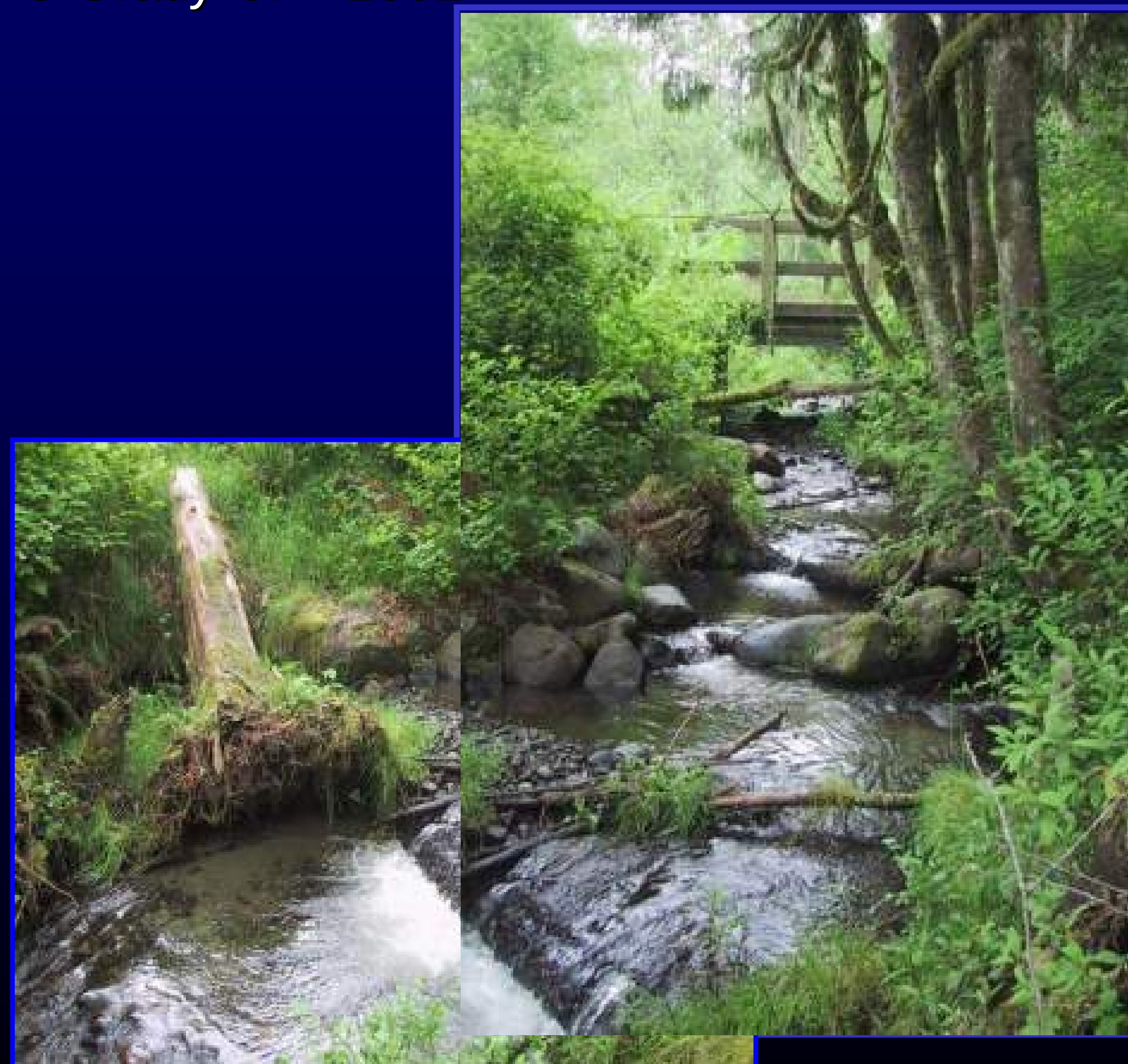
Channel restoration
for fish passage correction

Outlet Creek - 2002

Channel restoration for fish passage correction

Reference Channel

O'Grady Cr – 2002



Stream Simulation

Stream Simulation Design Process

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

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

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Design profile control →

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

Bed Design Objectives

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

- Does the bed satisfy project objectives?

Bed Design by M&B* Channel Types

Increasing slope
Decreasing mobility

Based on channel type of reference reach

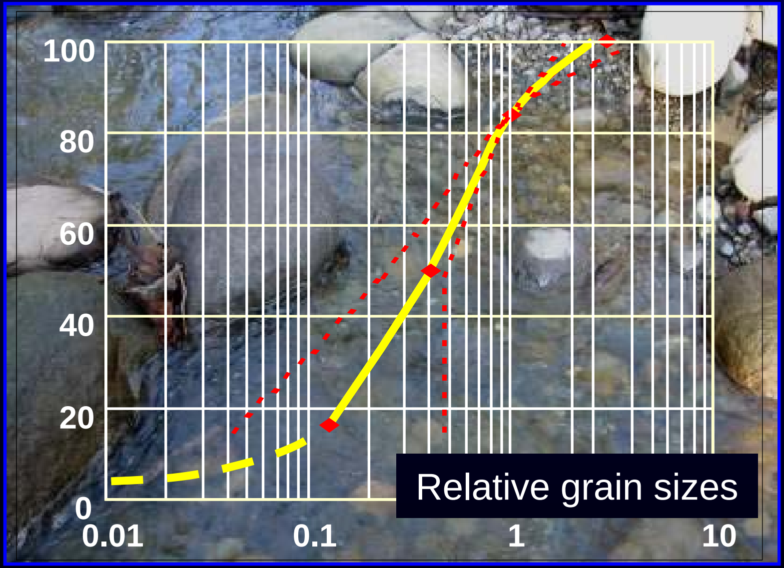
- Dune-ripple; construct or recruit
- Pool-riffle / Plane-bed; construct and let form develop
- Step-pool, forced channels; construct steps
- Cascades; construct
- Bedrock
- Clay

* 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}

Fuller-Thompson

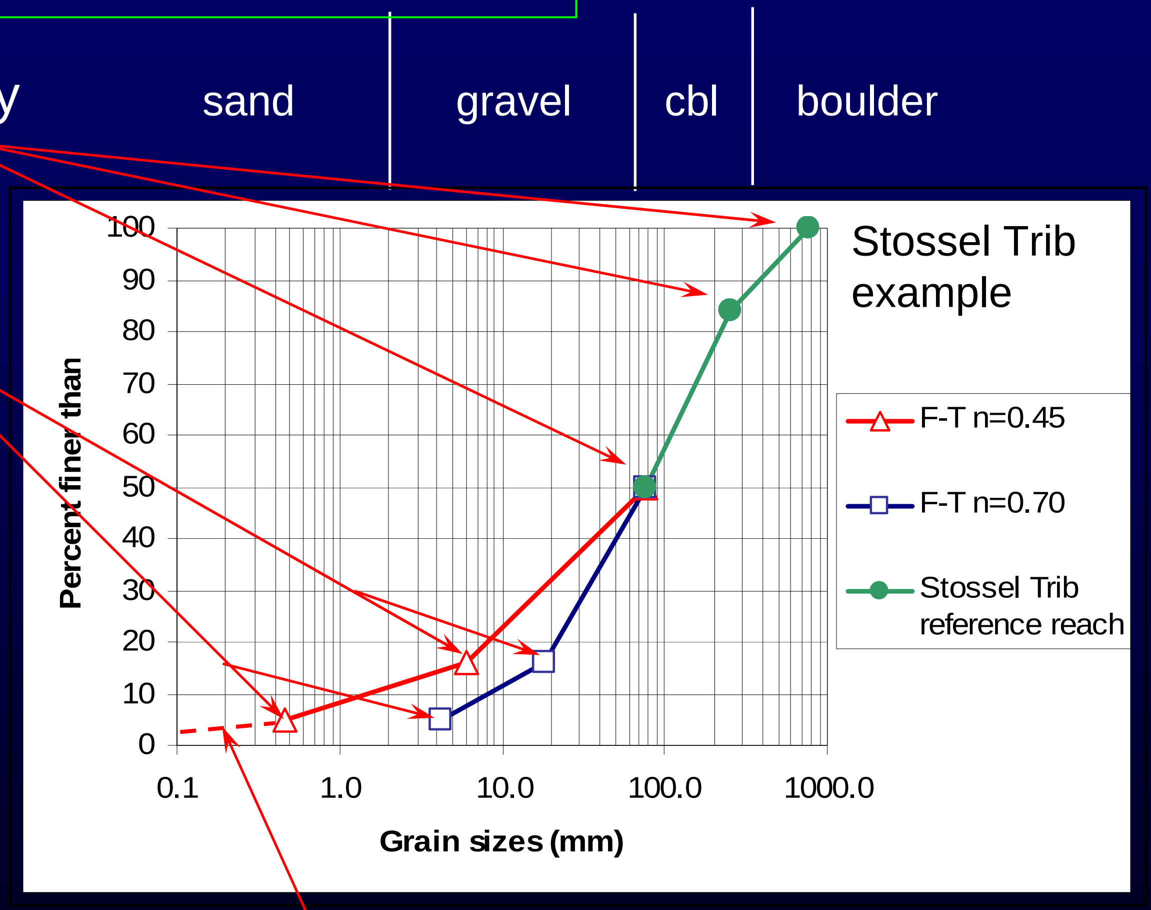
$$P = \left[\frac{d}{D_{100}}\right]^n$$

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

Simplify to:

$D16 = 0.32^{1/n} \times D50$

$D5 = 0.10^{1/n} \times D50$



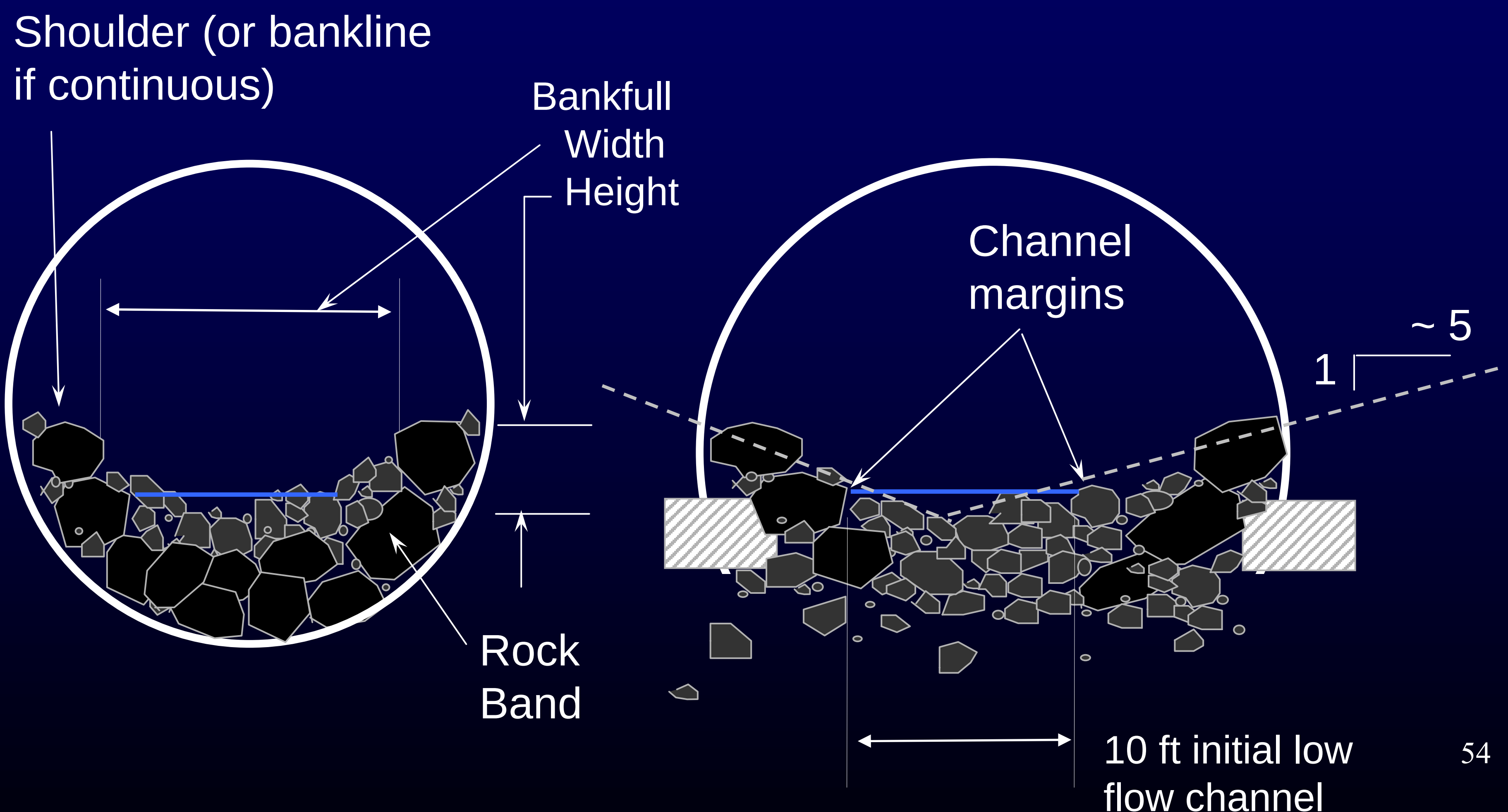
Verify 5% fines are included

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

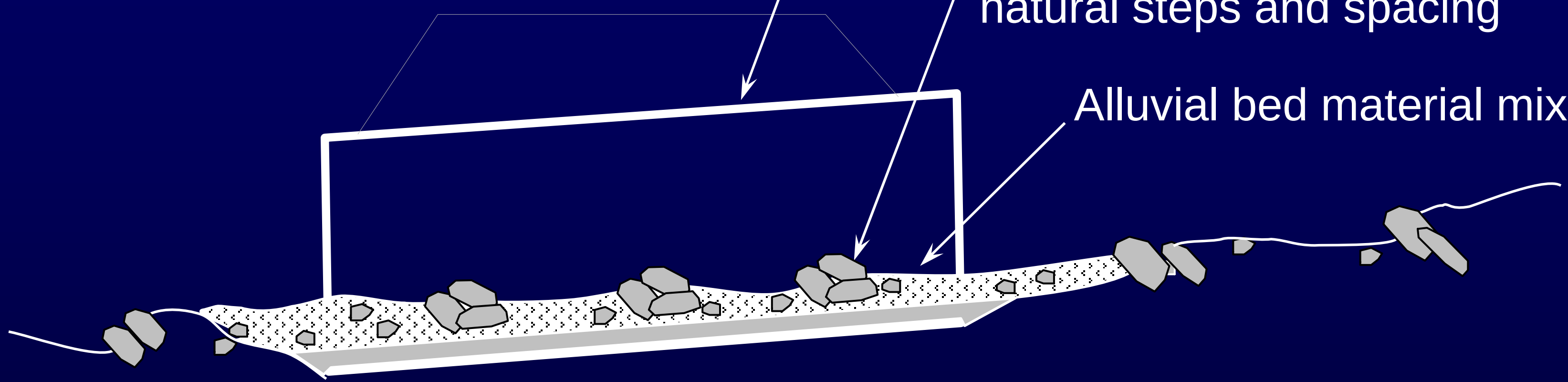
Stream Simulation Bed
Channel cross-section



Rock Bands

The (not) Rolling Stones

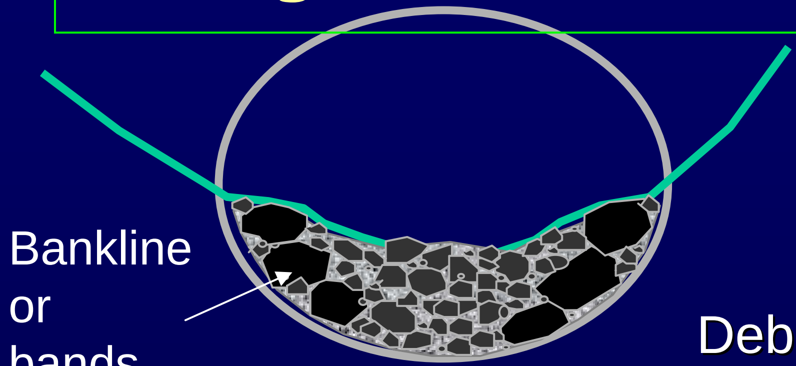
Steps



Step pool channel

"Set up" step pools and forcing features

Margins, Banklines



Special Considerations

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

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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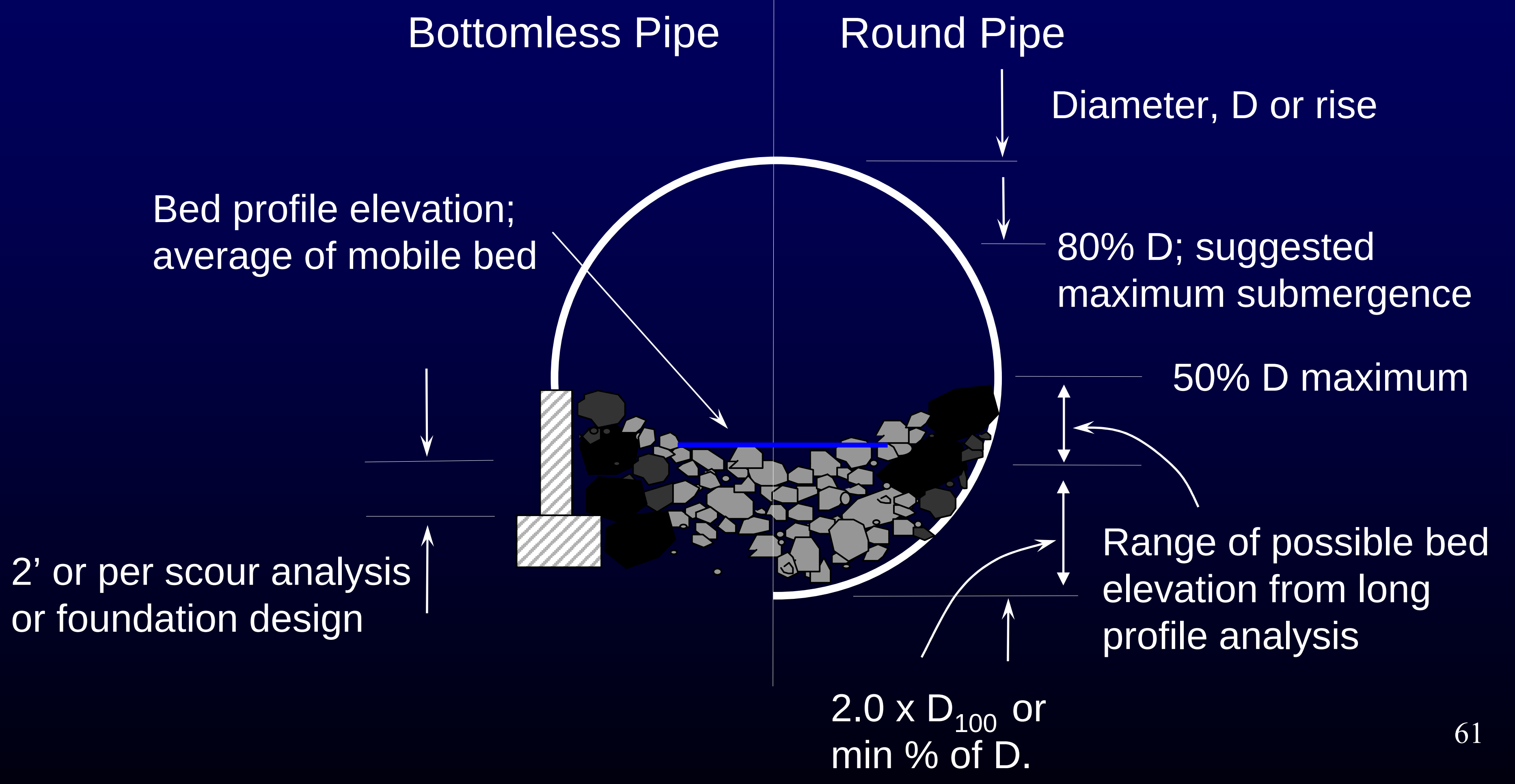
Design profile control →

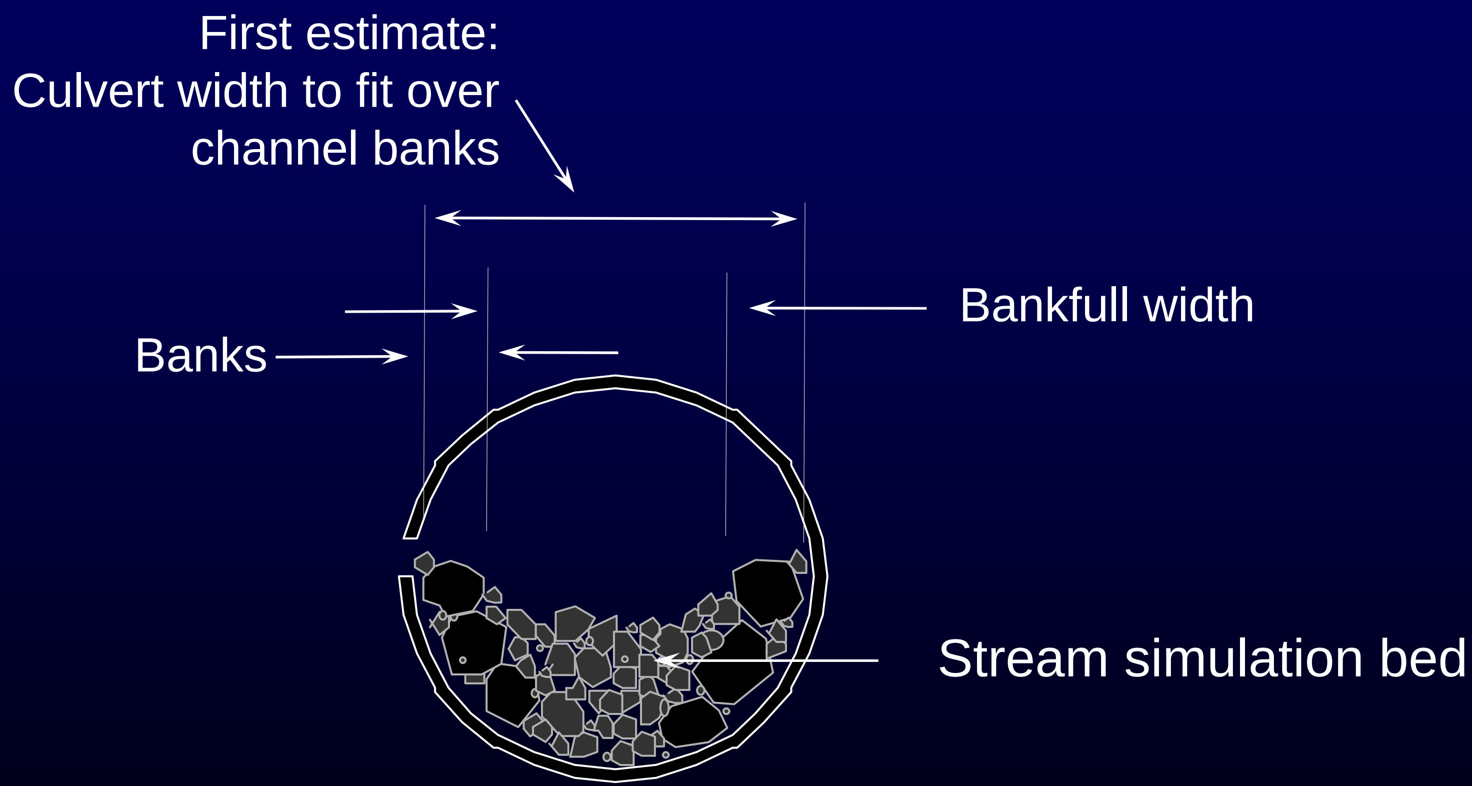
- Profile range
- Sustainability
- Floodplain function, connectivity
- Safety factor

Culvert Elevation




Stream Simulation
How big is it?

Stream Simulation
First estimate of culvert width



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Verify reference reach
↓
Bed shape
and material
↓
Structure width,
elevation, details
↓
Mobility / stability
↓
Design profile control

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

Mobility / Stability Analysis
Three purposes

Mobility

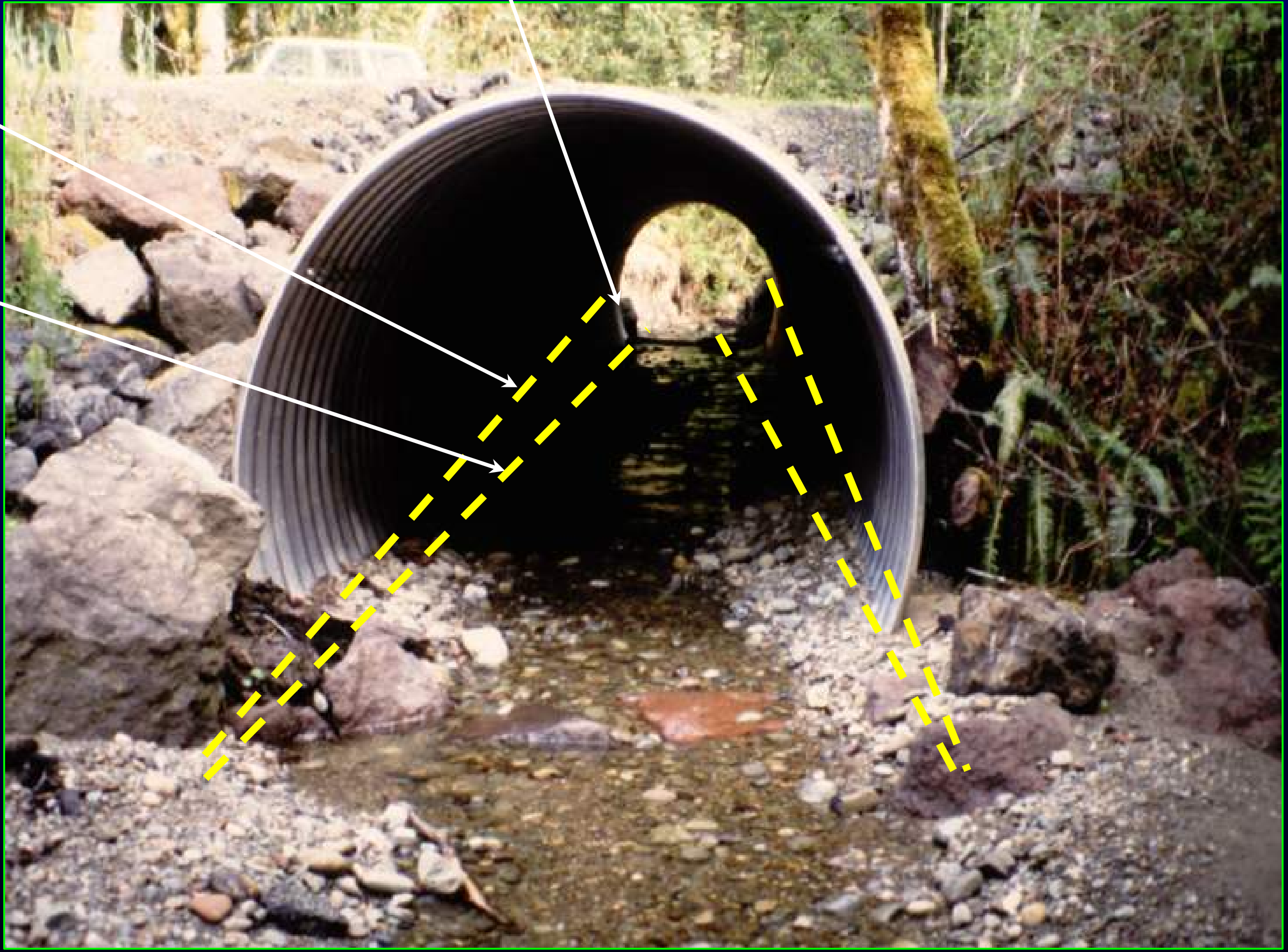
1. Is channel shape and bed material stream simulation? – project objective

Stability

2. Does bed stay in place?
3. Is culvert stable?

Bed Failure

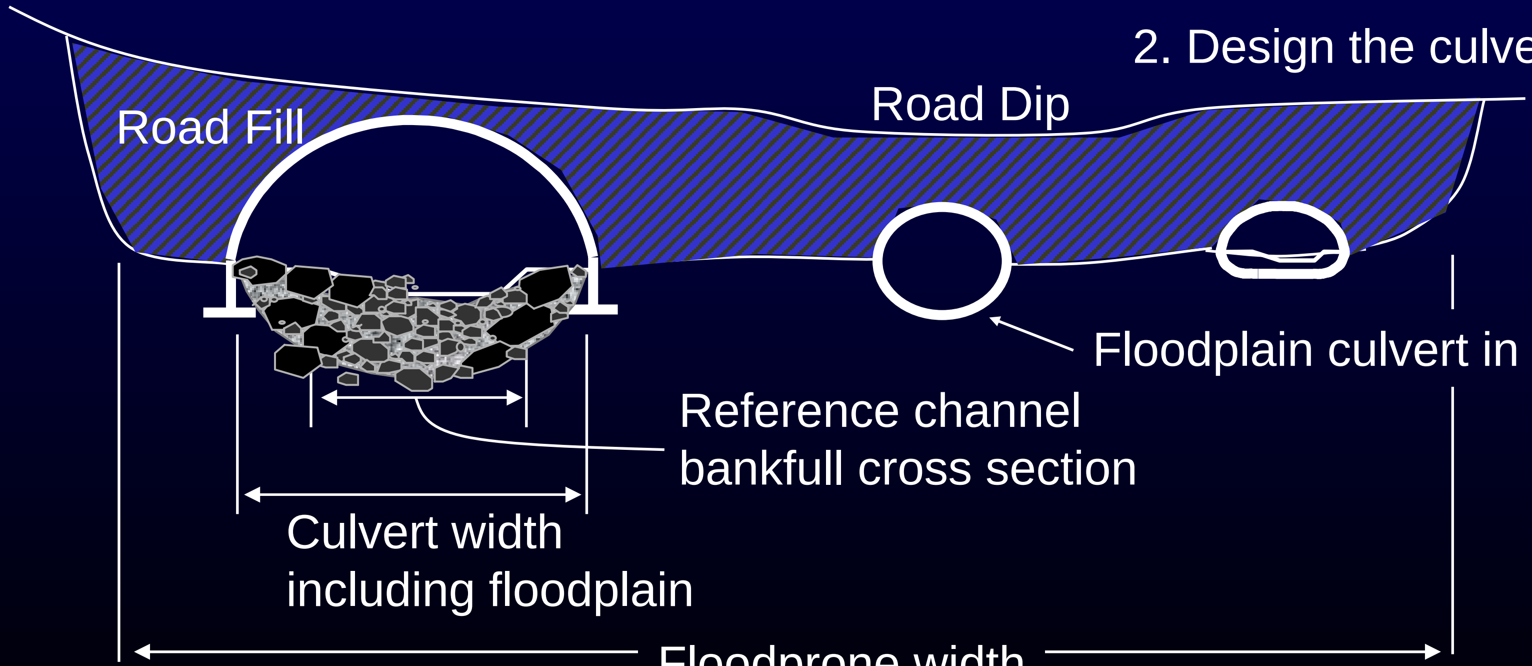
Stimson Ck.
Width ratio = 1.0
Slope = 2.2% (5%)



Culvert too narrow, bed material too small.

Design for sustainability

1. Design the channel and floodplain
2. Design the culvert to fit



Risks and Design/construction strategies

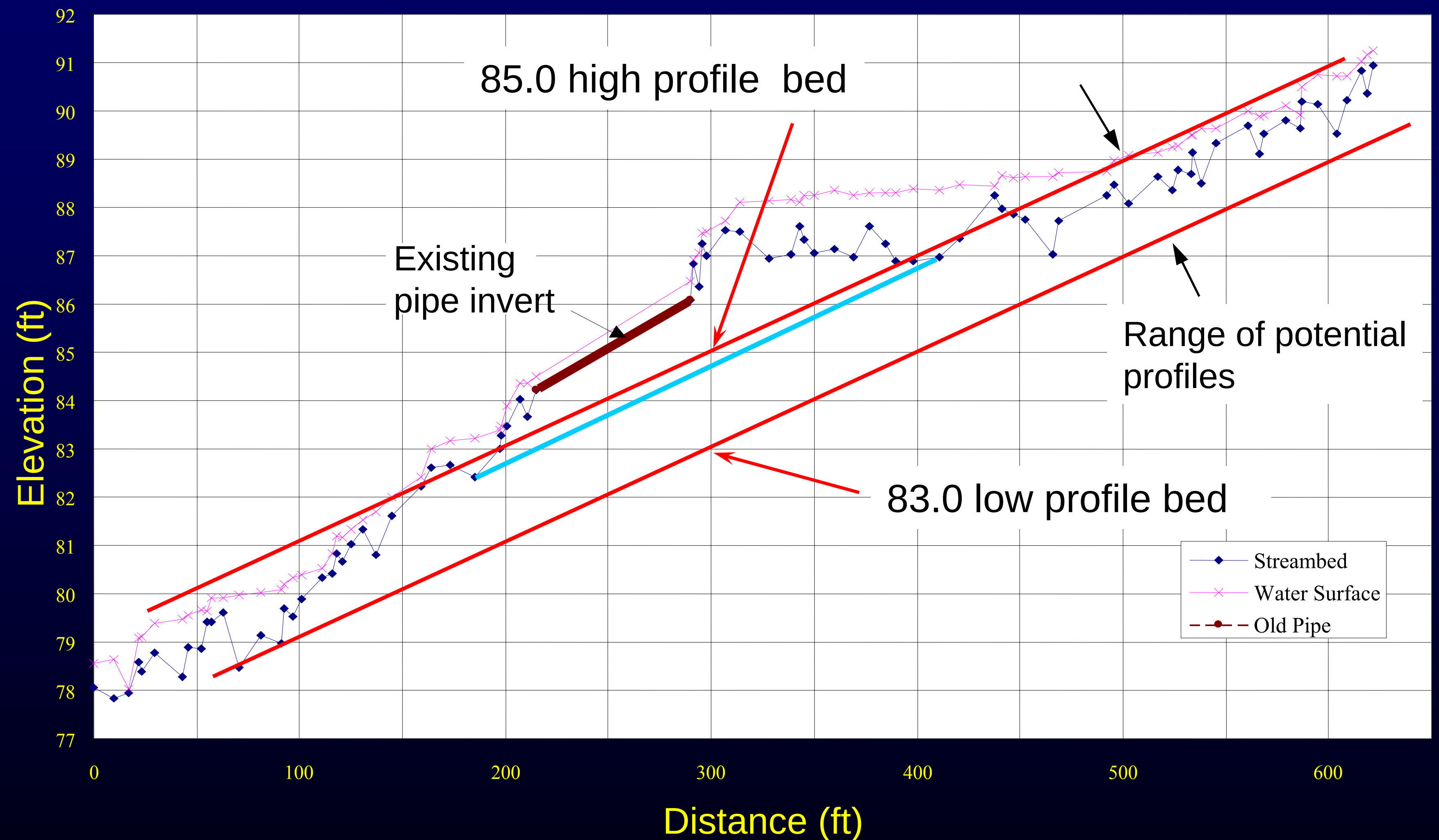
Risk	Design/construction strategy
All culverts	
Debris blockage, flows	• Limit headwater depth • Efficient upstream transition
Stream diversion	• Build sag in road • Design for plugging, failure
Stream simulation culverts	
Steeper than reference reach	• Minimize slope increase • Increase bed material 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

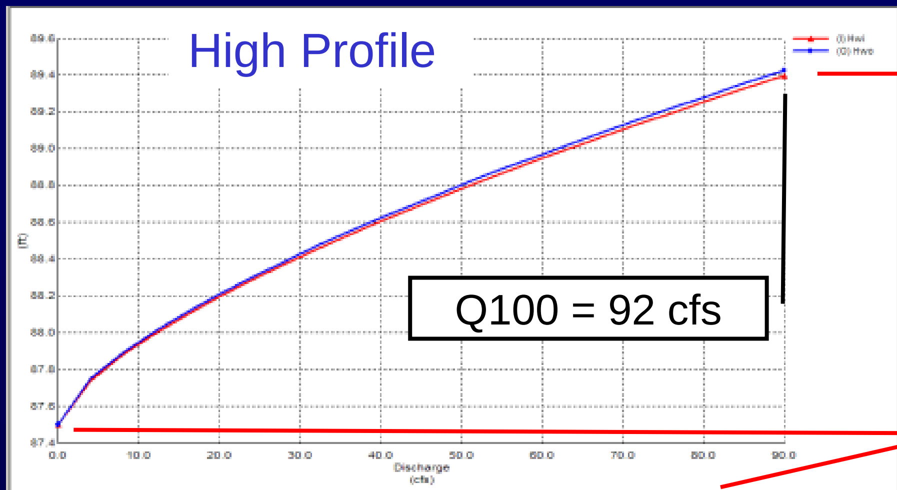
Culvert Capacity

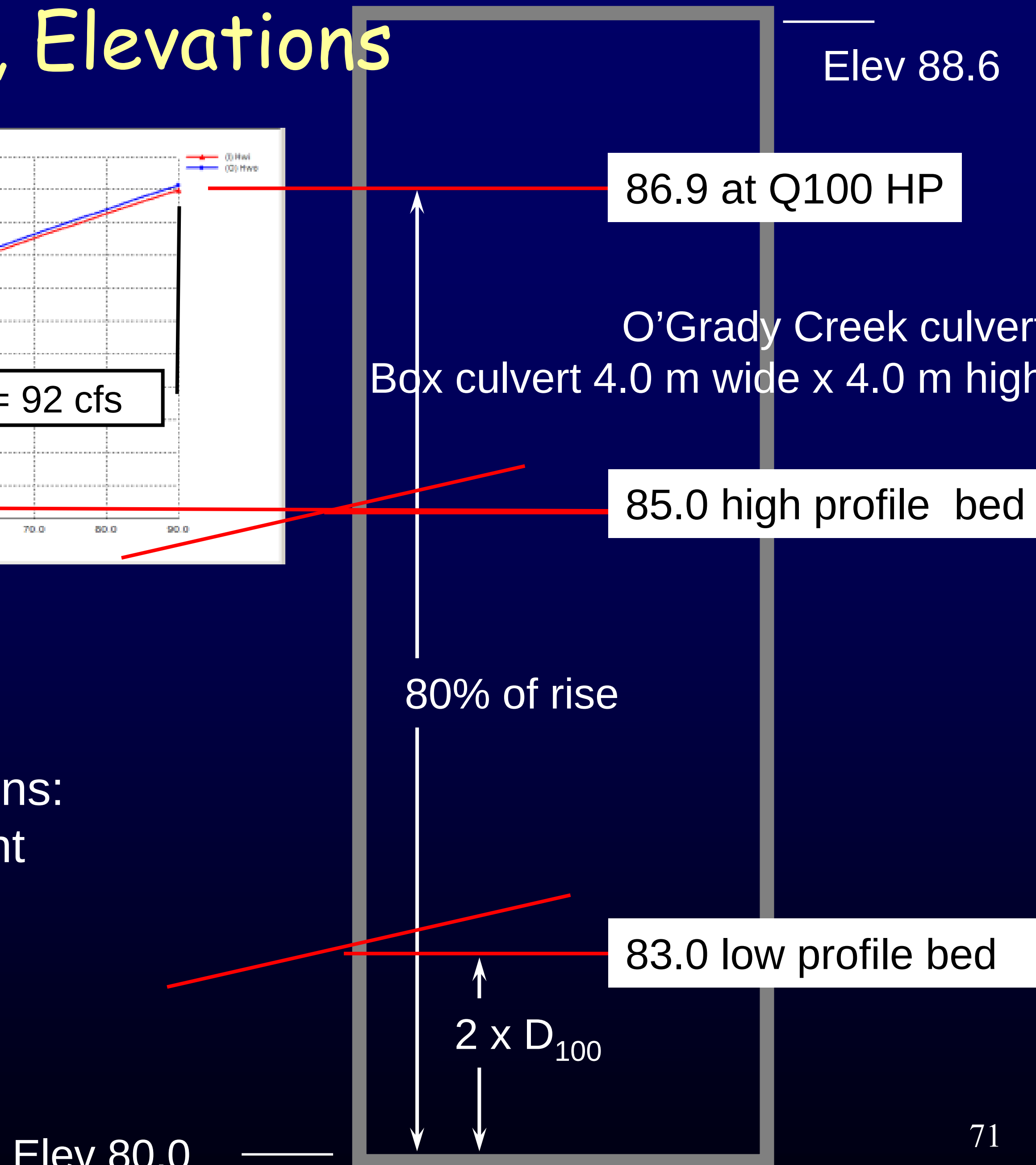
- Review range of project profiles.
- Analyze capacity with the high profile.
- Headroom for debris.
- Review risk of diversion.
- With debris, alignment is more important than culvert size (to a point).
- What are consequences of failure?

Culvert elevations, capacity



Culvert capacity, Elevations

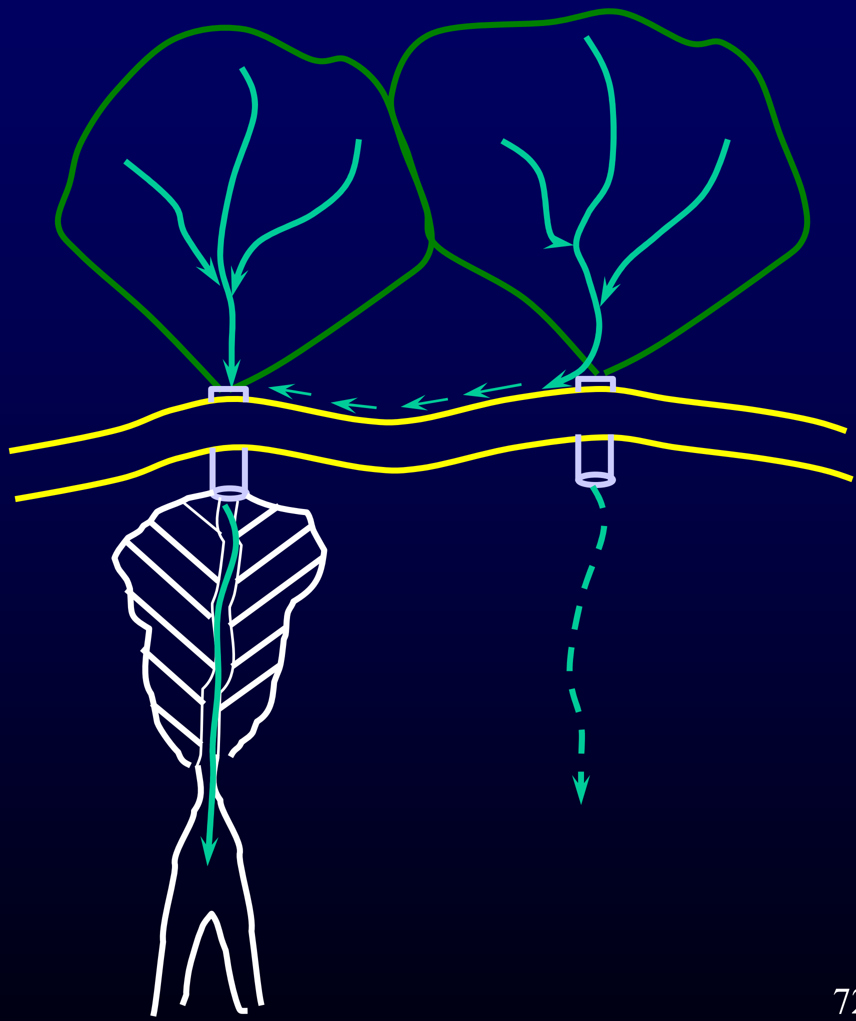




Other height considerations:

- cover, vertical alignment
- openness ratio

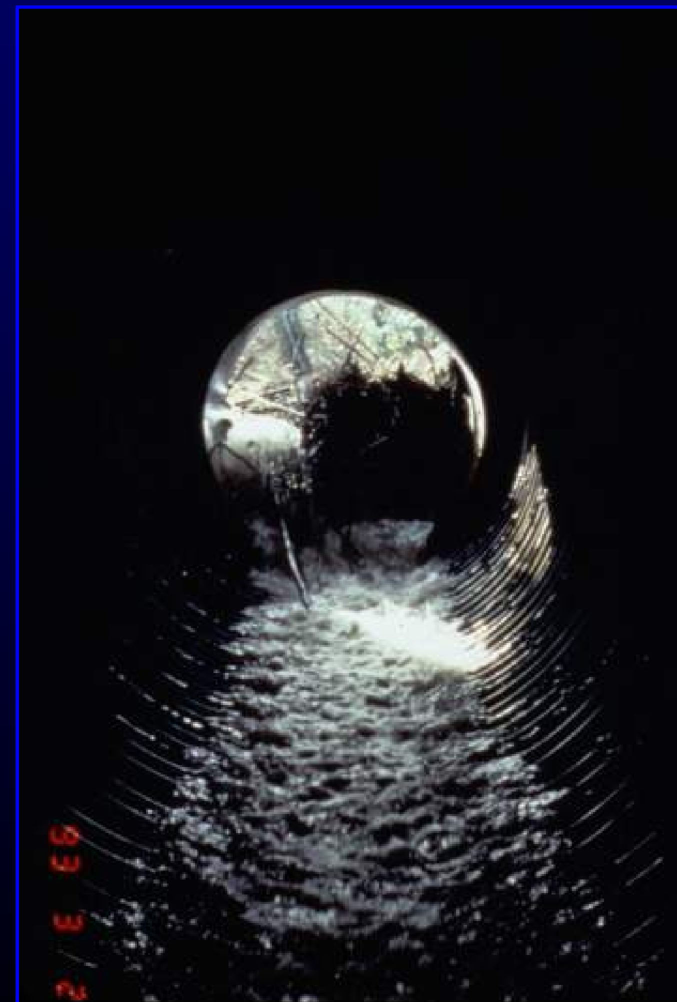
Diversion

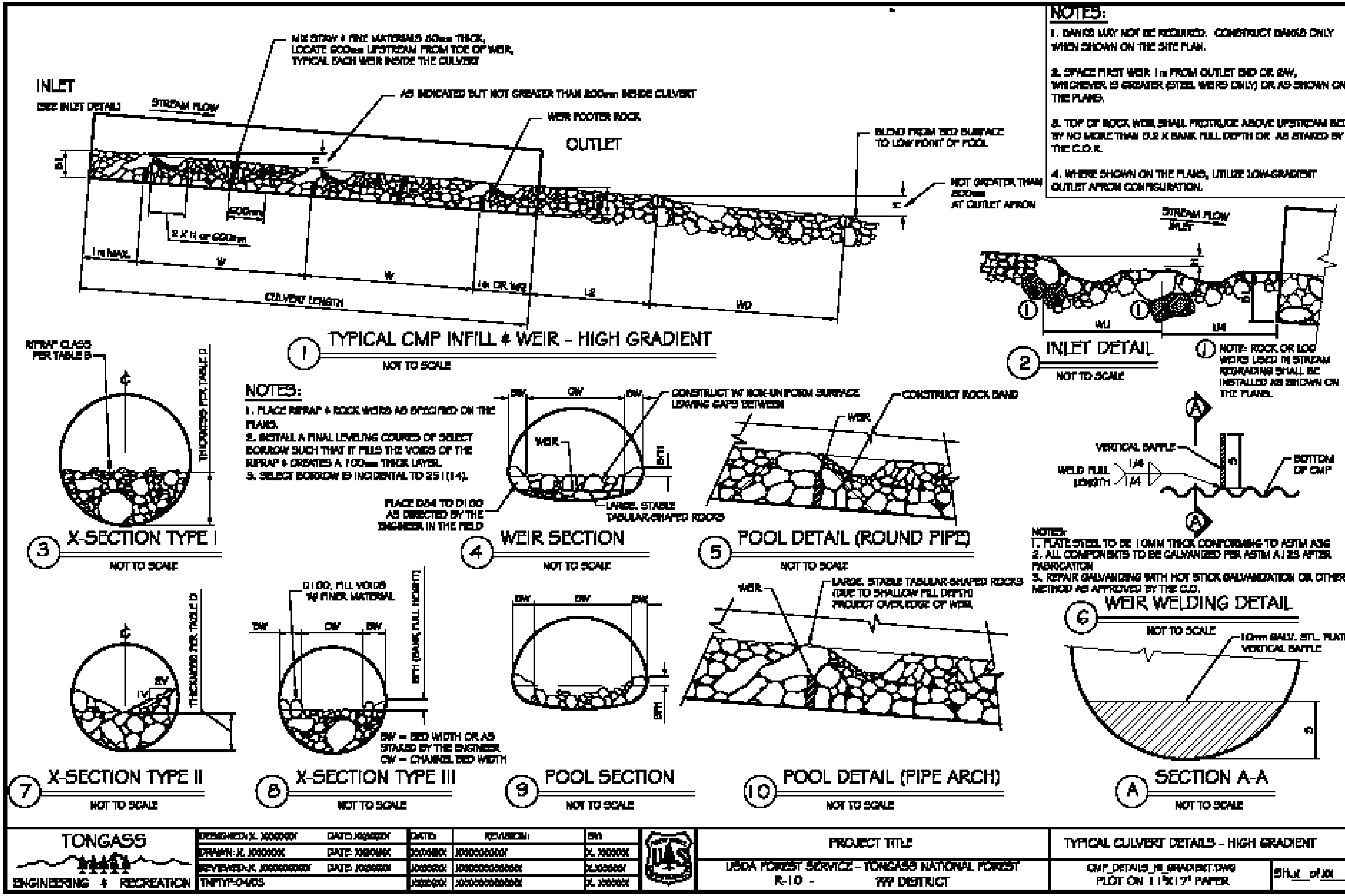


Debris

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

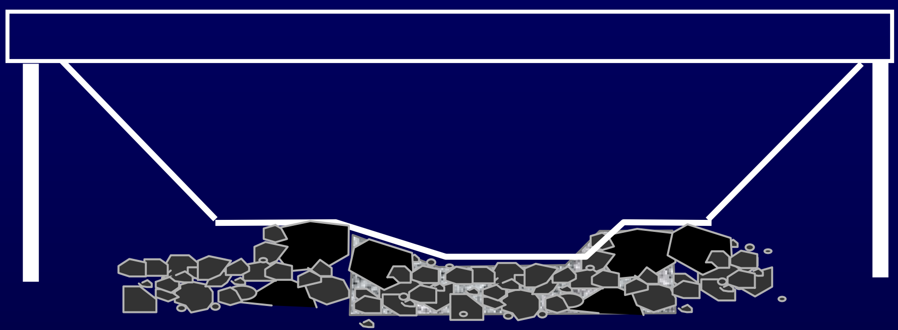
Solutions: Culvert width, alignment, and transition.



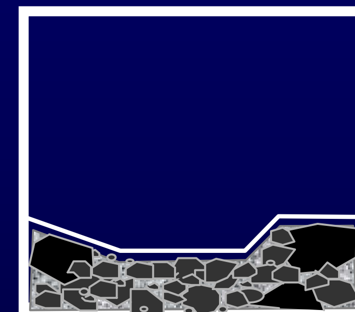


Bob Gubernick

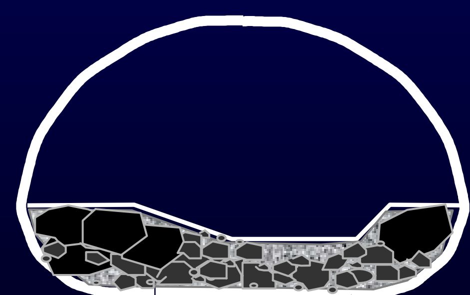
Stream simulation regardless of type of structure



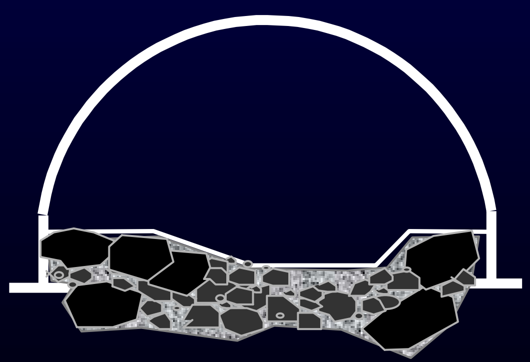
Bridge



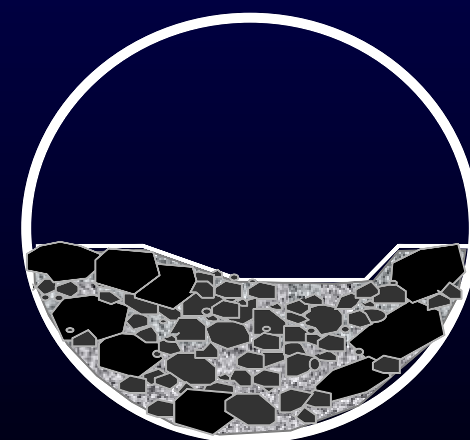
b. Box



c. Pipe Arch



d. Bottomless Arch



e. Embedded Round

Not necessarily better just because it’s a bridge.

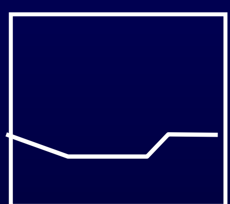
Bottomless compared to pipe

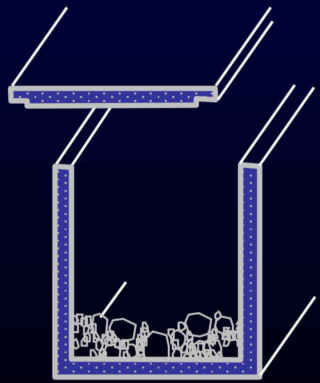
Bottomless

- 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 and corrosion
- Construction duration increased by cast-in-place concrete
- High shear strength of bed reduces risk of bed failure
- Compaction easier without round shape

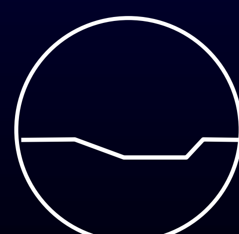
Pipe compared to bottomless

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



Bankfull width structure after 16 years


Barnard


Pringle Ck.
Stream width 9.1 ft, slope 5%
Culvert bed width 9.3 ft, slope 6%
Unit Power = 6.3 ft-lb/sec/ft³
Barnard

And this is was our conclusion.

What does all this mean for barrier assessment?

- What are assessment objectives:
  - Fish, target species, aquatic organisms, ecological connectivity

- Assessments might be biological, <u>physical</u>, ecological

Objective: Target species

- Physical assessment: Back-calculate a hydraulic design
  - Calculate hydrology, hydraulics
  - How are uncertainties treated?
  - Estimate probability of passage/barrier

Objective: Aquatic organisms

- Physical assessment: Simulation of channel
  - Is there an appropriate reference reach?
  - Is bed material similar?
  - Are bed forms similar and cross-section?
  - Is channel self-sustaining?

Example - Stream Simulation WDFW Effectiveness Monitoring

- Comparison of 19 stream simulation approximations to natural channel
- Independent variables: Width ratio and slope ratio
- Dependent variables
  - Bed particle size distribution
  - Inlet contraction
  - Inlet scour
  - Depth distribution analysis
  - Pool spacing
  - Residual depth
  - Bed stability

Bob Barnard, WDFW

Objective: Ecological connectivity

- Physical assessment: Channel context
  - Debris and sediment
    - “Fit” natural channel
    - Alignment
  - Potential vertical and lateral adjustment
  - Self-sustainability

Acknowledgements to:

For Stream Simulation

- Washington Fish and Wildlife
  - Bob Barnard
- USFS AOP project
  - Kim Clarkin, San Dimas Technical Development Center
  - Bob Gubernick, USFS Tongass National Forest
  - Dan Cenderelli, USFS Stream Systems Technology Center
  - Kim Johansen, USFS Siuslaw NF
  - Mark Weinhold, USFS White River NF

Stream simulation design guidelines

- Washington Department of Fish and Wildlife
  - 2003 - http://wdfw.wa.gov/hab/engineer/cm/
- USDA – Forest Service
  - Soon to be published
  - Training available
  - Contact kclarkin@fs.fed.us