Stream Simulation to Hydraulic Design, Monitoring and Research results — Experience and Perspectives from 10+ Years of Practice from the USFS AOP Program

Stream Simulation AOP structure Chequamegon-Nicolet NF, Wisconsin

Stream Simulation AOP structure Tongass NF, Alaska

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Washington Office AOP Training and Design Team & R9 Technical Services Team

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Stream Simulation AOP
Tongass N.F.

Discussion Topics

- USDA Forest Service AOP and Design Priority Policy
- Stream Simulation Definition
- Research and Validation of existing methods from research
- Monitoring Results and modification to stream simulation design methodology (Current Practices)

National USFS AOP "Policy"

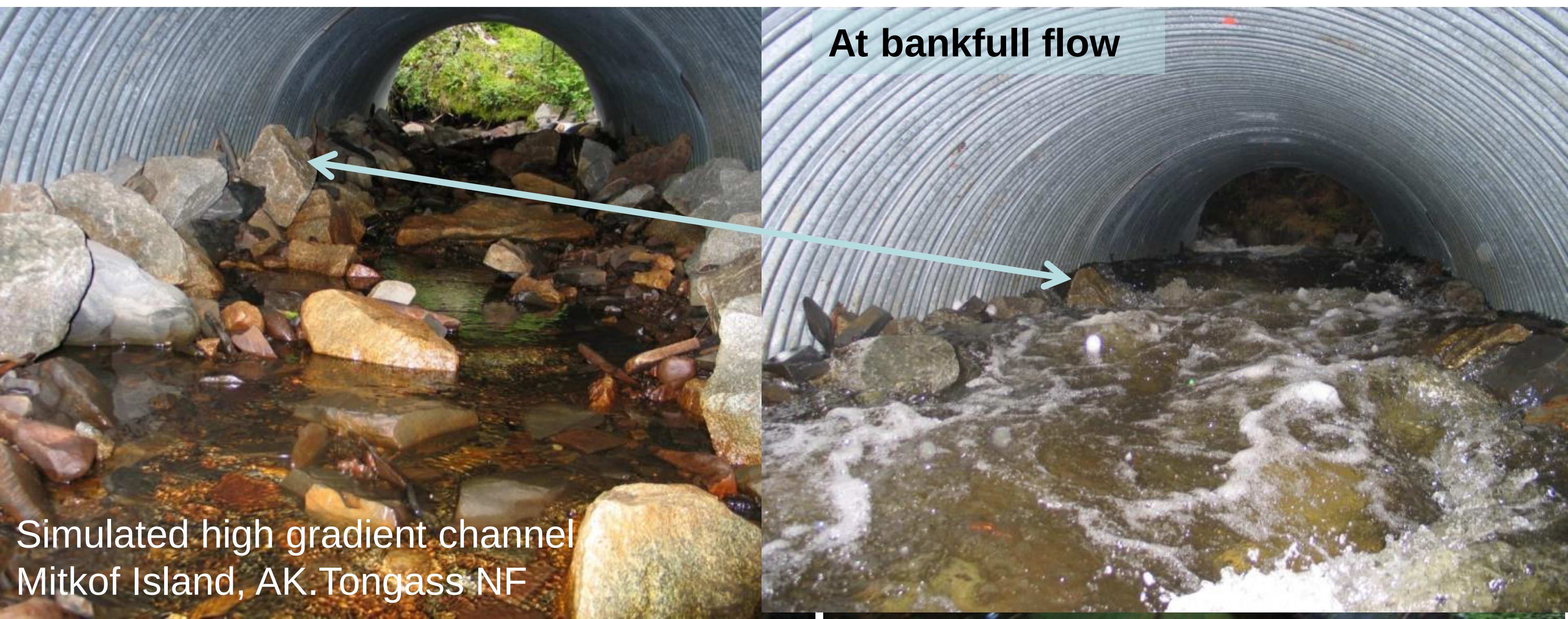
USDA Forest Service Transportation Structures Handbook FSH 7709.56b Chapter 60 Section 65.2

1. **Stream simulation strategies. Bridges, arches or embedded culverts provide stream simulation.**

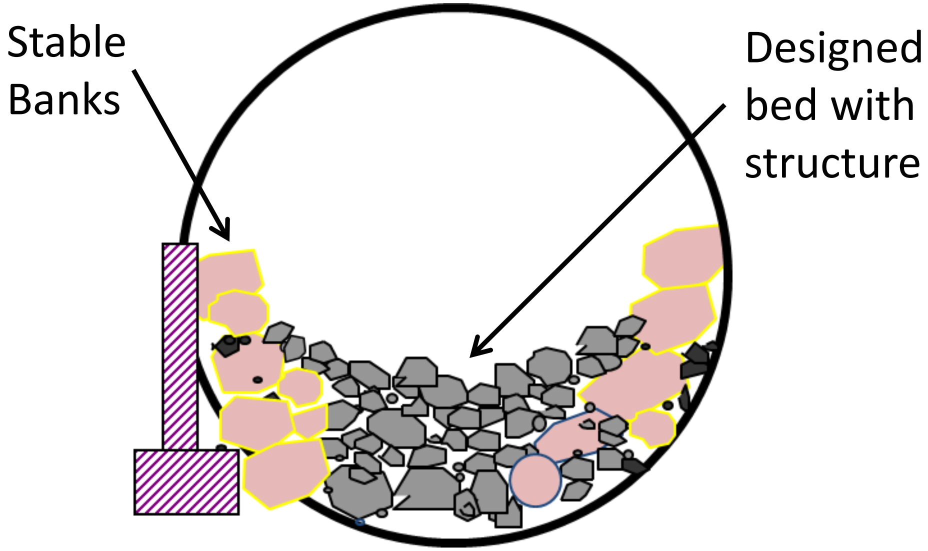
2. **Geomorphic-based Channel Design. Reconnects the upstream and downstream channel while meeting most fish and other aquatic organism movement and habitat needs.**

3. **Hydraulic design. Designs based primarily on hydraulic capacity should be limited to low stream gradients, where the culvert is constantly partially submerged. Baffled culverts or structures designed with a fishway are discouraged and should be used as a last resort,**

Stream Simulation Design Definition: A channel that simulates characteristics of the adjacent natural channel (“reference reach”), that will present no more of a challenge to movement of organisms than the natural channel.



Stream Simulation Culverts

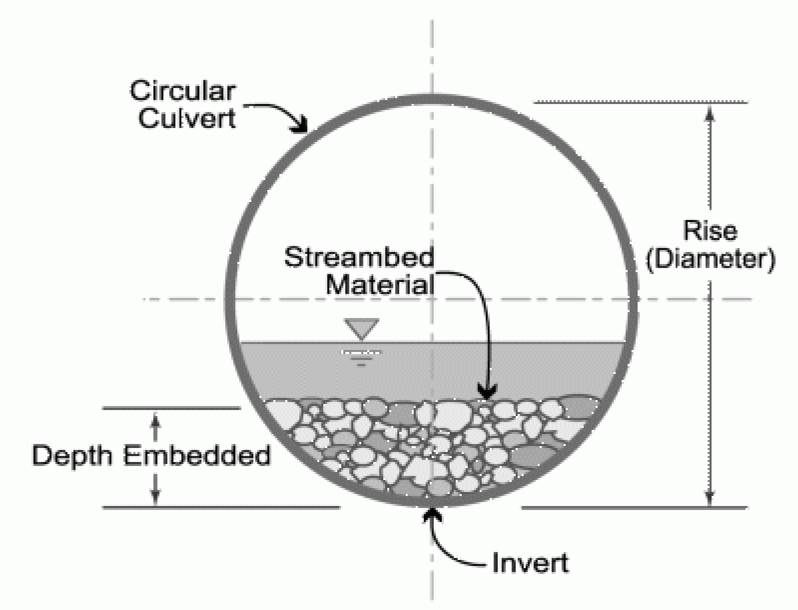


Stream Simulation Schematic

Stream Sim Structure
Chequamegon-Nicolet N.F.

- Bankfull plus in width and embedded by a factor of safety plus max residual pool depth from the reference reach
- Culverts are infilled with a streambed substrate and structural and roughness elements (ribs, steps, boulder clusters, etc.)

Embedded (Recessed) Culverts



Embedded Schematic

Embedded Structure
Tongass N.F.

- Usually left to infill naturally or are seeded with some material
- Design guidelines (width & embedment depth & slope) vary from State to State
- No streambed structure or banks are constructed

Research, Results, and Validation of Existing Stream Simulation Design Methods

Studies

- University of Minnesota
  - Performance assessment of oversized Culverts to accommodate fish passage 2011
  - Sediment transport through recessed culverts 2015
- Washington Dept. of Fish and Wildlife
  - An evaluation of stream simulation culvert design methods in Washington State 2014
- Cleveland State University
  - A study of bankfull culvert effectiveness 2015

K.Johansen

University of Minnesota - Performance assessment of oversized Culverts to accommodate fish passage 2011

Study

- Research was conducted to better understand the hydraulic conditions related to the practice of recessing culverts and other fish passage design elements over a range of landscapes in Minnesota.
- Design elements analyzed included bankfull width, slope, channel materials, side barrels and recessed culverts.
- Nineteen culvert sites evaluated.
- The main criterion used to evaluate performance of the culverts was the presence or absence of adequate sediment in the recessed culvert barrel.
- Six of the fourteen sites with recessed barrels had no sediment accumulation.

University of Minnesota - Performance assessment of oversized Culverts to accommodate fish passage 2011

Results

- **Principal Problem - Lack of sediment retention in pipe**
  - Inadequate transport in stream
  - site not in place long enough
  - Inadequate transport due to immobile stream beds (high gradient)
  - Improper design (width, slope) causing excessive velocities
  - Excessive sediment accumulation in side one of multiple barrel designs
  - Large flows removing deposited sediment
- **Channel Stability Concern - Head cut prevention**
  - Grade controls installed and no apparent headcuts

Univ. of Minnesota Sediment transport through recessed culverts 2015

Study objectives:

- What is the impact of filling and self filling a embedded culvert on streambed stability/roughness in the culvert?
- How does this change with flow rate/slope/grain size?

Channel Types and Slopes Used In Flume Study

Pool Riffle channel
0.002 to 0.02
Low slope gradient
Flume slope = 0.002

Step Pool channel
0.03 to 0.10 High slope gradient
Flume slope = 0.03

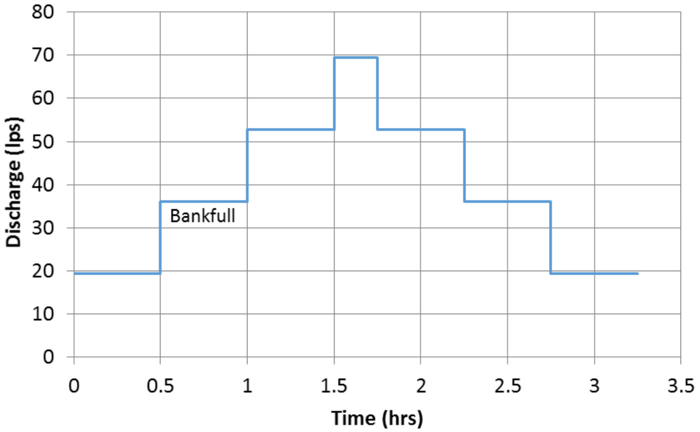
Plane bed channel
.01 to .03% Moderate slope gradient
Flume slope = 0.015

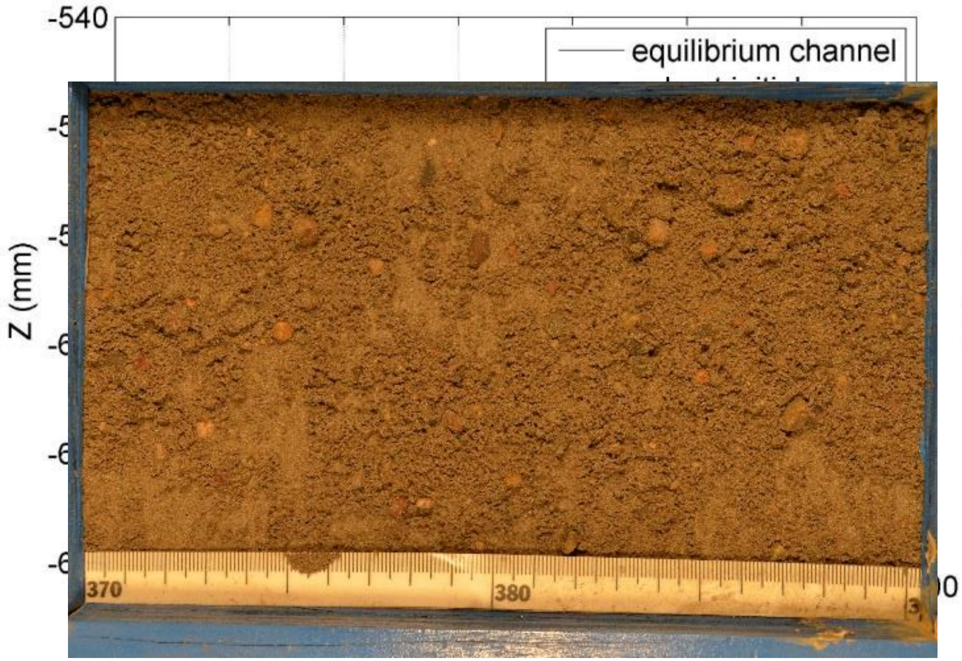
Experimental Setup

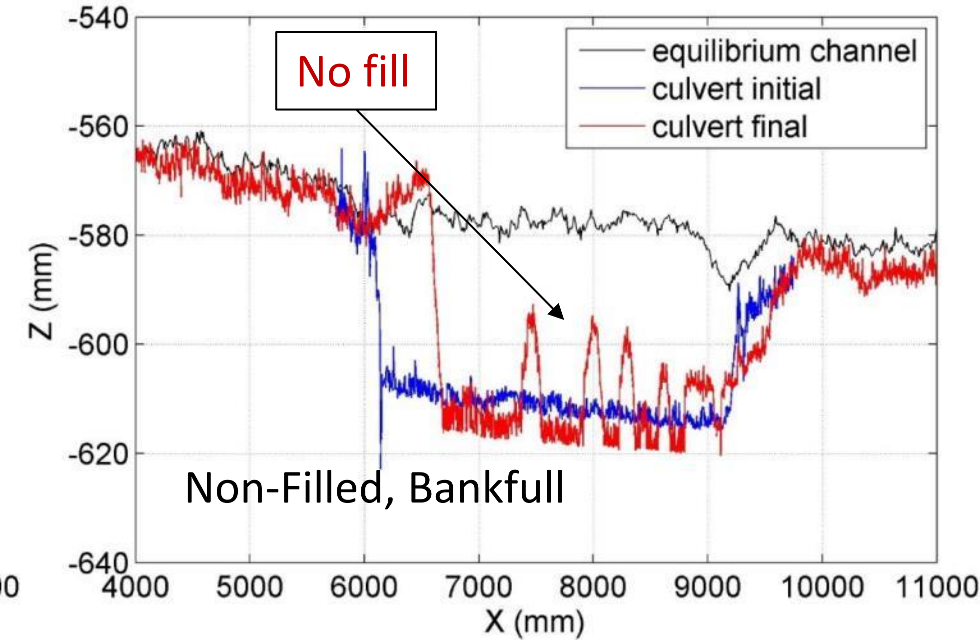
1. The equilibrium slope was developed at bankfull flow with banks along entire flume

2. An armor layer was developed with sediment recirculation

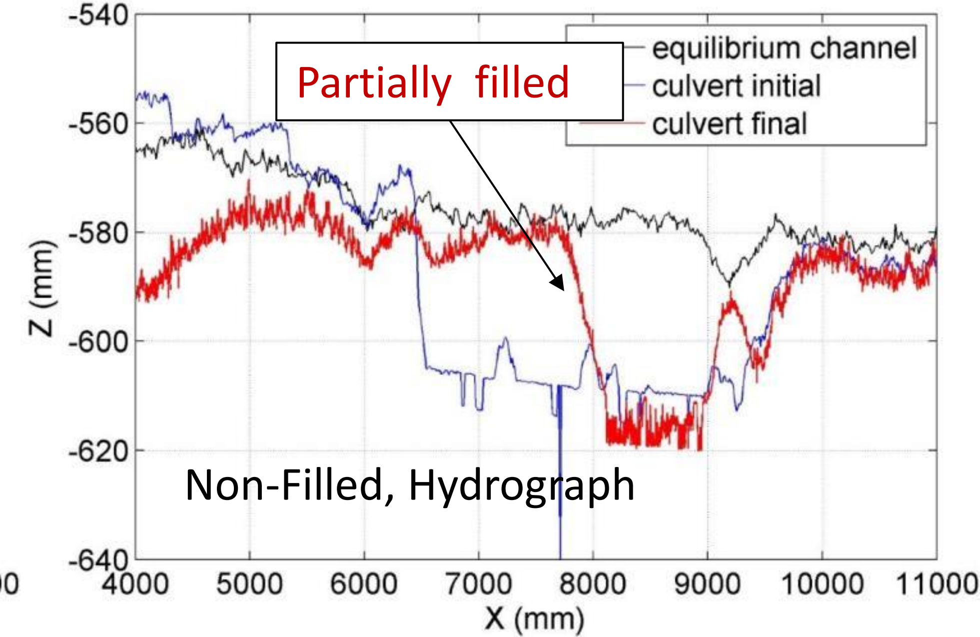
3. Culvert was set at 300 mm (scaled) below grade. Bankfull and overbank hydrograph experiments were conducted. “Filled” experiments with the equilibrium bed and “non filled” with material in culvert removed

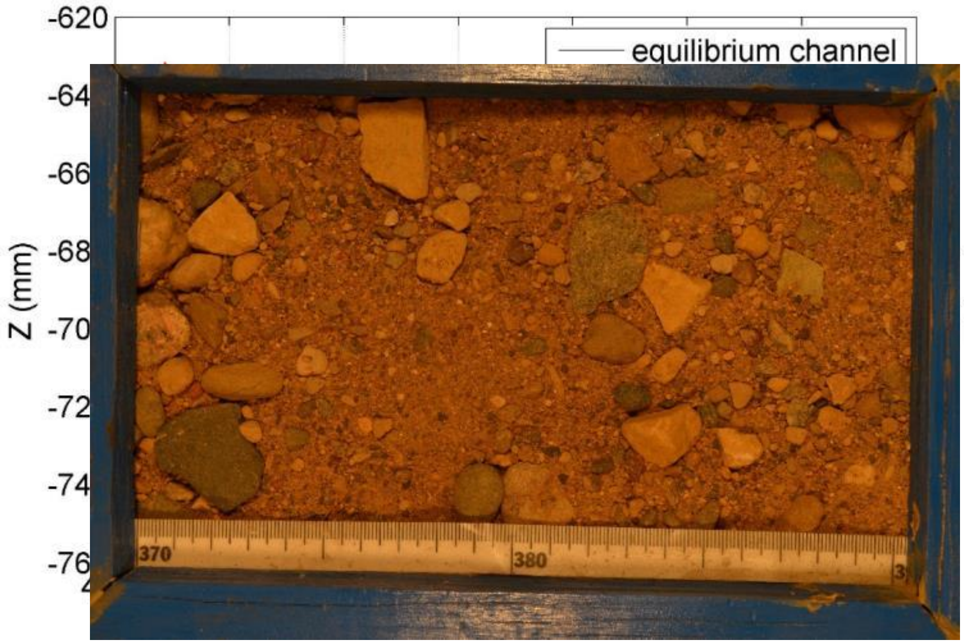


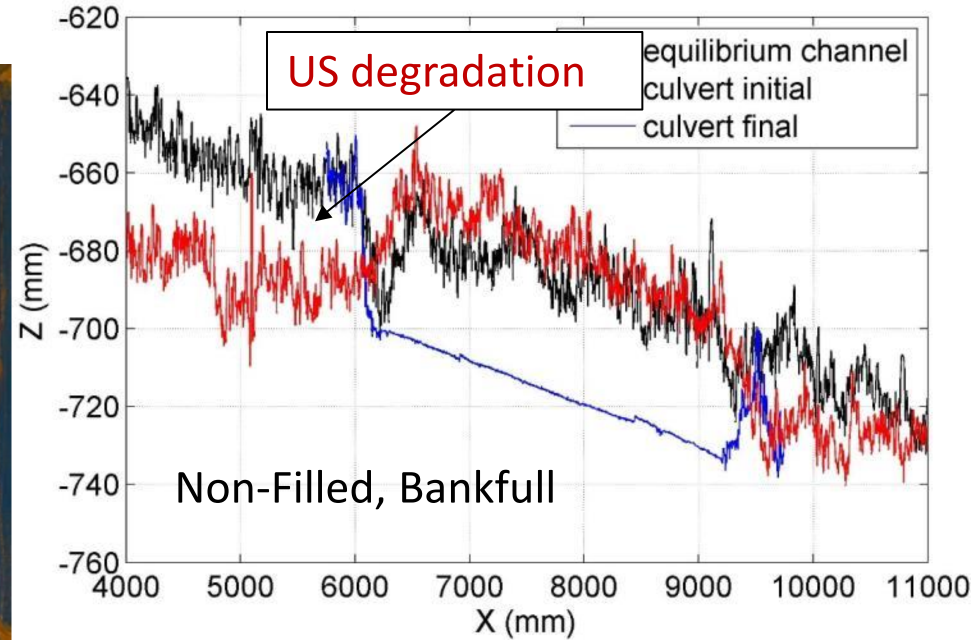




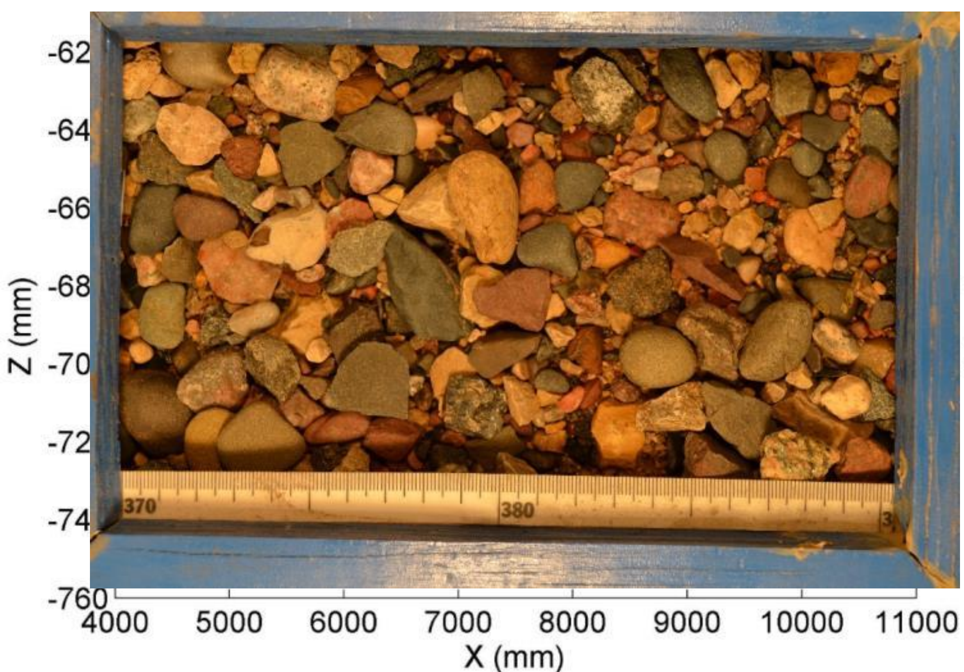
Low Gradient

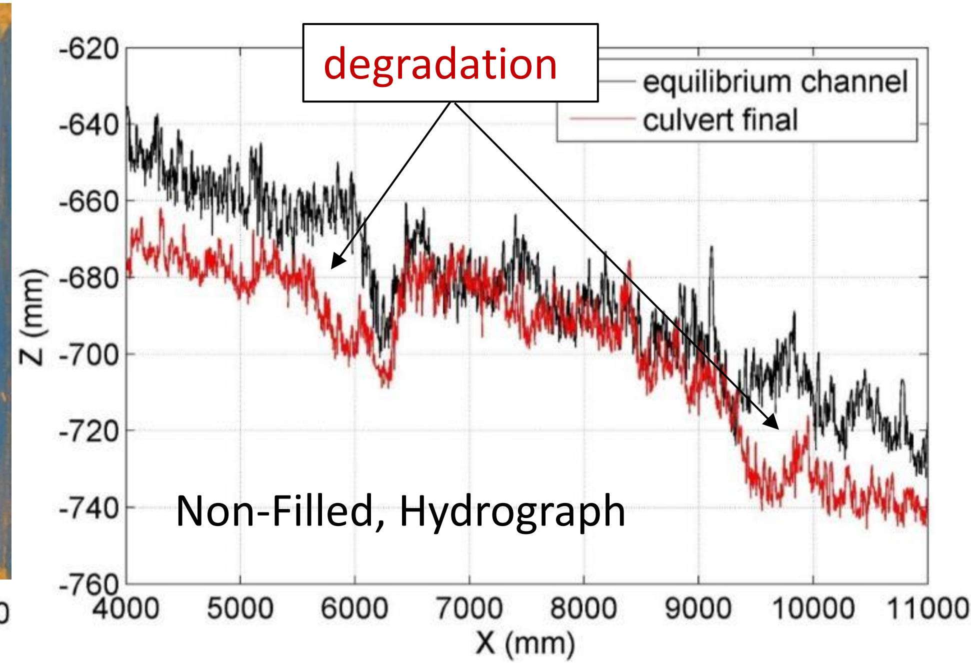






Moderate Gradient

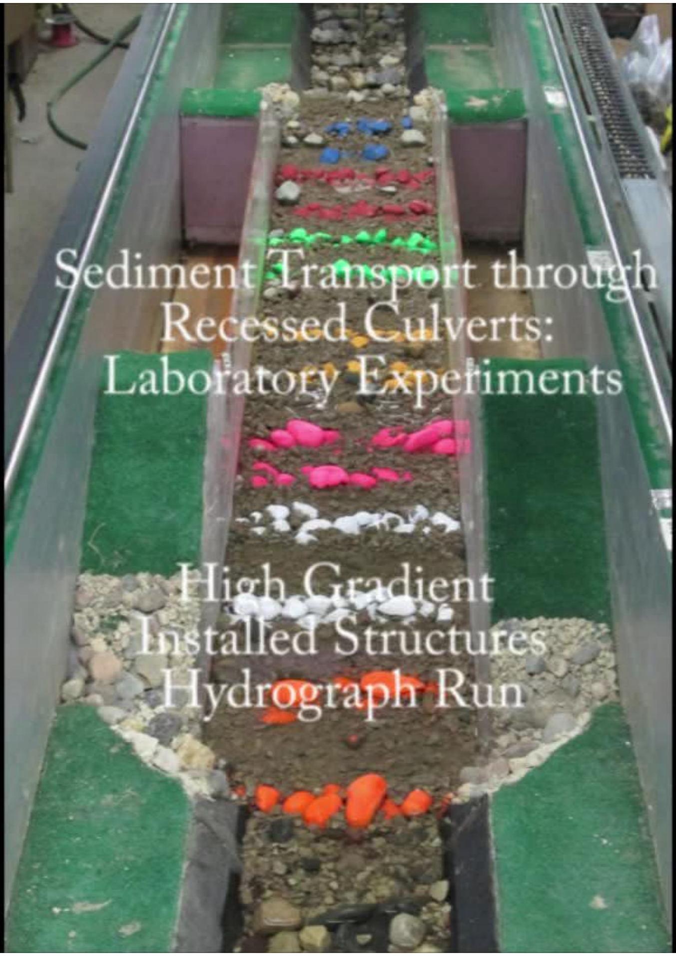


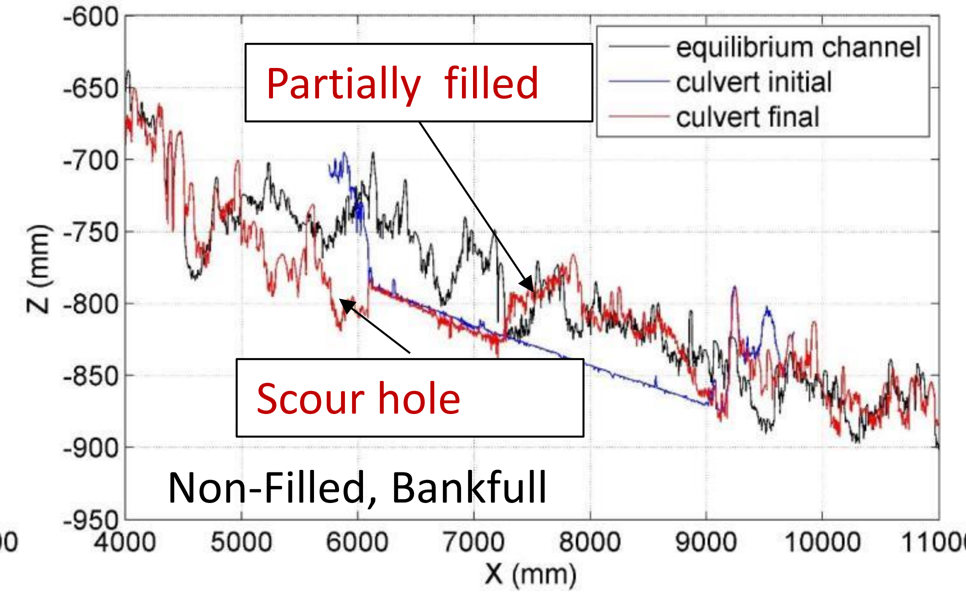


Low and Moderate Gradient Summary

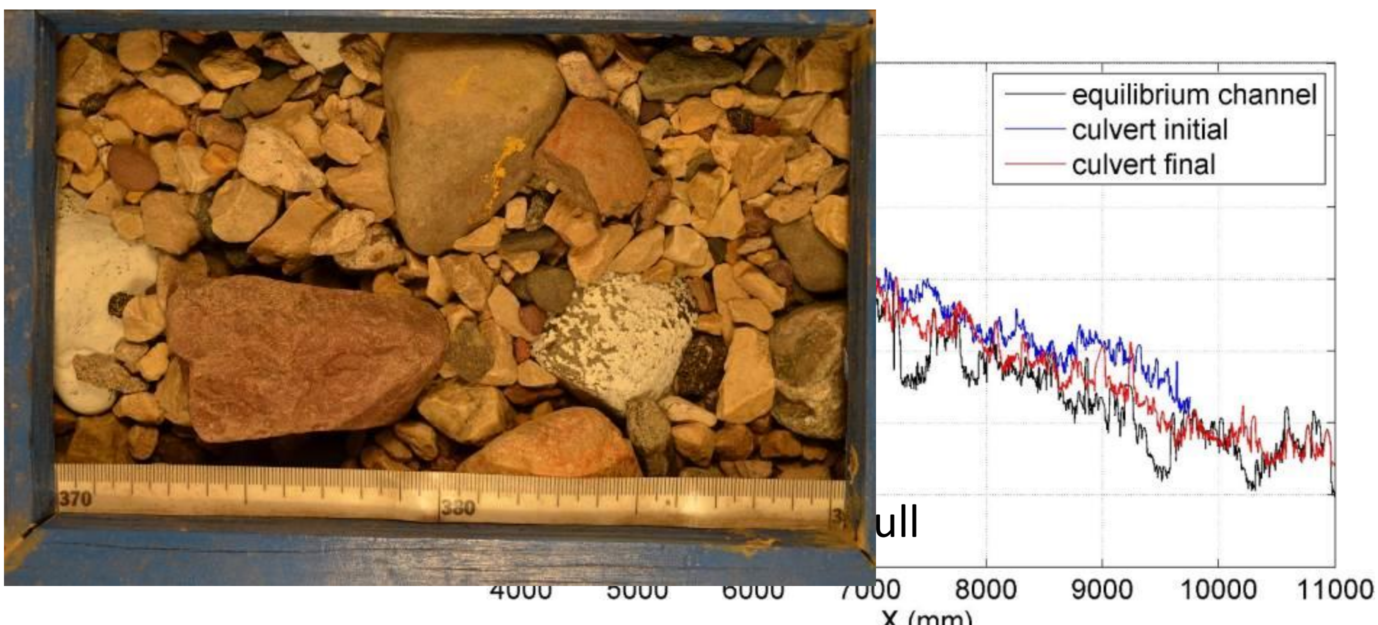
- Culvert width equal to bankfull width did not inhibit sedimentation in culvert
- Very different sediment dynamics in low slope and moderate slope experiments
- Site specific analysis of flow, shear stress estimates and mobility of sediments is needed to predict sediment movement into culvert
- Filling the culvert in general protected against upstream headcut and downstream scour

High Gradient – with Bed Structures

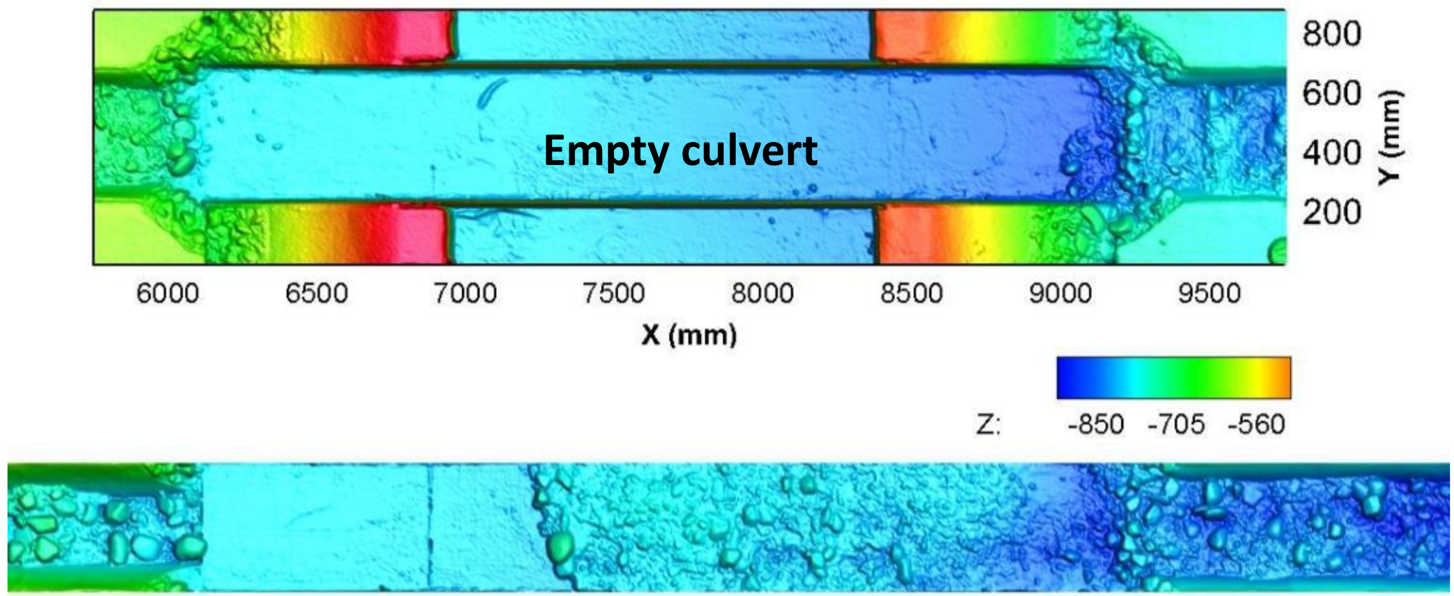




High Gradient



High Gradient, Non-filled

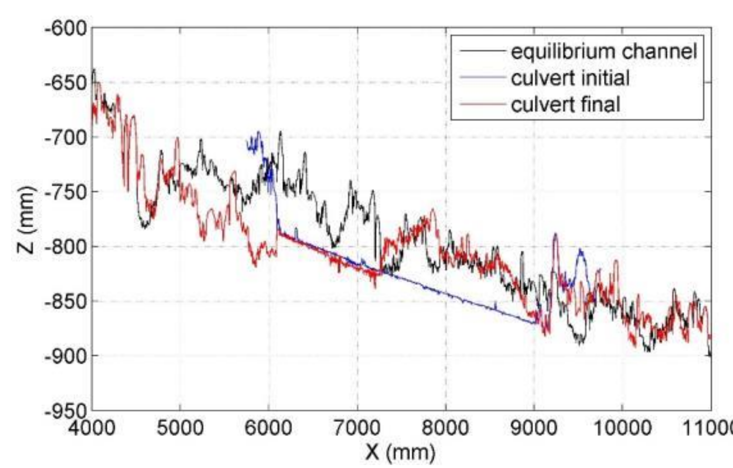


Flow →

After Bankfull Flow

After 1 hour of run time, some sediment had moved into culvert, but culvert had not filled.

Significant scour occurred upstream of culvert up to the location of the last immobile structure.



Summary – High Gradient

- Structures are important to maintaining sediment stability in culverts and upstream for high gradient systems
- Placement of grade controls within ½ BFW can cause failure of other downstream control during high flows
- Sediment filled into empty culvert only when upstream structures failed (resulting in significant scour)

Wa. Dept of Fish and Wildlife Research on Stream Simulation Structures - Barnard et al. 2014

- Culvert slope >1.25% of the ref reach had sediment 50% larger then those <1.25%
- Mean depth was shallower than ref reach.
- Sediment size, channel cross section, thalweg depth variance best determined at the time by design and constructed per the design.
- Complex bed structure inside stream simulation culverts do not form on their own. They must be designed and constructed at installation.

Cleveland State University Bankfull Culvert Design Effectiveness – Tumeo 2011

- Ohio DOT embeds and allows culverts to "Self Fill"
- Embedment requirement is 10% of the rise!

- Found that culverts set >1% did not retain stream sediment
- Installed structures were not always implemented "As Designed"
- Recommendations for Ohio design methodology - Don't install embedded culverts over 1%!!!!

Take Home Messages from Research

- How we design and implement stream simulation or embedded structures matters!
- Design methods that just state criteria/standards as is the case for most of state and municipal DOT's and State and Federal Regulatory agencies don't accomplish the desired out come
- Understanding the stream, proper analysis methods, sufficient data, Interdisciplinary team work and Inspection at critical construction times are crucial for success

Monitoring Results and modification to stream simulation design methodology (Current Practices)

Studies

- To Fill or Not to Fill – Experiments on the R10 - Tongass N.F. and R9 - Chequamegon N.F.
- Maximum scour depth computation method change
- Banks – Abrasion protection (steel and Aluminum
- Flood response of Stream Simulation Culverts during T.S. Irene 2011
- Economics????

Field Experiments – Chequamegon - Nicolet N.F.

Site Conditions:

- Low gradient sand bedded channels (<0.002).
- Minimal offset from upstream to downstream channel
- Vegetation controlled banks

Design:

- Utilized USFS stream simulation design Methodology
- No infill placed
- Some sites no bed or bank structure placed. Some had bed structure placed

Embedded culvert with no bed structure placed. Sand bed is fairly flat and has full coverage. No head cut observed

Field Experiments – Chequamegon - Nicolet N.F.

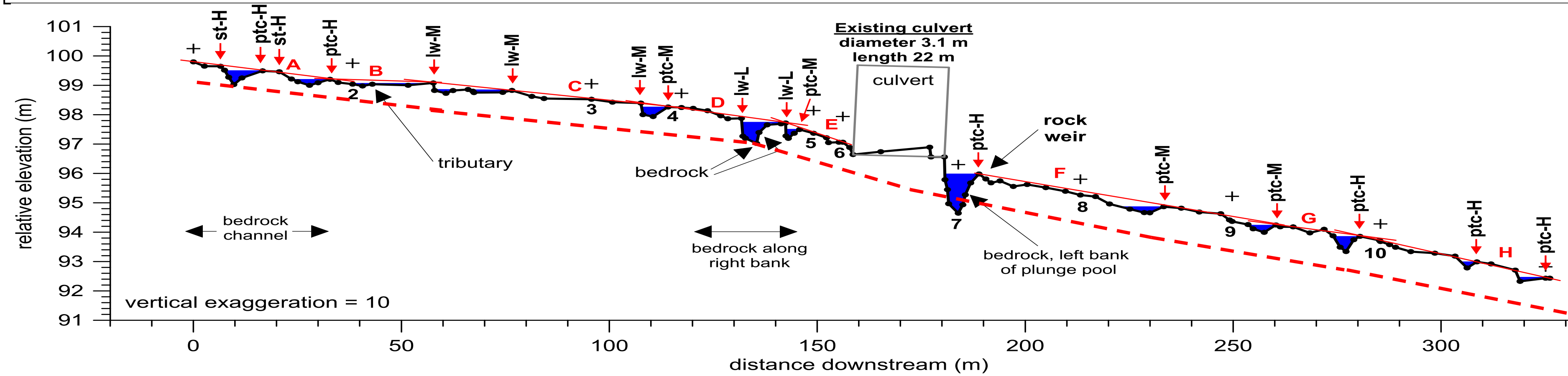
Conclusions:

- Not infilling is appropriate for most sand bedded channel conditions
- Stream bed should not be offset by more than 0.5ft without a careful evaluation of a longitudinal profile. Some offsets are due to upstream aggradation some from downstream adjustments
- Utilize some bed structure to produce a thalweg and some bed complexity

Embedded culvert with no bed structure placed during construction. Sand bed has maintained a thalweg and bed has topographic relief

Delineation of the Lower Vertical Adjustment Potential Line (Max Scour)

- Choose deepest pool along channel not influenced by the undersized culvert.
- Adjust line to reflect scour/fill processes that occur during floods. Recommended criteria:
  - 1.00 x Pool Max Depth (PMD): Step-pool channels, S > 5%, boulder-cobble boundaries.
  - 1.25 x PMD: Step-pool channels with S < 5%, cobble-gravel boundaries.
  - 1.50 x PMD: Steep riffles with ribs, cobble-gravel boundaries.
  - 1.75 x PMD: Riffles, gravel-cobble boundaries.
  - 2.00 x PMD: Riffles, sand-fine gravel boundaries.
  - No adjustment for bedrock.



BANKS AND ABRASION PROTECTION

Corrosion rate increased due to abrasion from bedload

Tropical Storm Irene August 28, 2011

Failure Mechanism During Floods

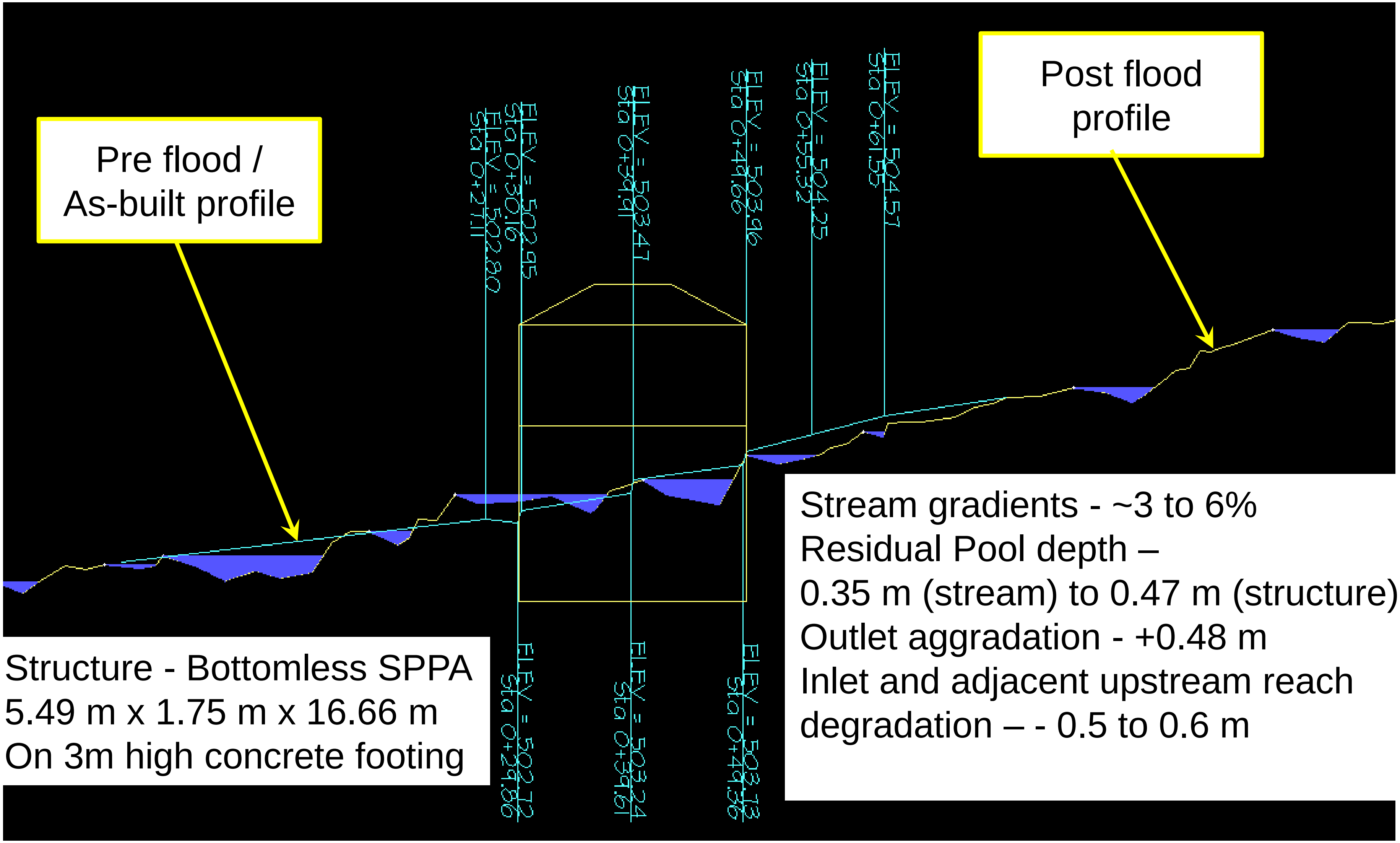
Failure Mechanism

- Hydraulic Exceedance (capacity)
- Sediment "Slug"
- Woody Debris Lodgment (slower by collection of woody debris and sediment buildup)
- Debris flow (Large / catastrophic -Natural or from upstream crossing failure)

Stream Simulation Design
Jenny Coolidge Brook

Post Irene Condition
Outlet

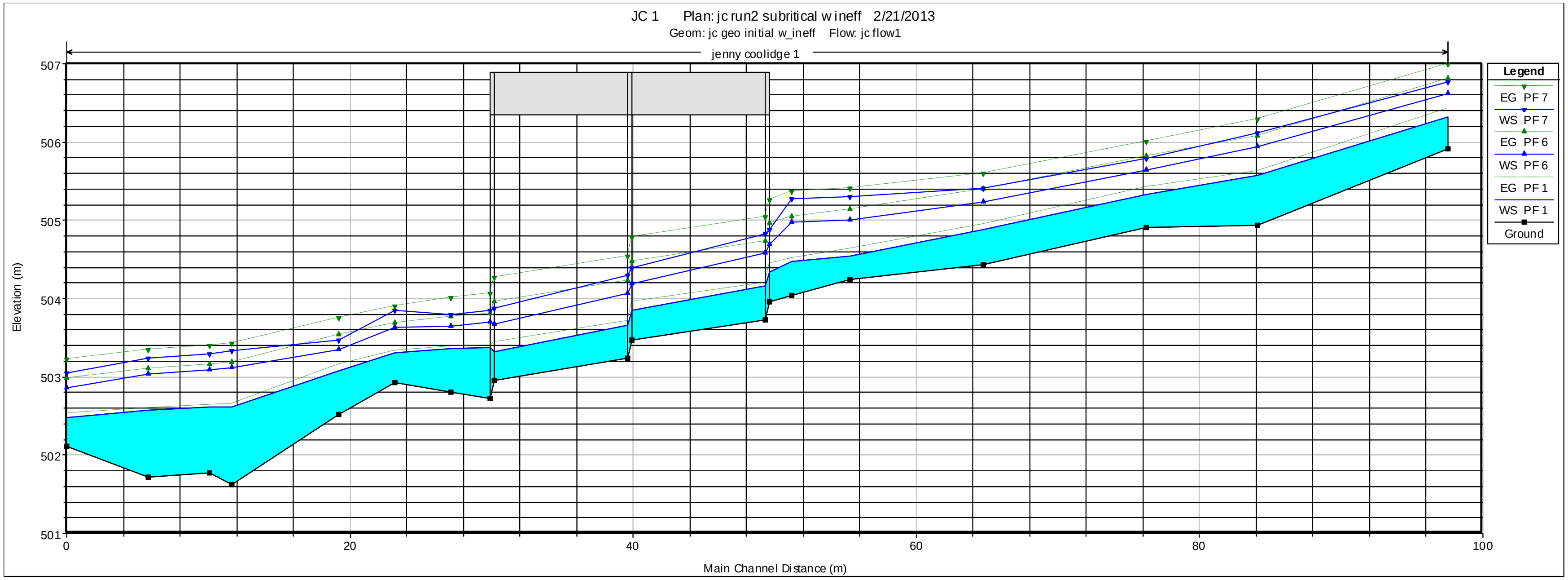
Jenny Coolidge Brook – Pre & Post Flood Profile



Structure - Bottomless SPPA
5.49 m x 1.75 m x 16.66 m
On 3m high concrete footing

Stream gradients - ~3 to 6%
Residual Pool depth –
0.35 m (stream) to 0.47 m (structure)
Outlet aggradation - +0.48 m
Inlet and adjacent upstream reach
degradation – - 0.5 to 0.6 m

Jenny Coolidge Brook
Preliminary Hydraulic Analysis



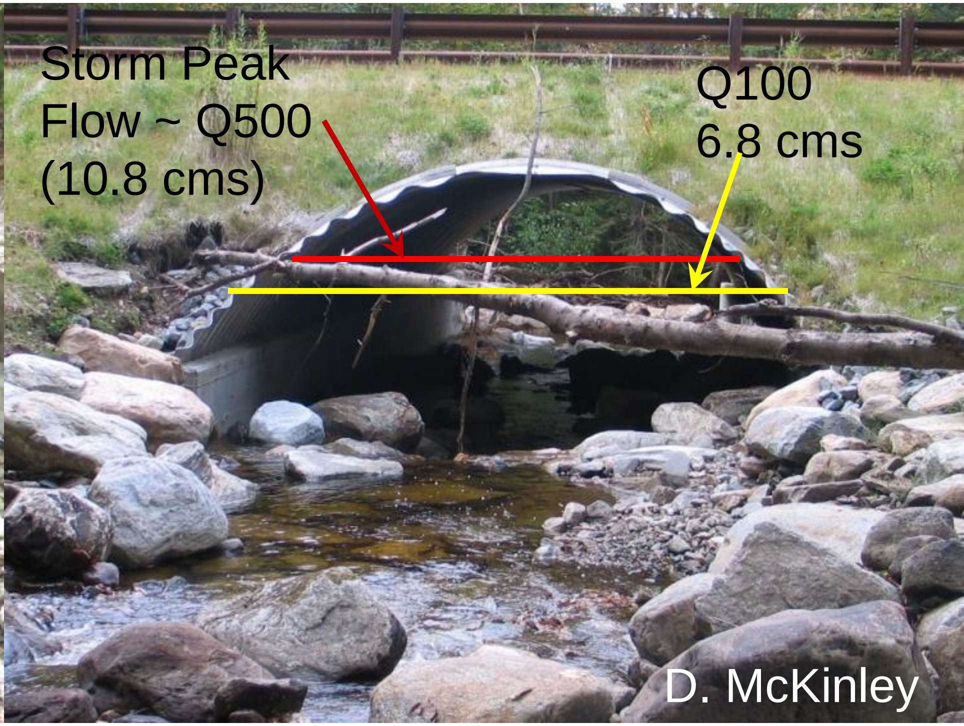
- Original As-Built conditions modeled
- Roughness determined by empirical methods (Limerinos & Jarrett method)
- Regression equations used to determine flows.
- Flood indicators surveyed in the field both up and downstream
- Modeled Q500 flow approximately matches flood indicators in several locations

Stream Simulation Flood Proof!

Green Mountain National Forest - FR17A - Bottomless Arch Inlet

Completed Construction 2010

Post TS Irene September 2011



Storm flows did not overtop the road. Minimal scour on left side of arch

Stream Simulation Flood Proof!

Green Mountain National Forest - FR17A - Bottomless Arch Outlet

Competed Construction 2010

Post TS Irene Sept. 2011

D. McKinley

J.Krohn

Lost largest boulders near outlet and some roughness along stem walls.
Structure and road undamaged and structure passes all aquatic organisms

Stream Simulation Design

Jenny Coolidge Brook

Pre Irene Construction
Inside Structure

Post Irene Condition
Inside Structure

Stream Simulation Design

Jenny Coolidge Brook

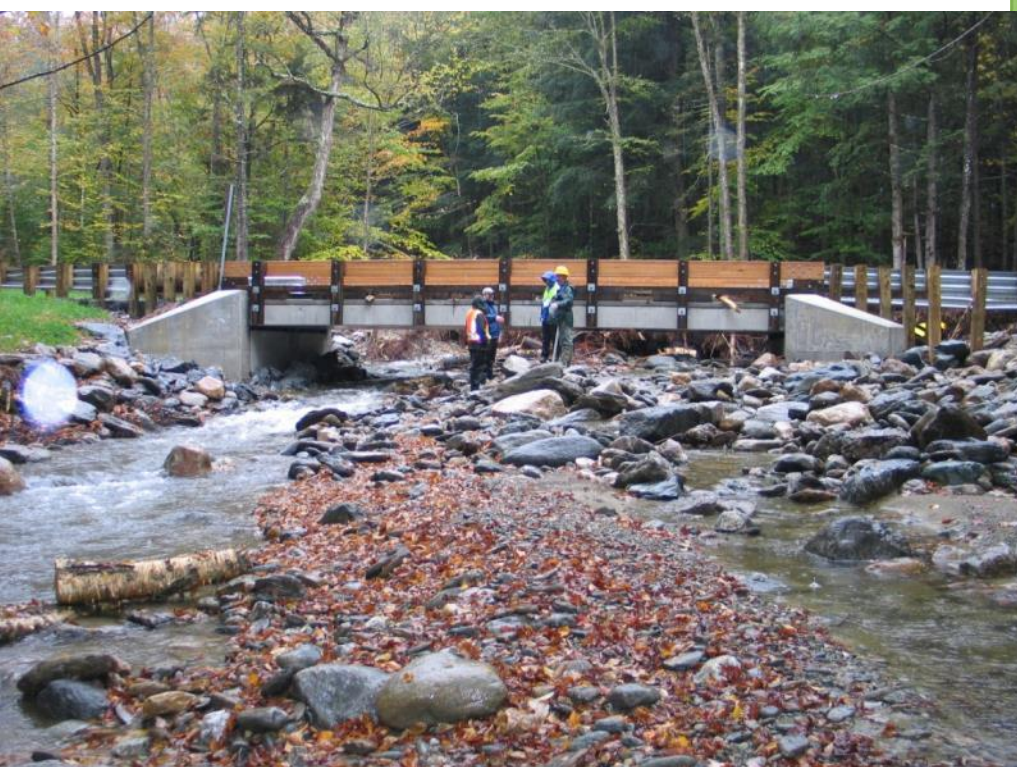
Bed degradation

Pre Irene Construction
Upstream of Structure

Post Irene Condition
Upstream of Structure

Poor Geomorphic Location

I Fought the Fan and the Fan Won!



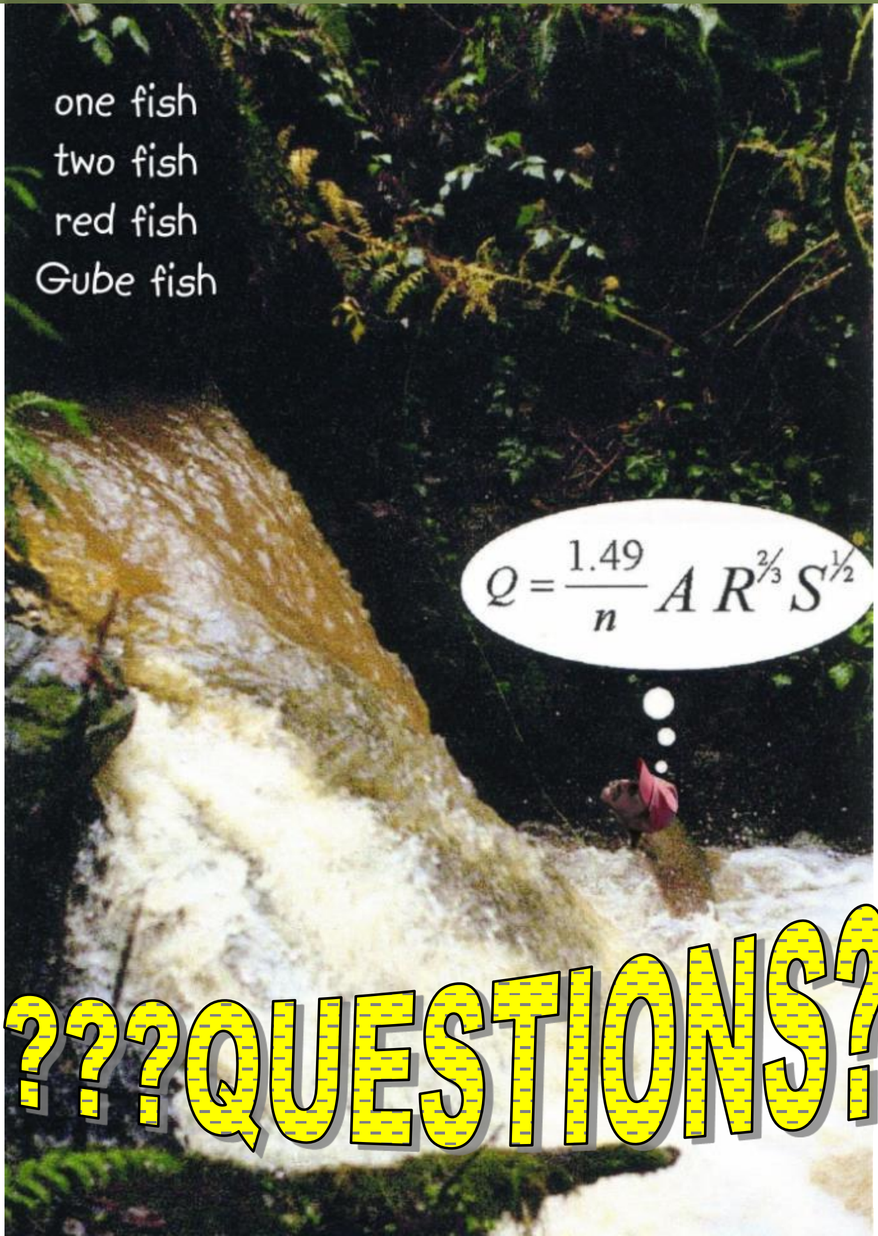
Even Good Designs In Poor Locations Fail If They Are Not Designed To Fail!

Diversion Potential

Small plugged culverts can create big messes on hill slopes. Failure point not built into the design

Sustainability and flexibility over time. 100% passage for all A.O.'s

Mitkof Isl. Tongass NF 4% stream gradient



???QUESTIONS???

Art By Tomas Dunklin