History and ecological context of road-stream crossing designs

U.S. Department of Transportation
Federal Highway Administration

FOREST SERVICE
U.S.
DEPARTMENT OF AGRICULTURE

U.S.
FISH & WILDLIFE
SERVICE

A brief history of AOP at crossings

- <70's - Minimal concern for AOP at road-stream crossings
- 70's - USFS, FHWA, states develop culvert design guidelines
  - Hydraulic method
  - Focus on fish, especially adult salmonids
- 90's – ESA listings, improving science
  - MOU's to restore sp, lawsuits, floods
  - Inventories, assessment protocols, passage programs
  - Issue broadened to ecological issues
  - Stream simulation introduced
  - Global concern
- 00's – Ecological goals, refined science
  - Aquatic organism passage
  - USFS program, Forest and Fish

So how big is the problem?
Western USFS - $331M worth of work

Forest Service Region	Est # of culverts on fish-bearing streams	Est # of barriers	Barriers
R10 – Alaska	2,016	1,574	78%
R6 – Washington	1,800	1,620	90%
R6 – Oregon	3,700	3,300	89%
R5 - California	447	193 *	43%
Total	**7,583**	**6,546**	**86%**

From Tom Thompson testimony to Congress
April, 2002

* Brenda Olson, R5

All Washington Culvert Barriers

State	8% - 2,700 culvert barriers
Private	64% - 21,460 culvert barriers
Federal	14% - 4,600 culverts barriers
County, Municipal	14% - 4,600 culverts barriers
Total	**33,000 culvert barriers (plus 6,000 dams)**

WDFW, 2001

Road-Stream Crossings in WI

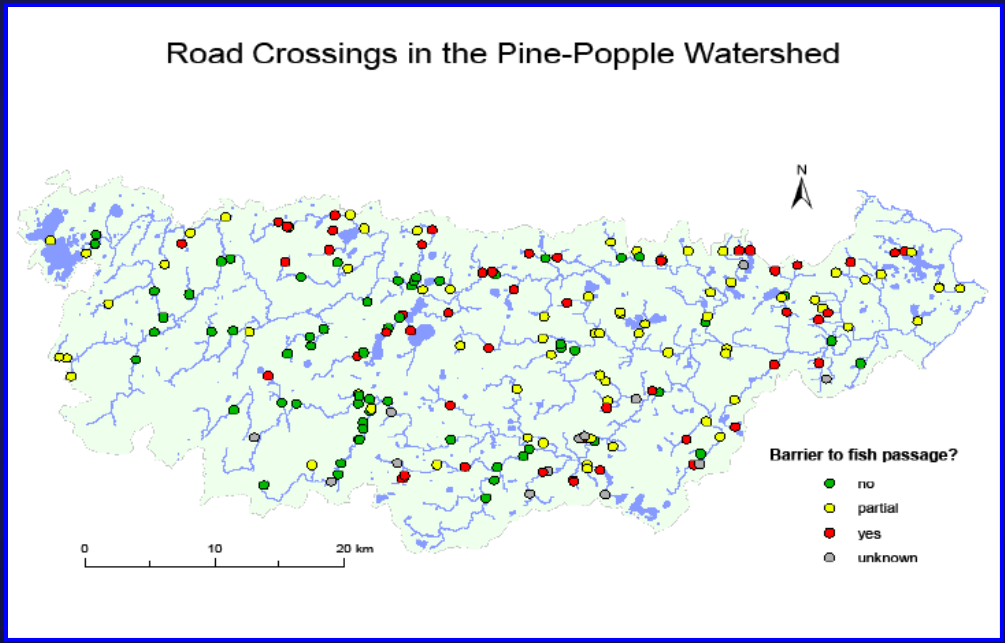
Road Type	Est # of Crossings
Interstate Hwy	1.3% - 817
US Hwy	3.2% - 1,982
State Hwy	8.6% - 5,381
County Hwy	20.6% - 12,776
Secondary Roads	66.2% - 41,055
Total	**61,971**

WDNR GIS Analysis by Miller, 2008

Rd-Stream Crossing Barriers: East

- Wisconsin
  - 29% of 62,000
  - 18,000 (250/cty)
- Other States
  - GA 34%
  - WV 69%

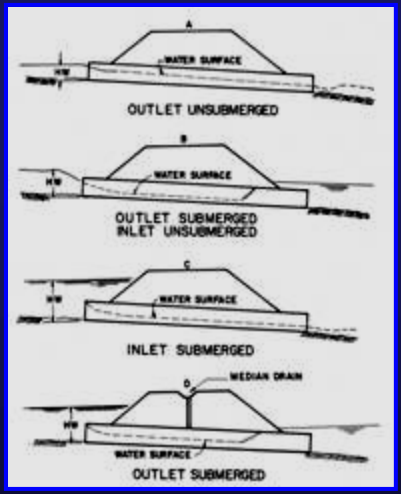
(Miller, 2008)



176 crossings, 29% total barriers
(Fedora and Simonson, 2008)

A brief history of culvert design

- <70's - Engineering
  - Min (construction) cost (design for failure?)
  - Hydrology and hydraulics (H&H)
- 70's and 80's - Engineering and Fish
  - Min cost with multiple obj
  - H&H: baffles, roughened culv, debris
- 90's and 00's – Engineering and Ecology
  - Balance cost with trans & eco obj
  - Pass AO, bedload, debris
  - Max structure life
  - Stream simulation



Introduction to Culvert Design Methods

Conceptual performance standards

Geomorphic concepts and setting

Protection, restoration of critical habitats

Traffic, road, safety, other objectives

Funding available

Design methods

- Hydraulic (H&H)
  - No slope-TW
  - Slope
  - Baffles
  - Roughened
- Stream Simulation
- Other

Introduction to Culvert Design Methods

H&H: No Slope-TW

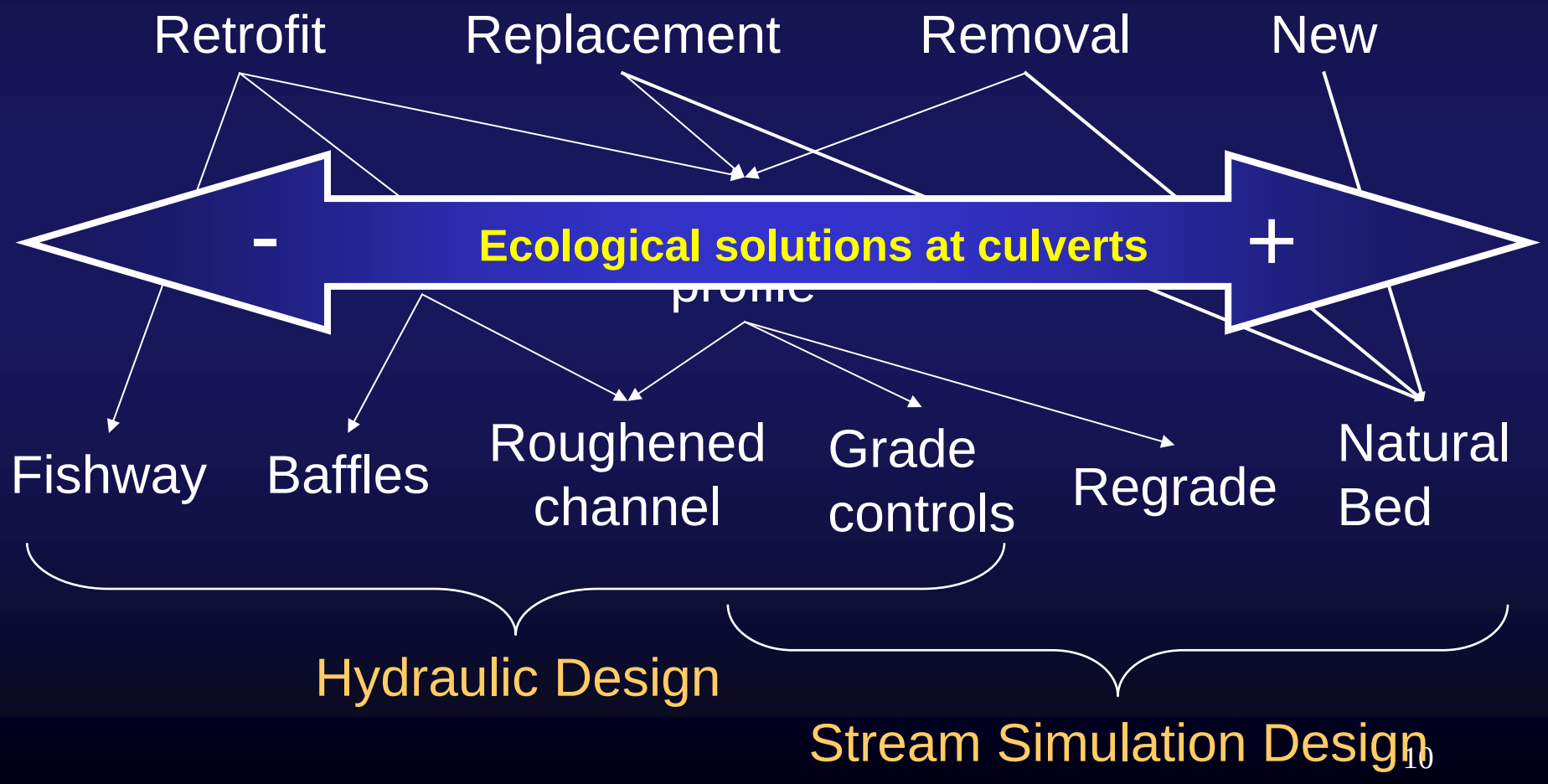
Stream Simulation

H&H: Slope

H&H: Baffles

H&H: Roughened

Types of Culvert Design Projects and Tools



- **Ecological solutions at Road Crossings** +

Natural channel with

- Bankfull channel
- Flood plain
- Ecological processes

- **Ecological solutions at Road Crossings** +

Hydraulic Design - Objectives

- Pass flood flows
- Pass target species at certain flows

- **Ecological solutions at Road Crossings** +

Stream Simulation - Objectives

- Pass flood flows and debris
- Passage of all aquatic organisms
- Maintain most ecological processes

- **Ecological solutions at Road Crossings** +

Full spanning bridge - Objectives

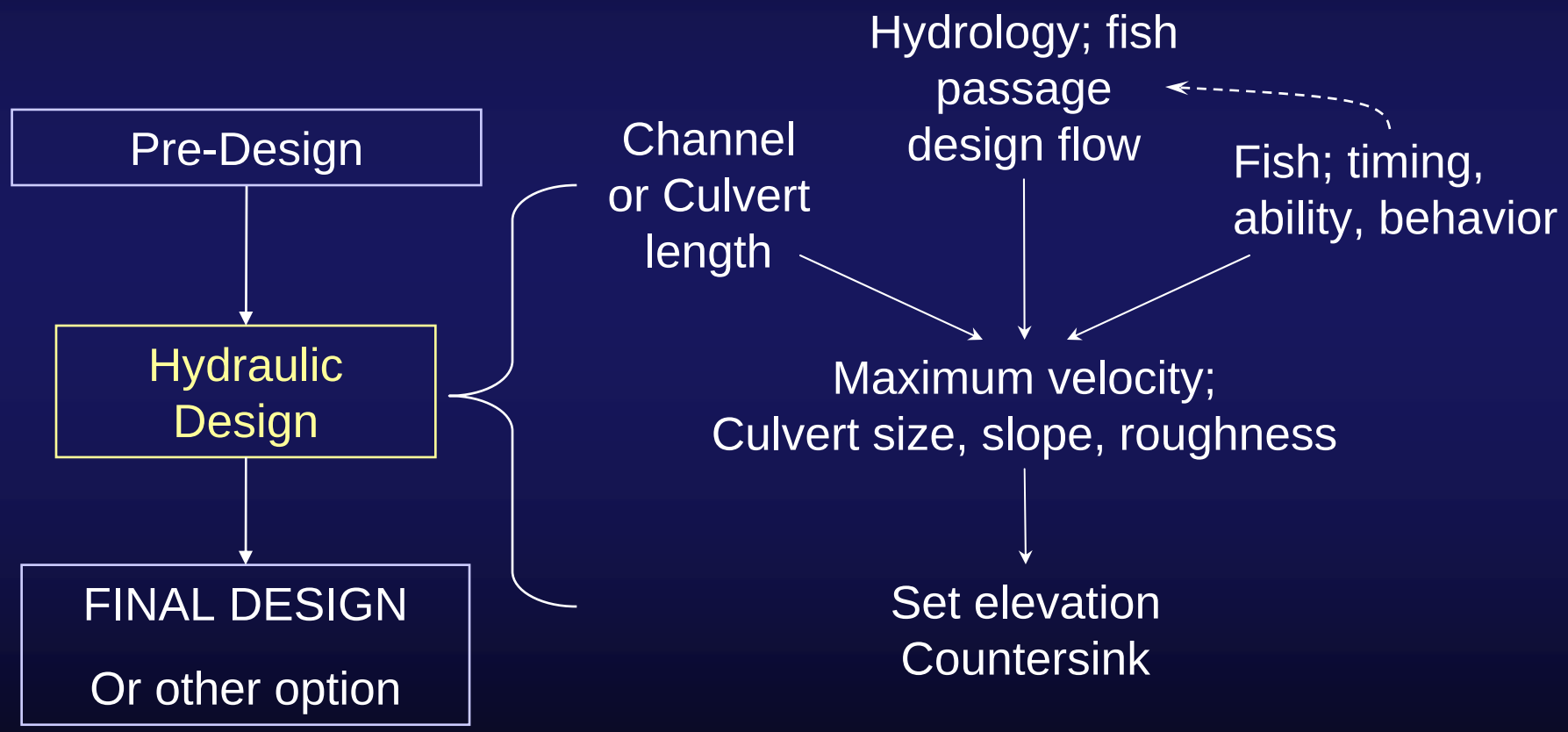
- Pass flood flows and debris
- Passage of all aquatic organisms
- Maintain all stream and floodplain processes

Typical AOP design options - Premises

- Hydraulic: A structure with appropriate hydraulic conditions will allow target species to swim through at design flows.

- 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.

H&H Design Option

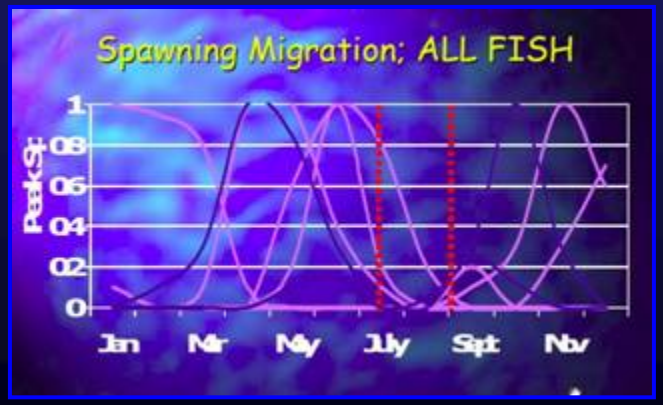


H&H Design Parameters

- Biological
  - Target species
  - Timing, swimming ability, behavior
- Hydrology
  - Max capacity design flow
  - Low and high fish passage design flows
- Hydraulics
  - Velocity, depth, length (plain culvert)
  - Roughness, turbulence (baffles, roughened)

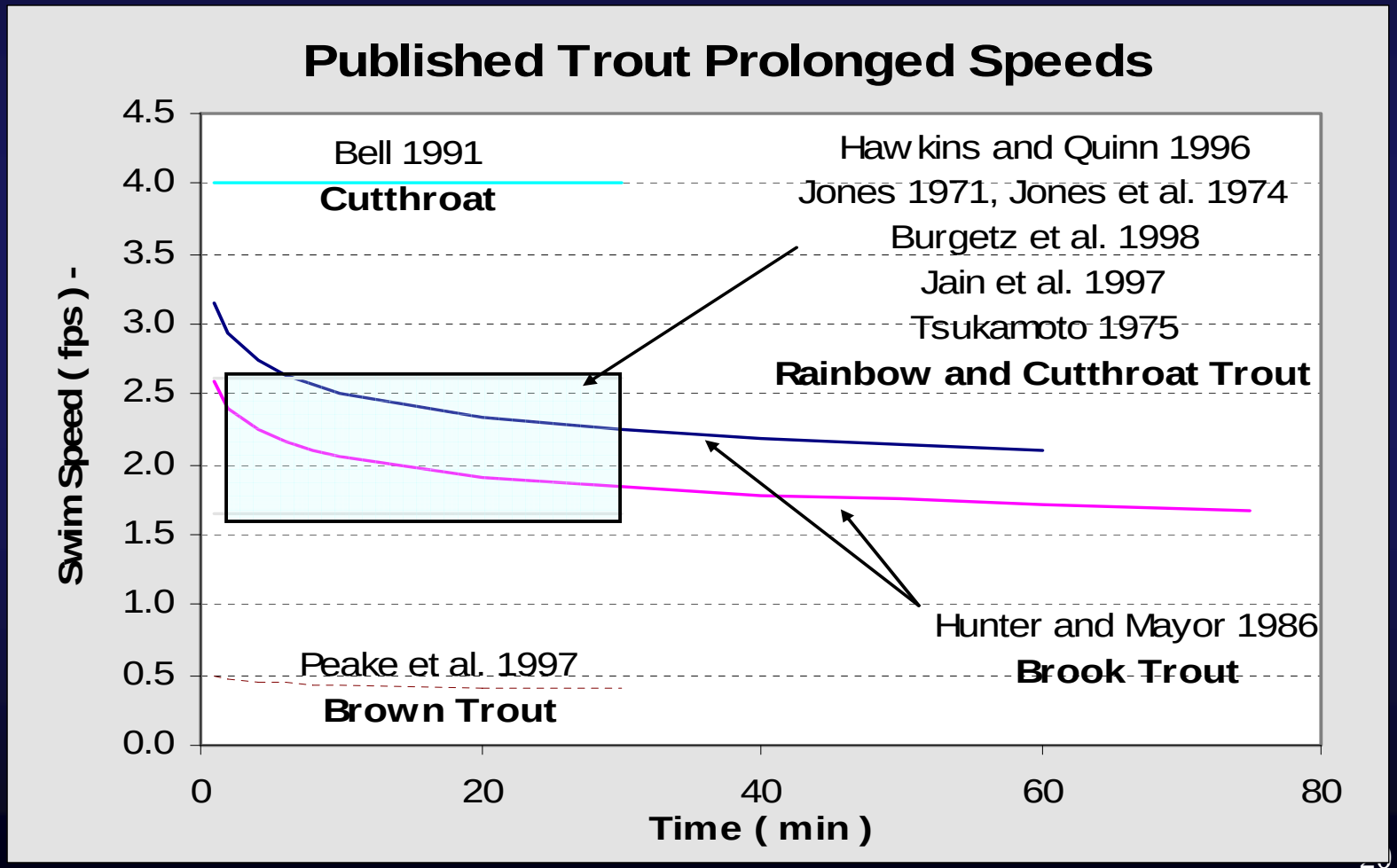
H&H Design Parameters: Biological

- Target species; what are they?
  - Weakest fish and species of community? (Other species may limit due to timing.)
  - Migration timing?
  - Behavior?
  - Swimming ability? jump, burst, prolonged
  - Default? (Washington: 6” trout year round)

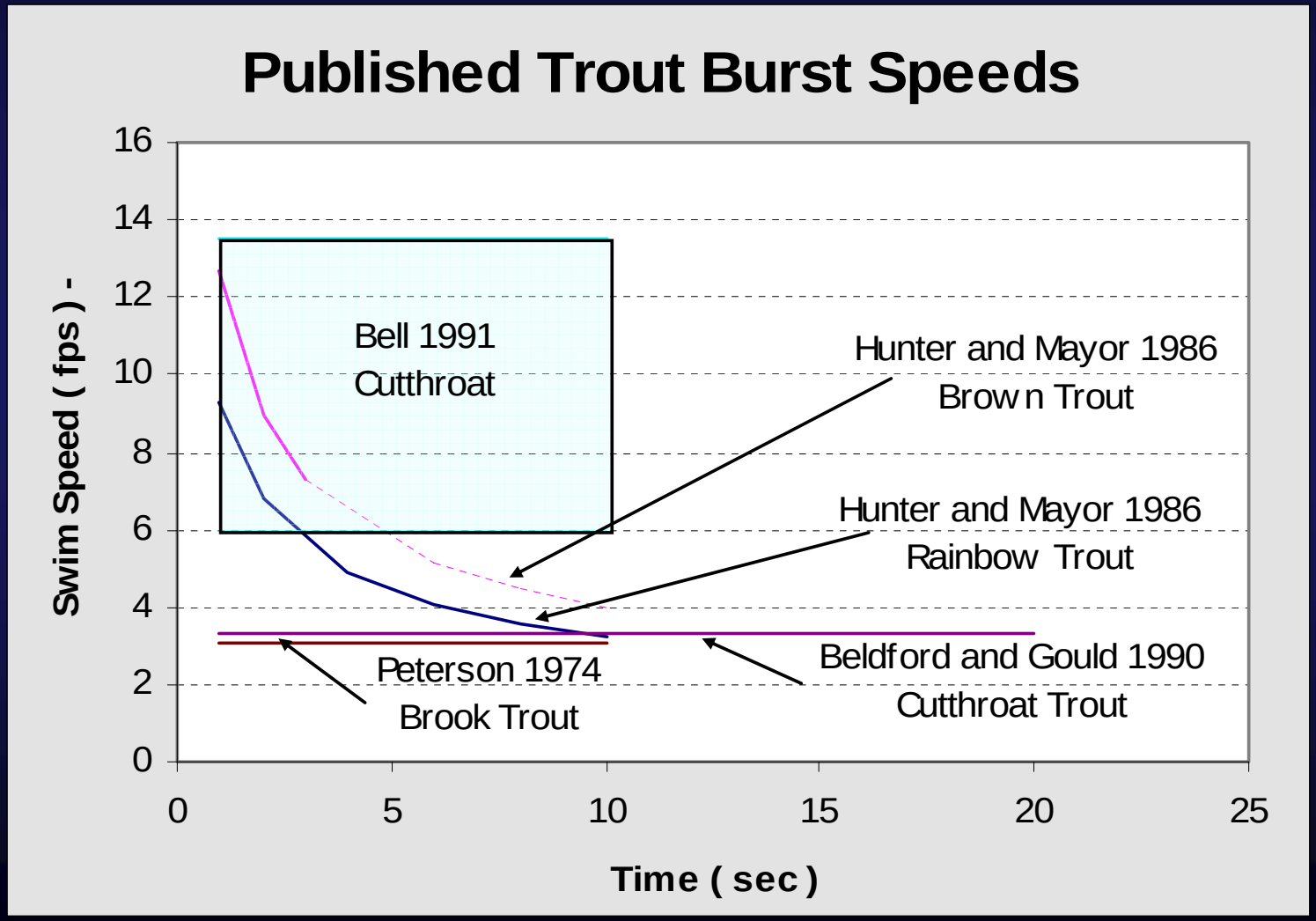


(Source: Hudy 2006)

Limited and Uncertain Fish Swimming Speeds - Prolonged



Limited and Uncertain Fish Swimming Speeds - Burst

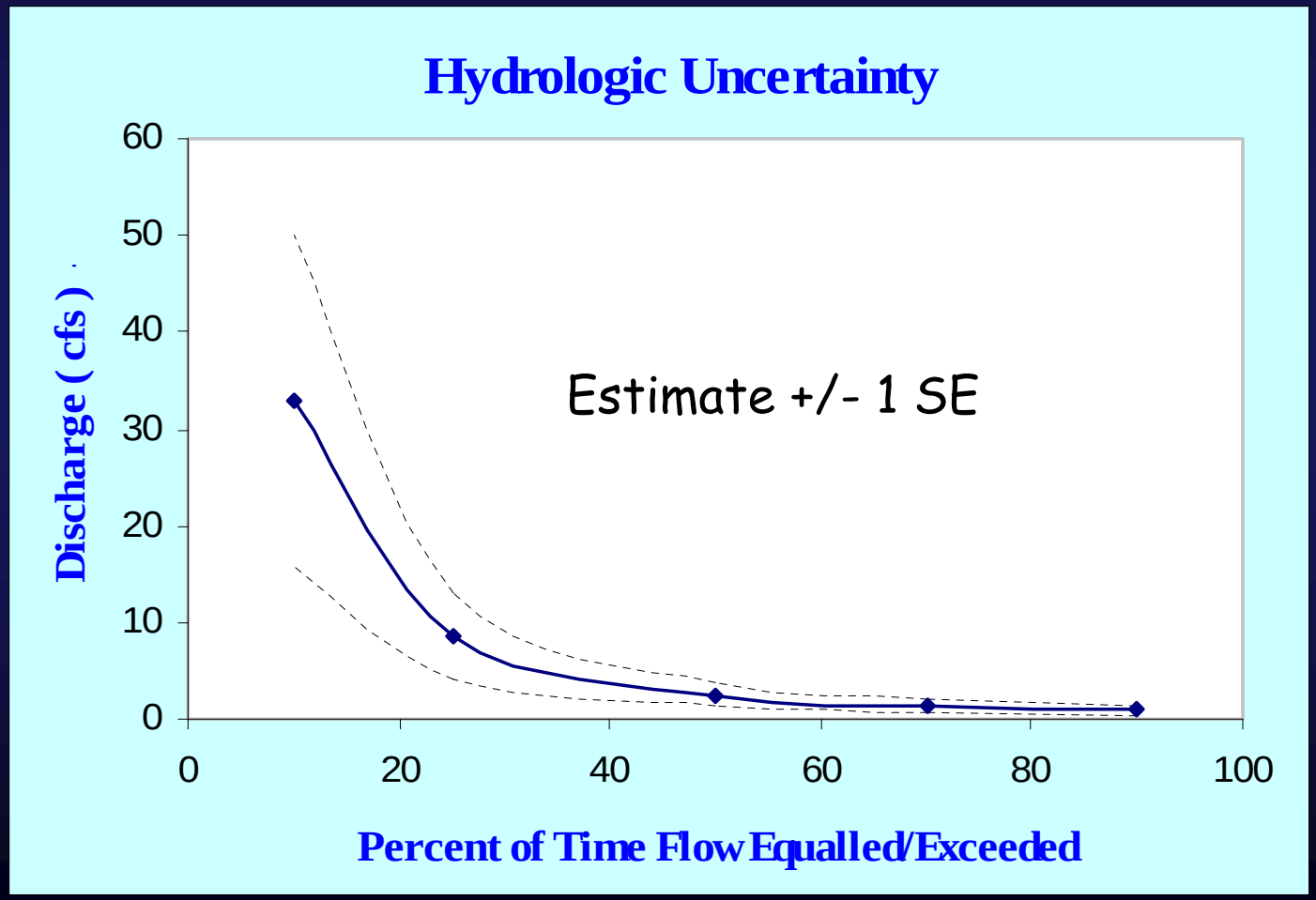


H&H Design Parameters: Hydrology

At what flows must velocity criteria be applied?

California	Alaska	Washington	NMFS
High Hydraulic Design Flow			
• 100-year flood	• 50& 100-year flood	• 100-year flood	• 100-year flood
High Fish Design Flow			
• 10% exceedance discharge for migratory period, or • 5% annual exceedance discharge	• Q_2D_2 $Q_2D_2 = 0.4 \times Q_2$	• 10% exceedance discharge for migratory period	• 1% exceedance for migratory period (adults), 10% annual exceedance (juveniles), or • 50% of 2-year flood • Discharge of the cross sectional area of active channel
Low Fish Design Flow			
• 50% annual exceedance discharge	• None Required • Match existing stream conditions	• 2-year, 7-day low flow	• 50% annual exceedance (adults) • 95% annual exceedance (juveniles)

Transfer of Hydrologic Data to Ungaged Sites Causes Uncertainty



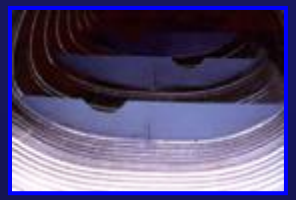
H&H Design Parameters: Hydraulics

Roughness and slope control velocity and turbulence

- Plain Culvert (model hydraulics)
  - Key pts: culvert roughness, slope, vel, depth
  - Design: culvert size-slope-length
  - Benefits: simple, low cost for no slope
  - Limitations: passage uncertainty, bedload, debris

$$V = \frac{1.486}{n} R^{2/3} S^{1/2}$$

- Baffles (turbulence=resting=passage)
  - Key pts: lf pass-bw, hf pass-turbu
  - Design: culv sz-slp-leng; baffle sz-sp
  - Benefits: low cost
  - Limitations: turbulence, bedload, debris



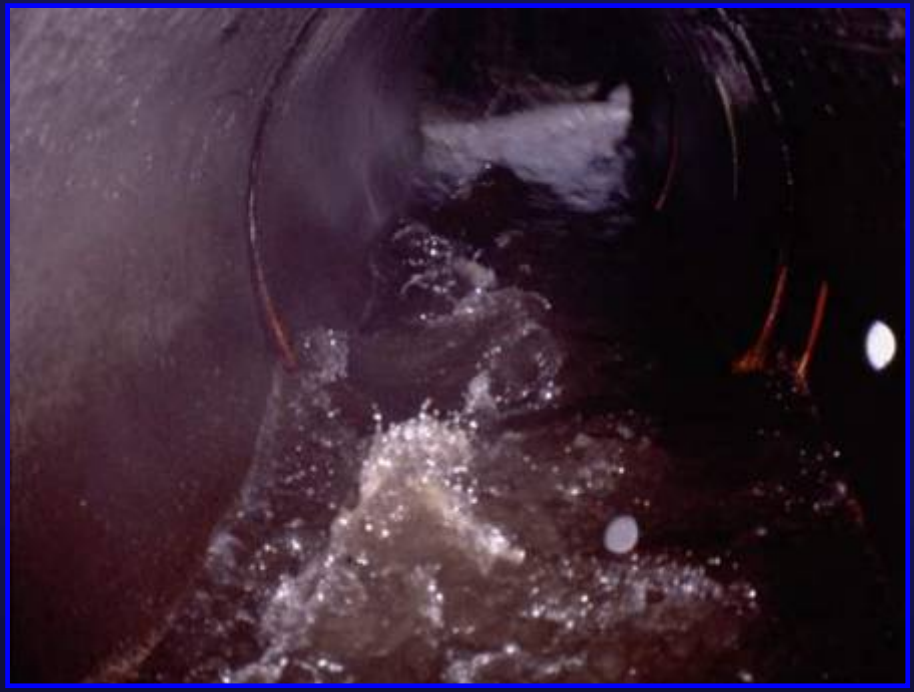
- Roughened channel (turbulence=resting=passage)
  - Key pts: Roughness mimics
  - Design: culv sz-slp-leng; mat amt-sp-reten
  - Benefits: bed stability, variety of passageways
  - Limitations: turbulence, low flow

Baffles

Baffles dissipate energy and reduce velocity by turbulence

Turbulence

- Generally good – but concern that extreme turbulence can disorient and fatigue fish
- May limit fish passage by creating hydraulic conditions not conducive to fish passage
- Measured by Energy Dissipation Factor (EDF).
- WA recommends EDF of 3-5 for adult salmon.



Example of EDF

Low Flow

Adult salmon design flow
EDF = 4 ft-lb/sec/ft^3

Two times design flow
EDF = 8 ft-lb/sec/ft^3

Roughened Channel is Hydraulic Design

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

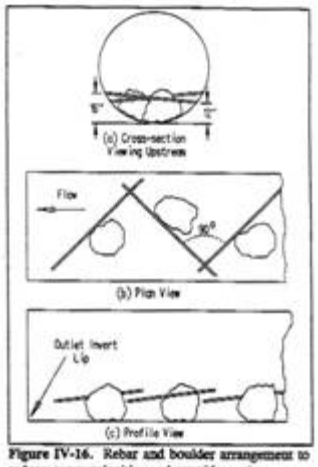


Figure IV-16. Rebar and boulder arrangement to reduce water velocities and provide resting locations for fish.

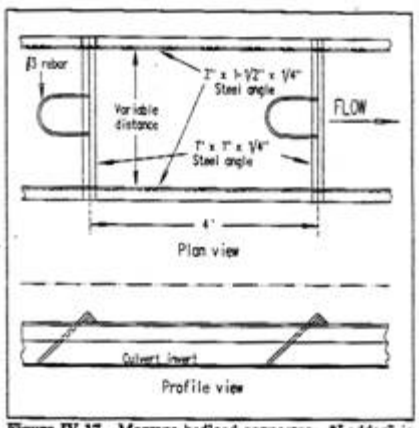
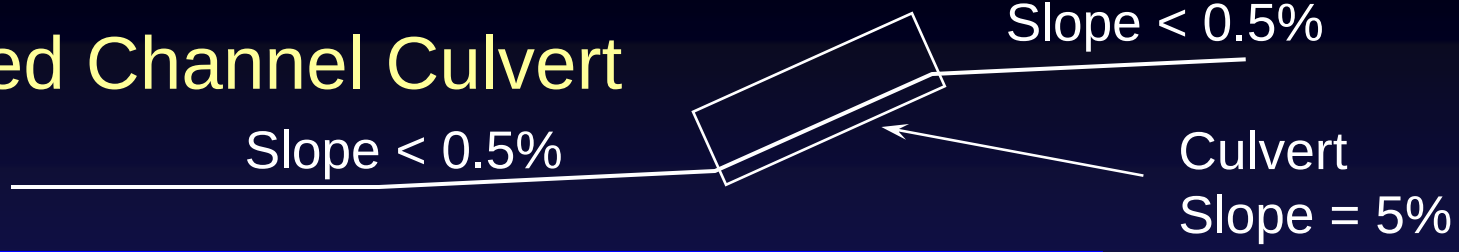
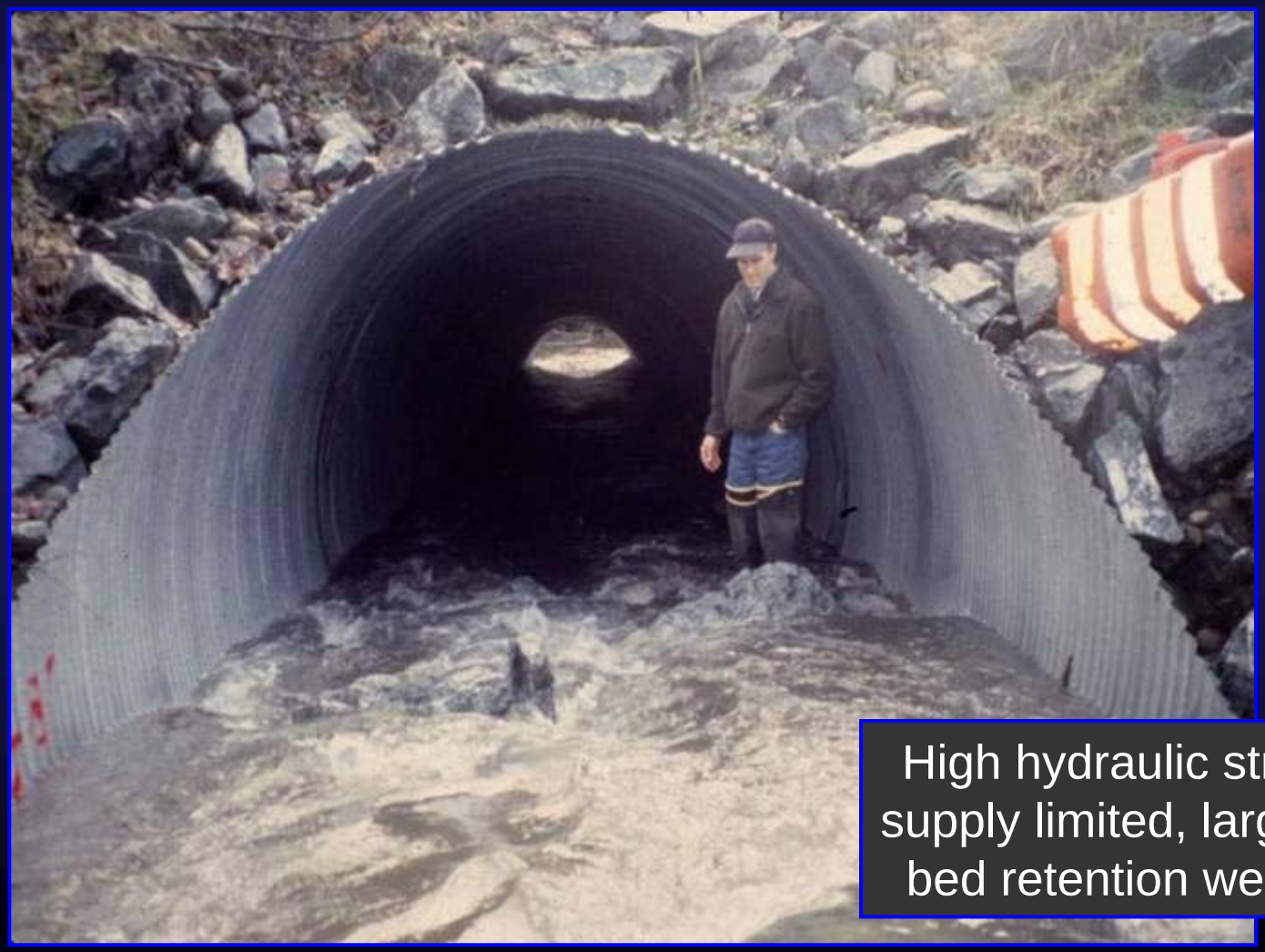


Figure IV-17. Montana bedload connector. "Ladder" is fabricated in 20-foot sections and bolted together when placed in culvert. Cross #-members and rebar loops are welded to side members.

Coal Creek
Roughened Channel Culvert





High hydraulic stress, turbulent, supply limited, large bed material, bed retention weirs necessary.

H&H AOP Final Thoughts
(Just did not work well)

- Complexities
  - Target species and life stages, other species?
  - Passage time periods
  - High and low passage flows
- Uncertainties
  - Fish swimming ability
  - Hydrologic estimates, standard errors of 25 -100%
  - Small scale hydraulics, turbulence barriers
- Cautions
  - Species rather than ecological focus
  - Debris and bedload transport, maintain channel continuity
- Applications
  - No slope - tailwater control (w/bfw check, low gradient)
  - Retrofits: baffles and roughened channels

Stream Simulation Design

Stream simulation design parameters

- Reference reach
  - Simulate natural channel
  - Bankfull cross section shape and dimensions
  - Channel slope
  - Channel structure
- Geomorphic design
  - Fits with and in equilibrium with adjacent reaches
  - Dynamically sustained over a broad range of flows
  - “Mobile bed in stable channel”

Stream Simulation Uncertainties

- Adequacy of reference reach
- Supply and transport of sediment
- WS and hydrologic stability
- Stream stability
- Constructed bed stability

Stream Simulation.

Pass sediment, debris, all aquatic organisms

- Ecological solutions at Road Crossings +