Climate Ready Culverts

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UNIVERSITY OF NEW HAMPSHIRE
STORMWATER CENTER

Funding

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Culvert Hydraulics

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Bridge Versus Culvert

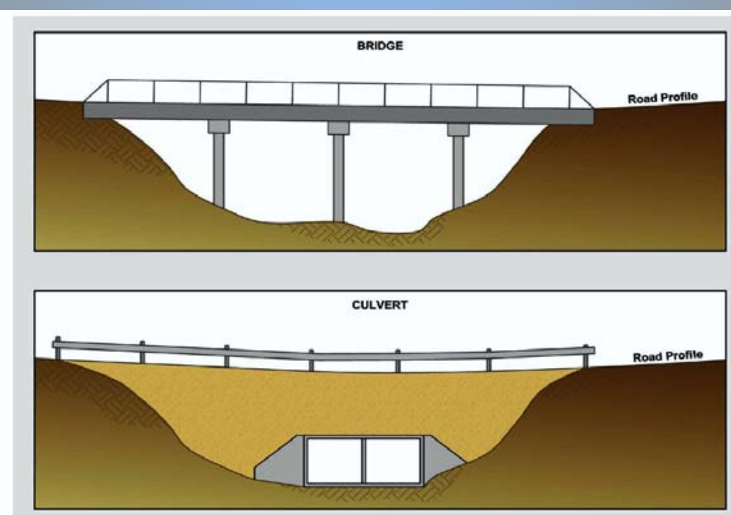

Figure 1.4. Bridge versus culvert at same location.

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Culvert Characteristics

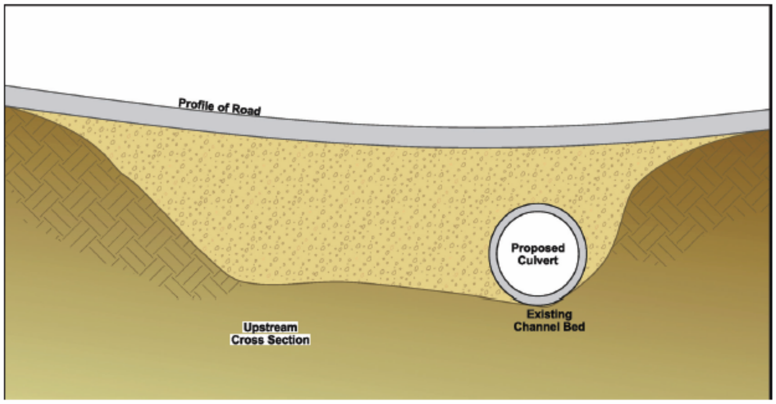

Figure 2.5. Road profile – valley section.

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General Culvert Hydraulics

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Inlet Control

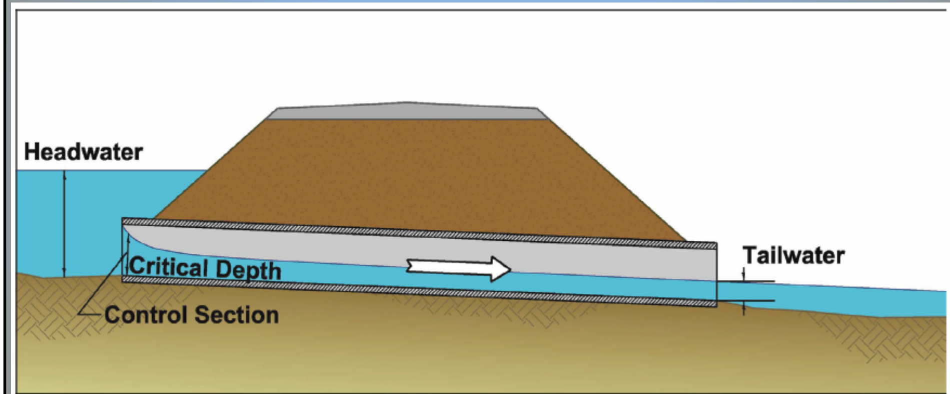

Figure 1.17. Typical inlet control flow section.

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Fun Fact

- Inlet Control is dictated by the fact that the stream crossings creates critical depth at the inlet. As such, anything downstream of this point does not affect the headwater depth.

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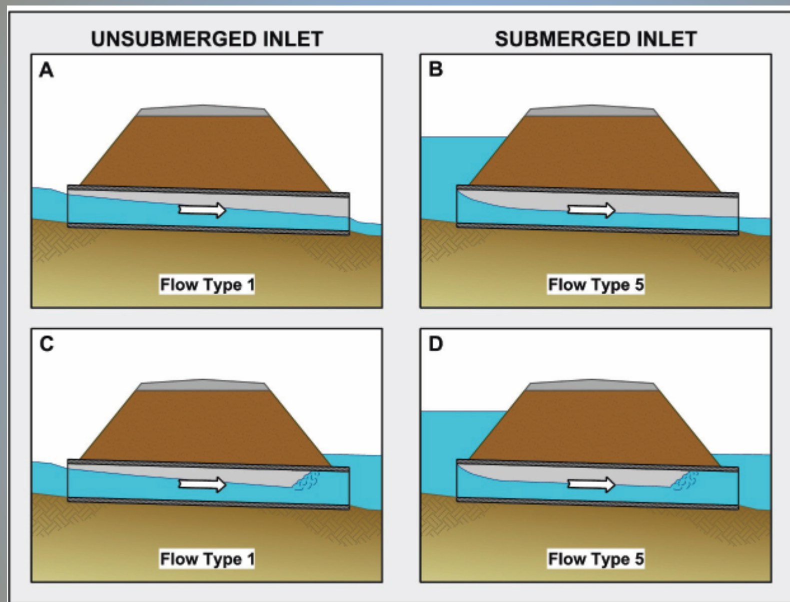

Figure 3.1. Types of inlet control.

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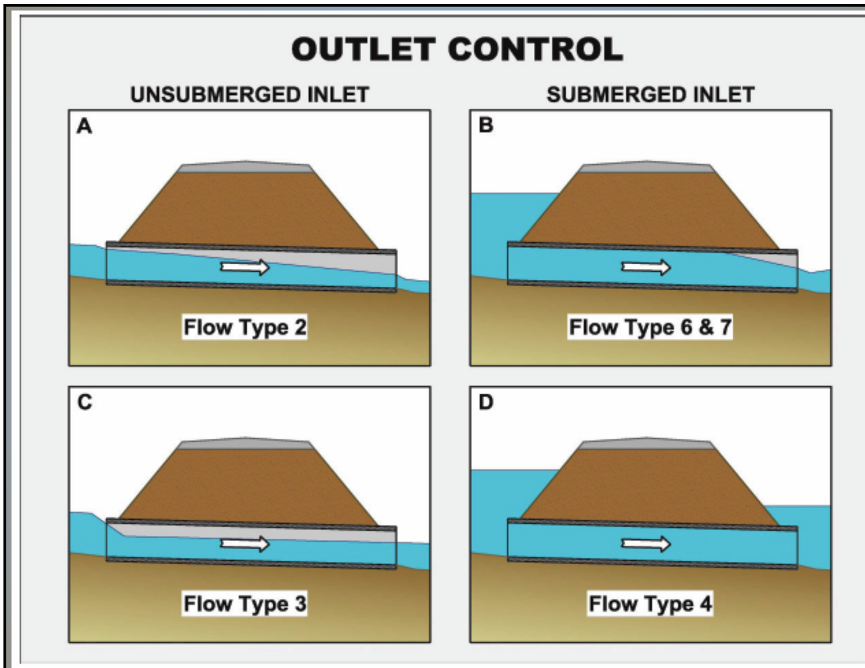

Figure 3.7. Types of outlet control.

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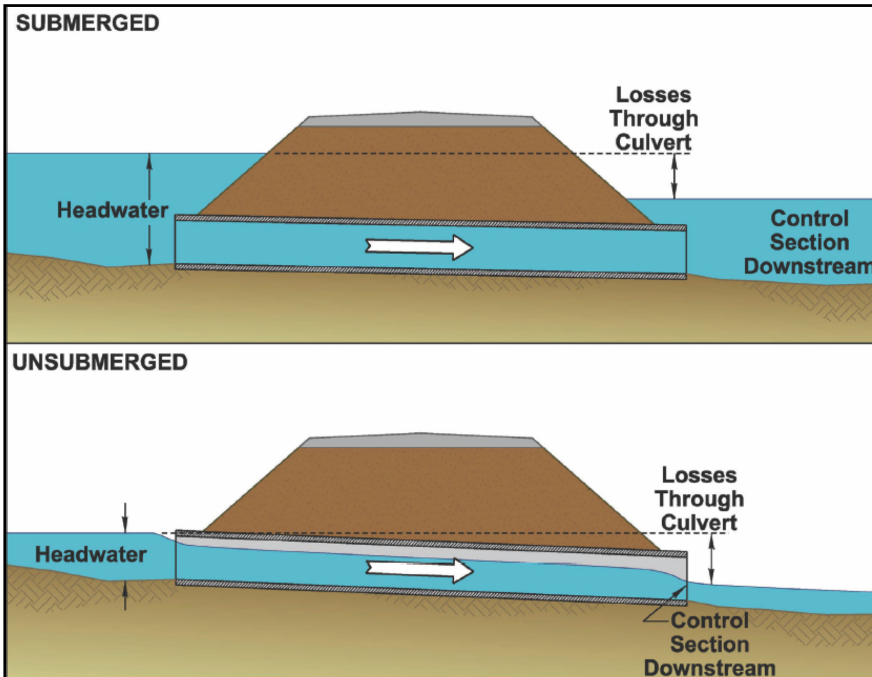

Figure 1.18. Typical outlet control flow conditions.

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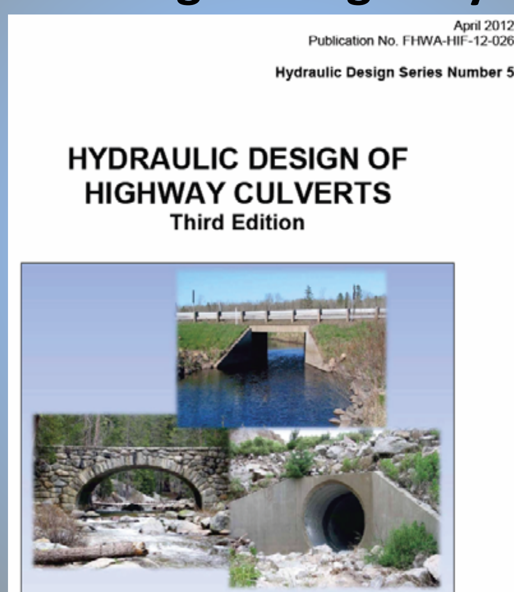
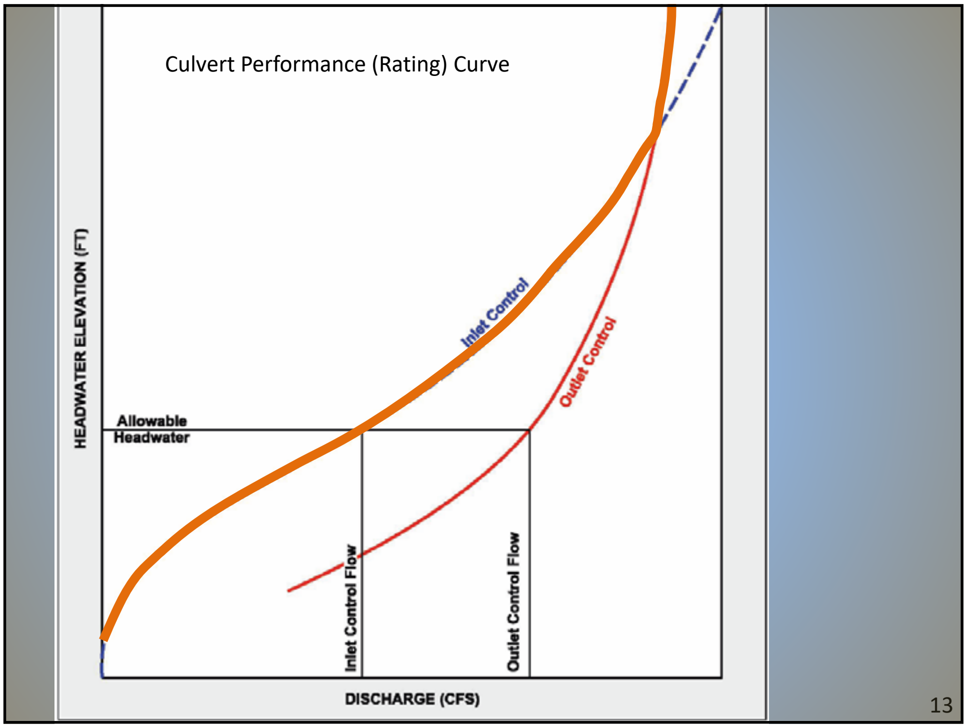
Hydraulic Design of Highway Culverts





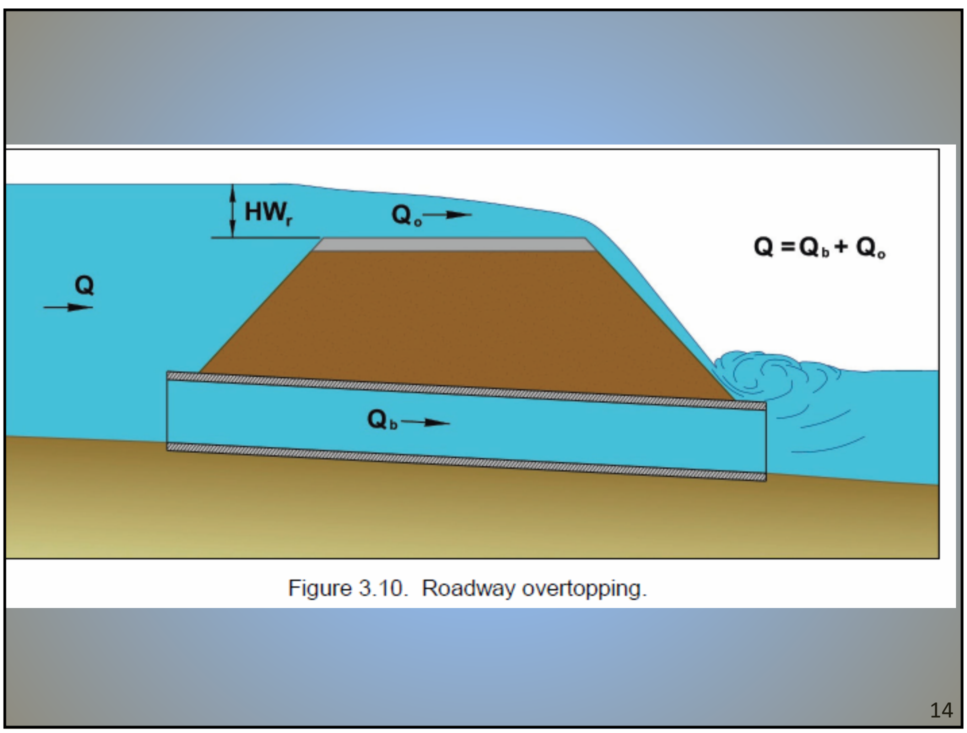


Figure 3.10. Roadway overtopping.

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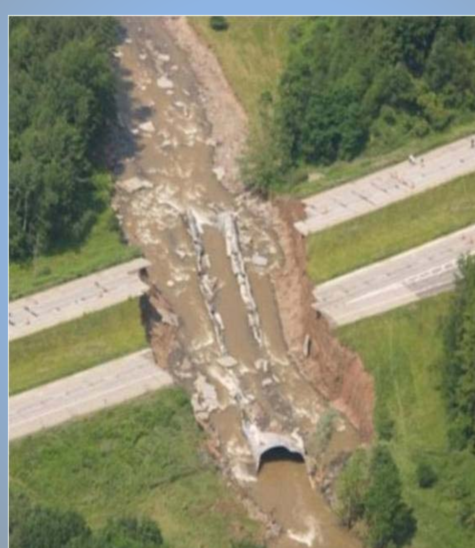
Culvert Hydraulics



Scour Hole, Perching

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Design for Fish Passage at Roadway-Stream Crossings

U.S. Department
of Transportation

Federal Highway Administration

Publication No. FHWA-HIF-07-033
June 2007

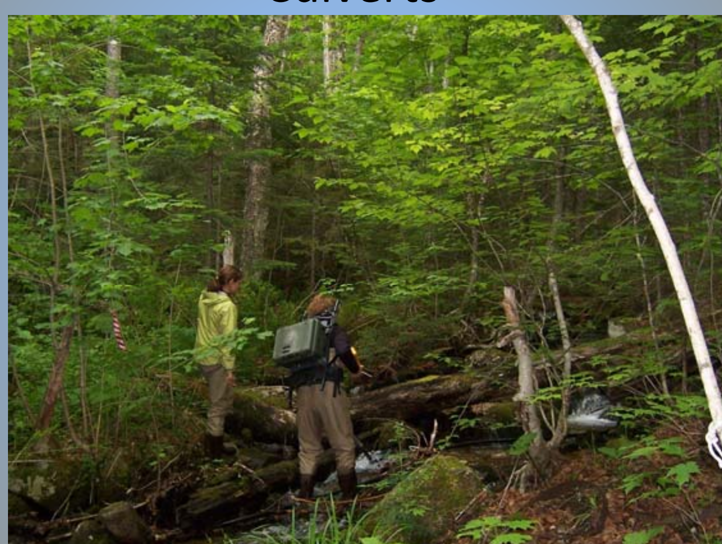
DESIGN FOR FISH PASSAGE AT ROADWAY-STREAM CROSSINGS: SYNTHESIS REPORT

Aquatic Organism Passage at Culverts

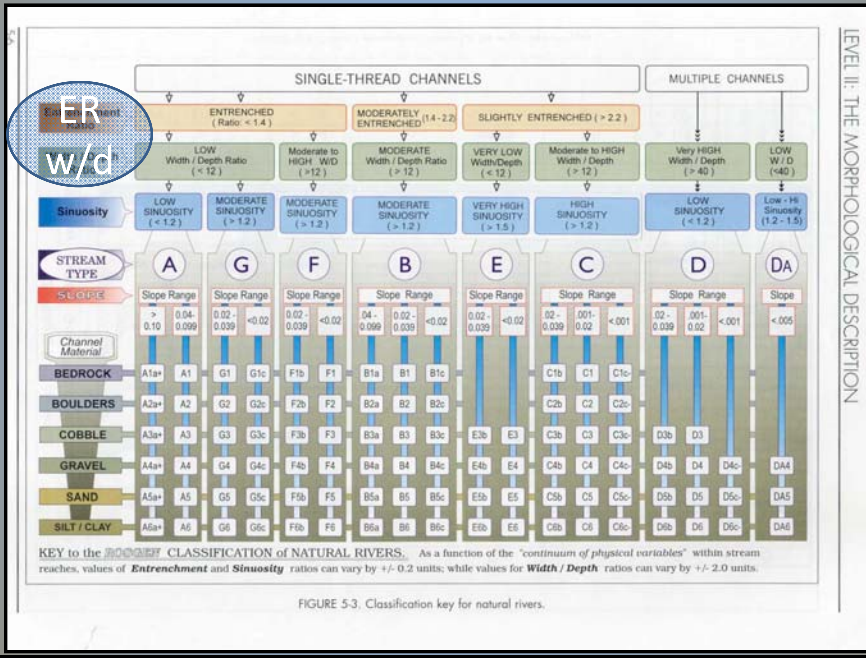
PIT Tags

PIT Tag Fixed Wand

Aquatic Organism Passage Design at Culverts



Rosgen Stream Classification



Relationship Between Stream Form and Habitat Quality

- Highest quality habitat

  B, C, E

- Lowest quality habitat

  D, F, G

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What to Remember: desirable geomorphic forms for high quality habitat

- Width to depth ratio
  - < 40
- Sinuosity
  - > 1.2
- Entrenchment ratio
  - > 1.4

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Common Stream Crossing Non-Geomorphic Characteristics

- Overwidened Section
- Narrow Section
- Slope Break

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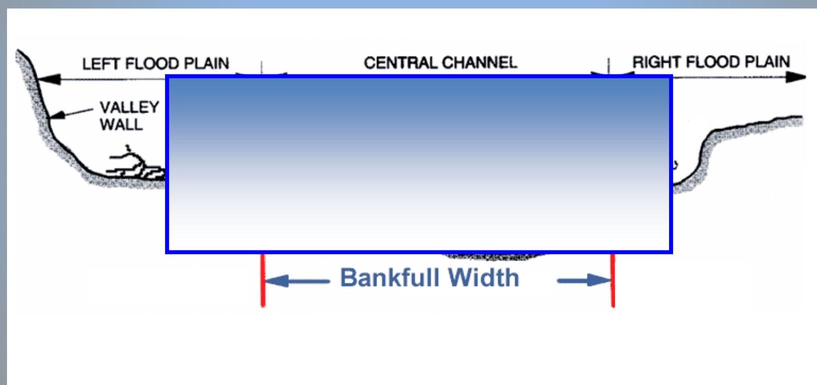
Overwidened Stream Crossing



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Geomorphic and Hydraulic Feedback of Overwidening

- Bridge section is wider than natural cross section
- Depth of *channel-forming* flow under bridge is shallower than in natural channel
- Sediment competence and capacity under bridge is reduced
- Deposition

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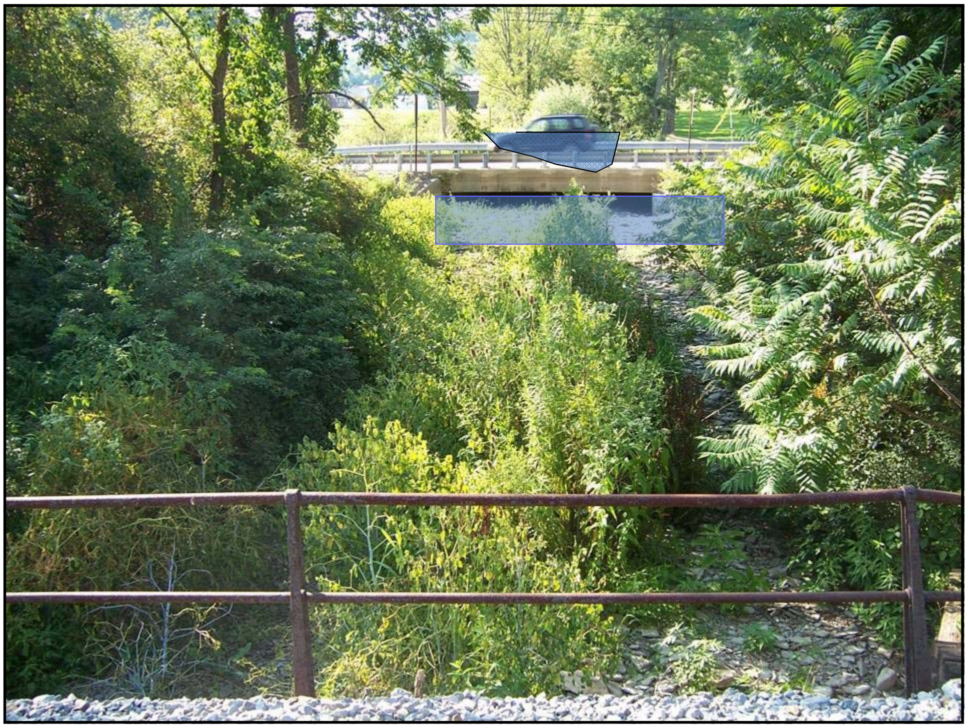

Narrowing an Overwidened Bridge

Start of Construction June, 2007

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Reconstruct Floodplain and Stream

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Two Years Later

Five Years Later

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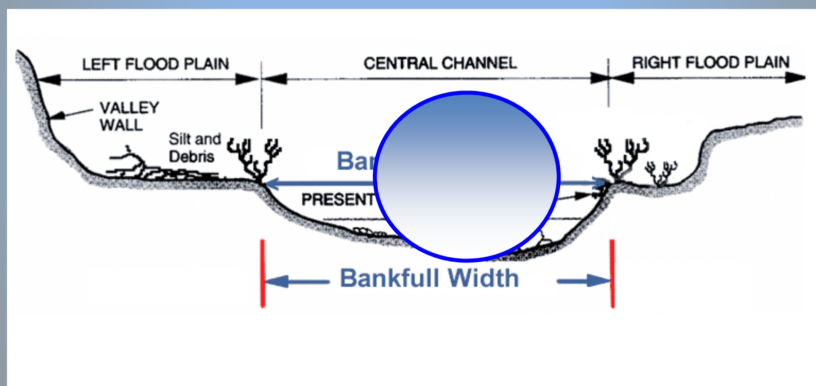
Undersized Stream Crossing



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Geomorphic and Hydraulic Feedback of Narrowing

- Hydraulic constriction backs-up water upstream
- Larger depth upstream means slower velocities reducing competence and capacity (Manning)
- Slower velocities result in overtopping and/or deposition
- In crossing (pipe/bridge), higher velocities than natural (continuity, Manning)
- Water leaving pipe extremely aggressive resulting in scour downstream

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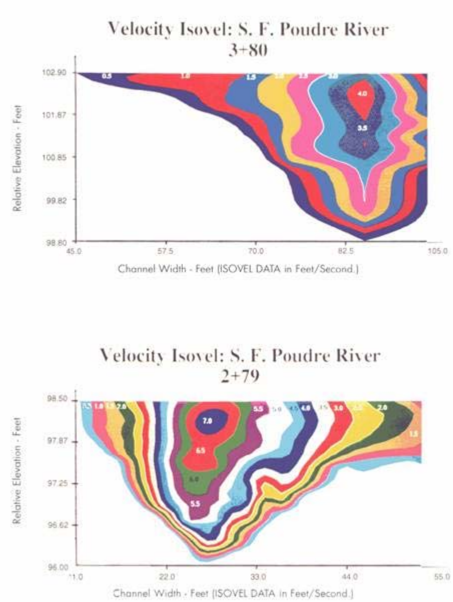

FIGURE 6-26. Velocity isovels at two separate locations on a "C3" streamtype reach; showing variation in stress velocity distribution. (Nankervis, USDA Forest Service, 1989)

Velocity distributions in a natural channel

Higher velocity results in higher shear

Mill Brook – Thornton, NH

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The Problem

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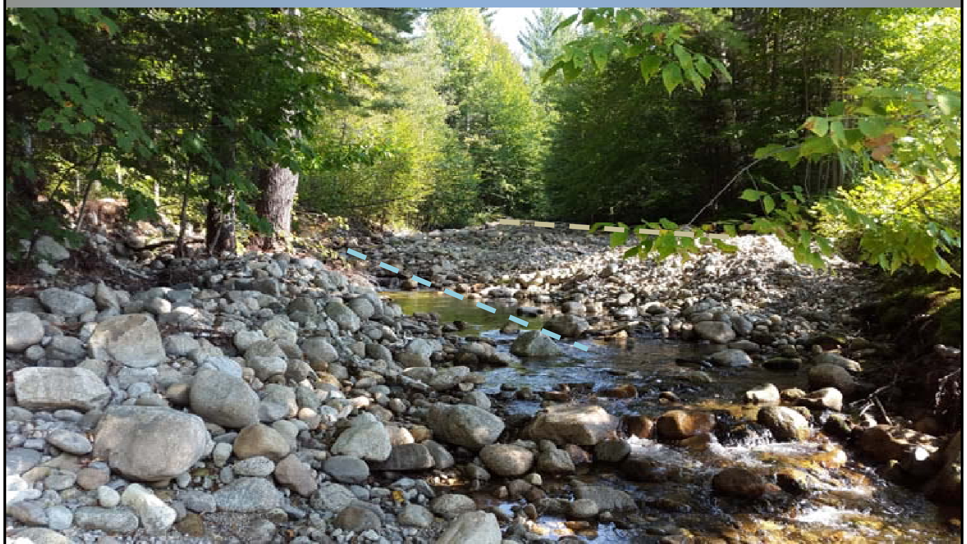

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Climate Change

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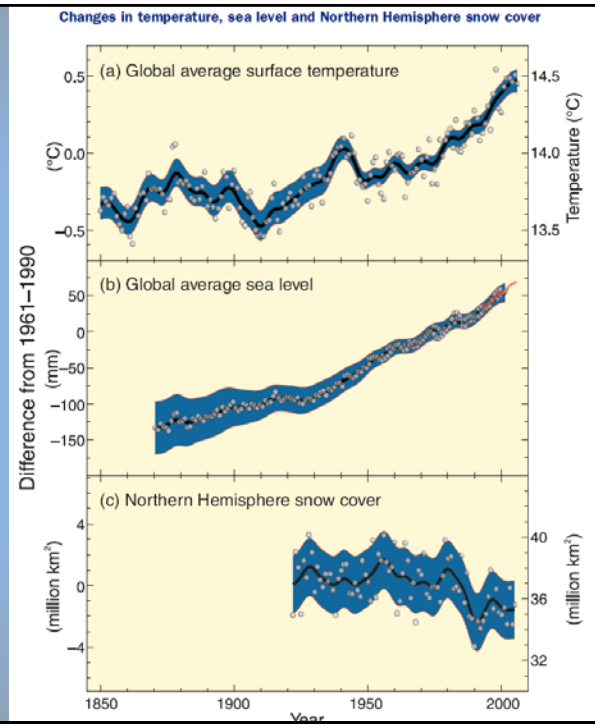
Observed warming over several decades has been linked to changes in the large-scale hydrological cycle



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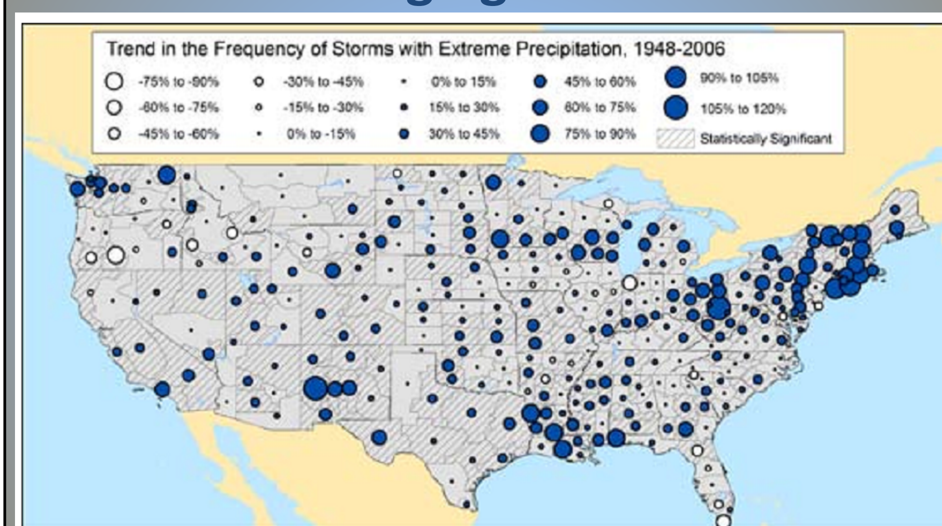
Changing Trends



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A study of the precipitation from the last 50 years in the Chicago area showed that storm depths used for SWM infrastructure design increased by 28 to 60% → infrastructure is underdesigned by 35% (Guo, 2006)

Design standards are static → our infrastructure is obsolete from the first day after construction

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Why are things changing in winter and spring in New England?

- Higher winter rain to snow ratio
  - Huntington et al. (2004)
- Earlier melting of snowpack
  - Hodgkins et al. (2006)
- March-April air temperatures up 0.7^{0}C, 1953-2002
- March-April air temperatures correlated with streamflow timing

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Mathias Collins, NOAA

JAWRA, 2009

- Annual instantaneous peak flows through 2006 at 28 rural, unregulated stations in New England
- Increasing flows at 25/28 stations
  - Significant increases at 10 stations
  - No significant decreases
- High frequency design flows (e.g. 1.5-, 2-, 5-year) appear most sensitive to post-1970 New England hydroclimate

What Can We Anticipate?

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Fifteen-model mean changes in

(a) precipitation (%),
(b) soil moisture content (%),
(c) runoff (%), and
(d)evaporation (%).

To indicate consistency of sign of change, regions are ***stippled where at least 80% of models agree on the sign of the mean change****. Changes are annual means for the scenario SRES A1B for the period 2080–2099 relative to 1980–1999.*

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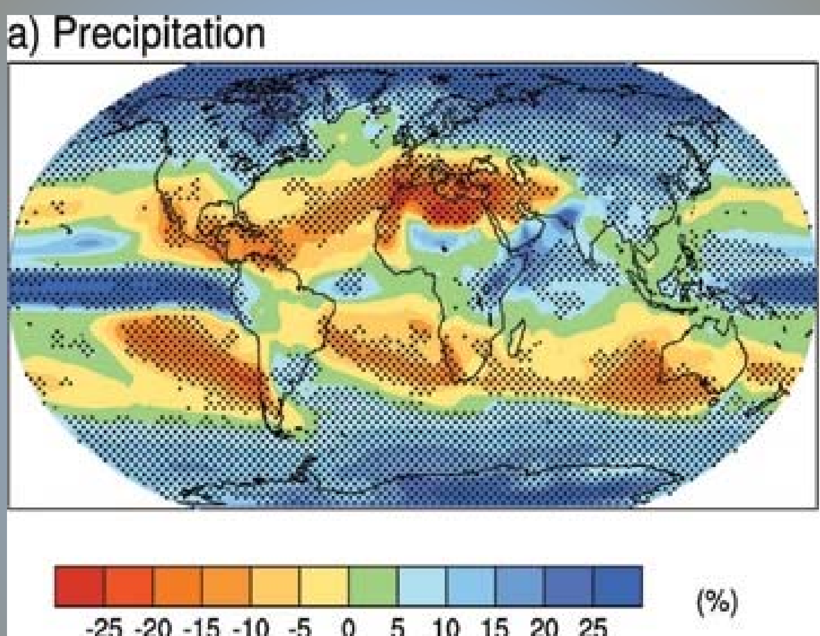

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Changes in extremes based on multi-model simulations from nine global coupled climate models in 2080–2099 relative to 1980–1999

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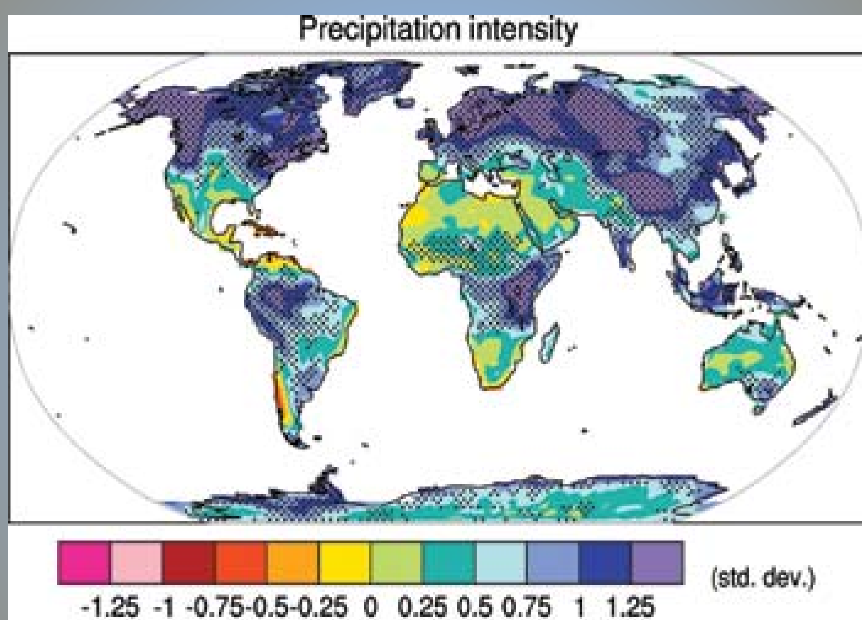

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How Much Increase?

- The apparent increase in the proportion of very intense storms since 1970 in some regions is much larger than simulated by current models for that period.
- Increases in the amount of precipitation are *very likely in high-latitudes*
- Runoff is projected with high confidence to increase by 10 to 40% by mid-century at higher latitudes

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Key Points (1)

- Climate change has already altered, and will continue to alter, the water cycle, affecting where, when, and how much water is available for all uses.
- Floods and droughts are likely to become more common and more intense as regional and seasonal precipitation patterns change, and rainfall becomes more concentrated into heavy events (with longer, hotter dry periods in between).
- Precipitation and runoff are likely to increase in the Northeast and Midwest in winter and spring, and decrease in the West, especially the Southwest, in spring and summer.

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Key Points (1)

- In areas where snowpack dominates, the timing of runoff will continue to shift to earlier in the spring and flows will be lower in late summer.
- Surface water quality and groundwater quantity will be affected by a changing climate.
- Climate change will place additional burdens on already stressed water systems.
- The past century is no longer a reasonable guide to the future for water management.

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Common "Design" Life for Our Structures

- 20 to 50 years (looking out to 2040 to 2060)
- Precipitation increase of ~10-20%
- Temperature increase of 1-2 degrees F

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Hydrologic Consequences

- Switch from snowmelt hydrology to runoff hydrology, especially in larger watersheds
- Higher design flows
- More runoff volume to manage
- Increased sediment transport
- Increased hydraulic attack on structures
- Expanding wetlands
- Higher SHWT

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So What's With Impervious Area?

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More Runoff

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Faster Runoff

- Now when it rains,
  water reaches the stream faster

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Higher Peak Flows

- Less infiltration = more runoff

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Coincidence

- Many of the effects of urbanization mirror those of anticipated climate change consequences
  - Higher peak flows
  - More intense runoff
  - Stream incision

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Far-Reaching Consequences

- Ecosystem genesis

  → new endangered species

    → loss of transportation route viability

- Higher temperatures means higher temperature runoff to systems already critically at the maximum for cold water fisheries…now, less dissolved oxygen

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Unanticipated Consequences

?

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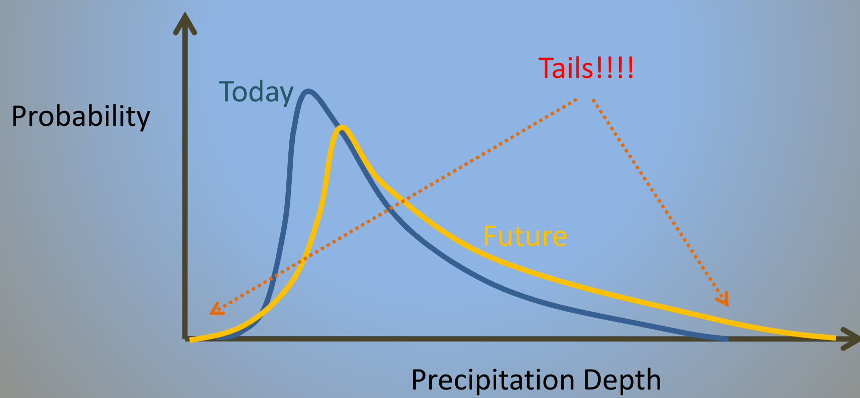
Precipitation

- Overall….wetter
- More important aspect…increased variability



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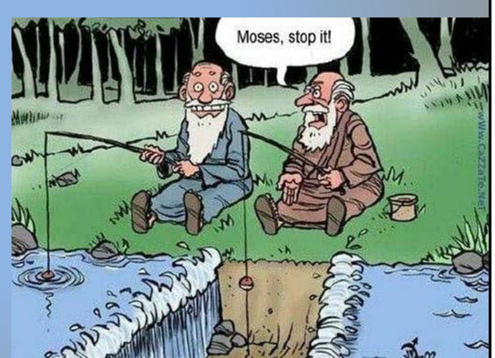
Wetter Aspect

- Larger Design Precipitation
- Possibly more contaminants flowing from impervious surfaces (TMDLs)
- More water means more hydraulic and aging attack on our structures



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Consequences to Existing Infrastructure

- Inability to pass original design flow at same headwater condition
- More frequent overtopping
- FEMA flood mapping now represents something less than 100-year
- Bridge/Abutment/Contraction/Pier scour
- Inadequacy of existing erosion protection measures

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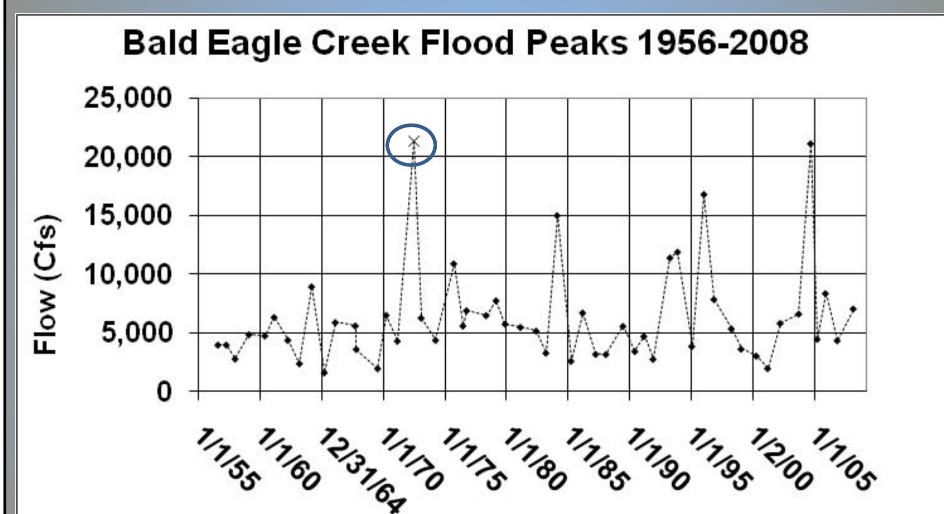

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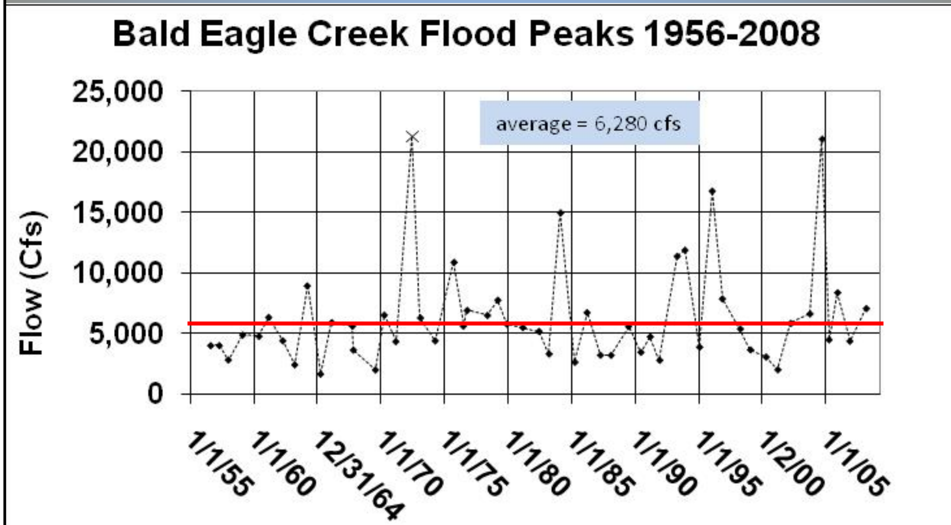

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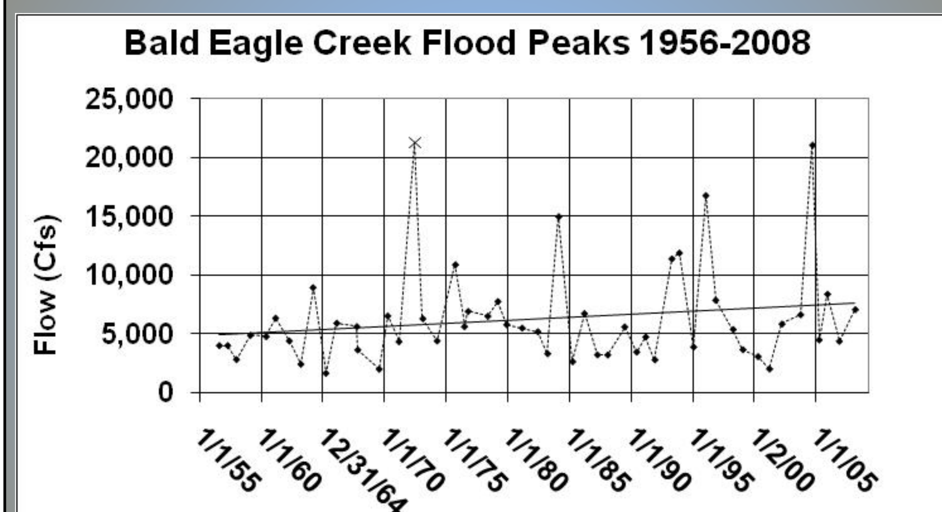

Increase in cfsm/yr

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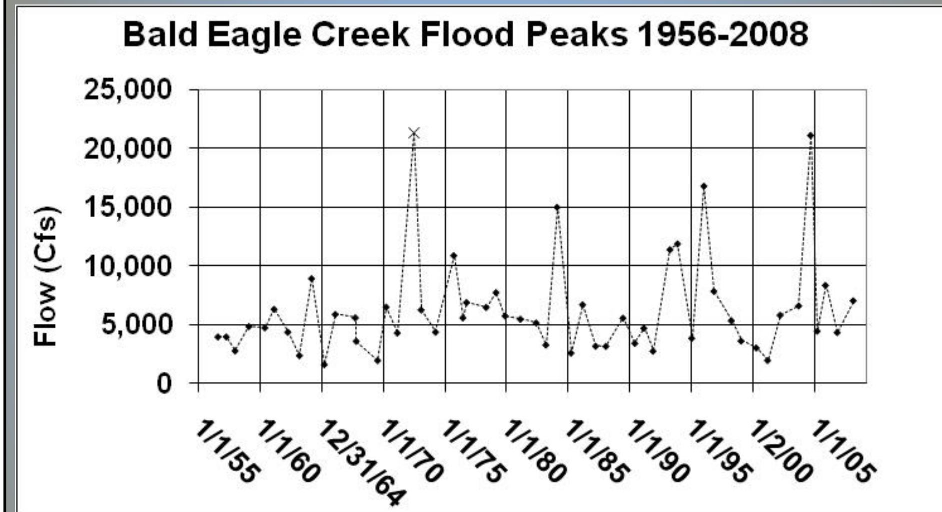

Forecast Method	1956-1971	1956-1972	1956-1978	1956-1988	1956-1998	1956-2008
Bulletin 17B	11578	22353	20332	20075	21986	23211

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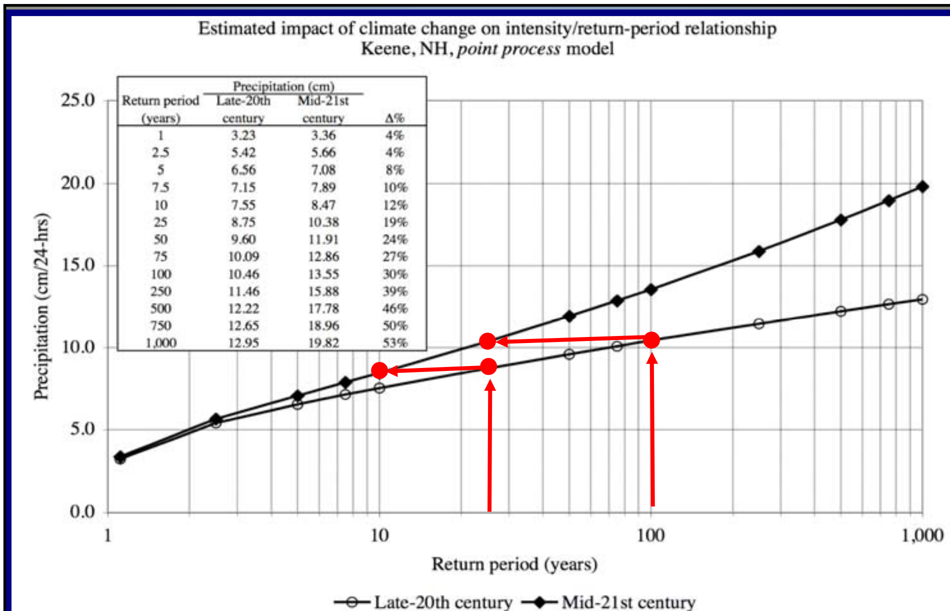

Return period (years)	Precipitation (cm) Late-20th century	Mid-21st century	Δ%
1	3.23	3.36	4%
2.5	5.42	5.66	4%
5	6.56	7.08	8%
7.5	7.15	7.89	10%
10	7.55	8.47	12%
25	8.75	10.38	19%
50	9.60	11.91	24%
75	10.09	12.86	27%
100	10.46	13.55	30%
250	11.46	15.88	39%
500	12.22	17.78	46%
750	12.65	18.96	50%
1,000	12.95	19.82	53%

Source: Stack et al.(2008)

Changes in FEMA Floodplain

- - - - - - - - - Existing 100-year floodplain mapped in 1980's
Estimated floodplain due to land use and climate change

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Consequences to Infrastructure and Economy

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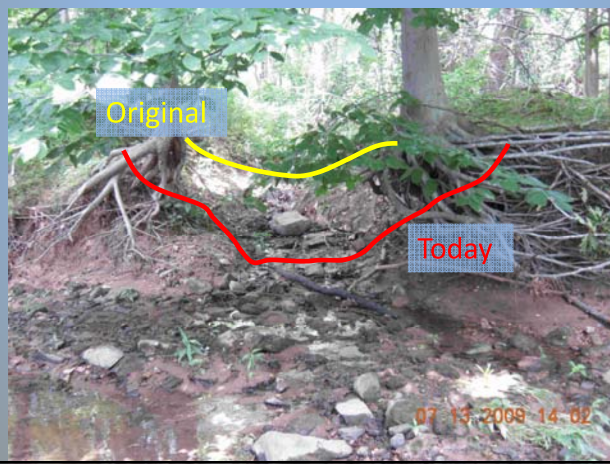
Incision of Tributaries

- The tributaries use the main stream as a foundation.



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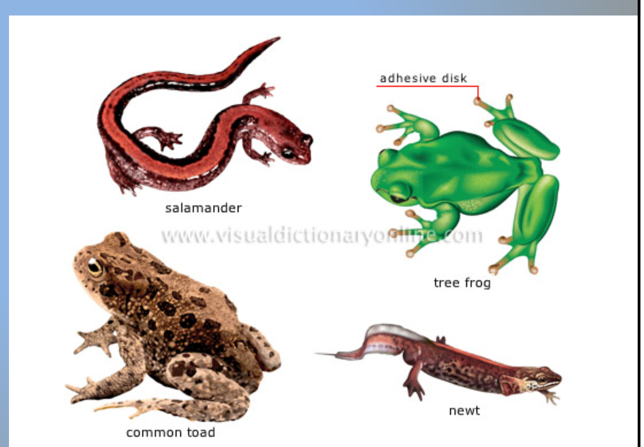
What About Habitat?

- Macroinvertebrates
- Fish
- Amphibians
- Mammals
- Algae
- Aquatic Plants
- Riparian plants
- Sediment
- Large wood
- Organic debris
- Birds
- Lizards
- Insects



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What Can We Mitigate?

Adaptation/Mitigation Measures

- Enlarge stream crossings
- Plan closures
- Determine temporary alternative routes/strategies
- Armor hydraulic infrastructure
- Pumping strategies

How Can We Adapt?

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- Oregon is raising bridges in response to the need to meet minimum clearance for ships to get under bridges

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Effect on Design Standards

- Temperature changes
- Precipitation
- Water levels
- Wind loads
- Storm surges
- Wave heights
- Soil Moisture
- Groundwater Level

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Existing Infrastructure

- Bridges and culverts (increased mean annual rainfall, increased intensity of rainfall events, sea level rise),
- Causeways and coastal roads (sea level rise and increased frequency and intensity of storm surges),
- Pavement surfaces (increased mean annual temperature),
- Surface drainage (increased intensity of rainfall events),
- Hillside slope stability (increased mean annual rainfall and increased intensity of rainfall events).

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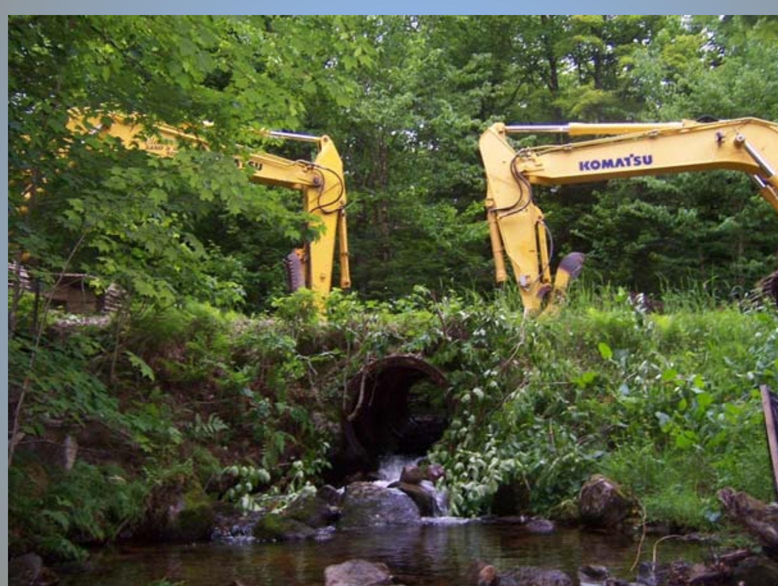
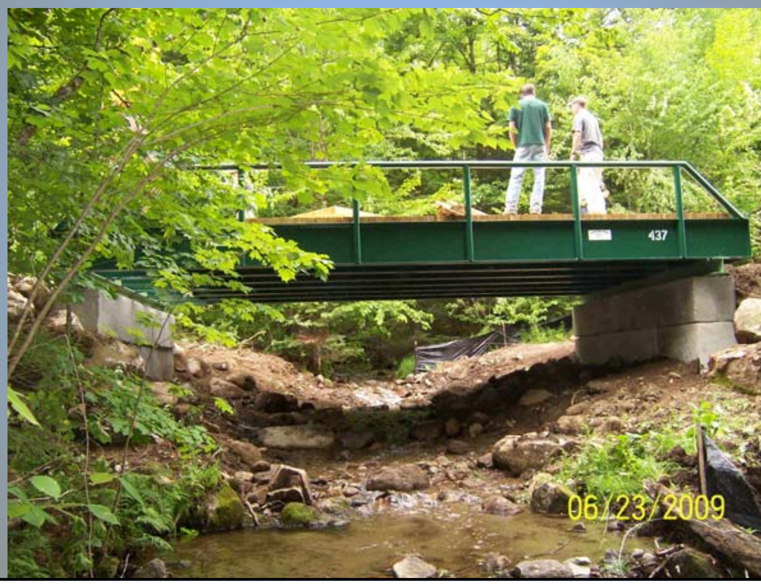
How Far North Were You?

Geomorphic Culvert Design



Build Geomorphic Stream Where Culvert Used to Be

Geomorphically-Sized Span



2 Years Later

Geomorphic? AOP?

Culvert Retrofit - Baffles

So How Should a Culvert be Sized for Hydrology and Fish Passage (AOP) ???

I refused to believe that my road worker father was stealing from his job….
but when I came home, all the signs were there

Objective

- Develop a *screening tool* that can estimate culvert hydraulics and assess risks of overtopping and aquatic organism passage
- Analyze stream crossings with limited field survey effort. But augmented with LiDAR data

Spreadsheet Model

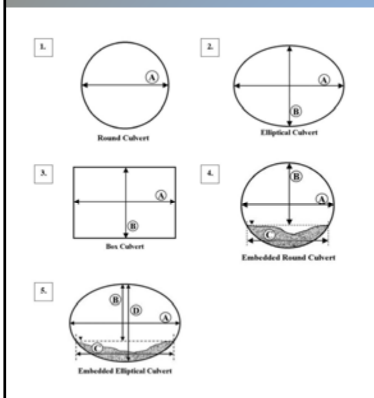
Project Background

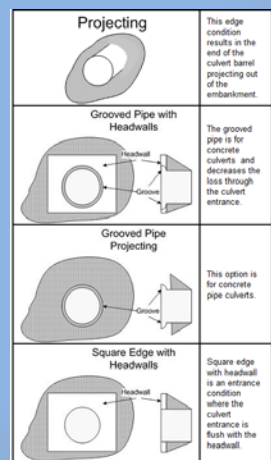
Culvert model previously created as a coarse hydraulic assessment of crossing performance

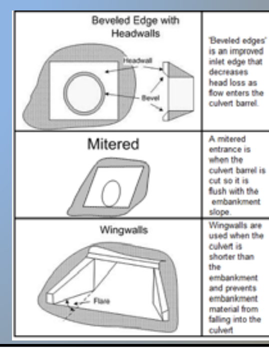
Special Transportation Project Funding provided by FHA through NH DOT to SNHPC and TU

Data already collected from Culvert Assessment AOP and Fluvial Erosion Hazard studies along with field data to be verified and collected

Culvert Data Collection - Section

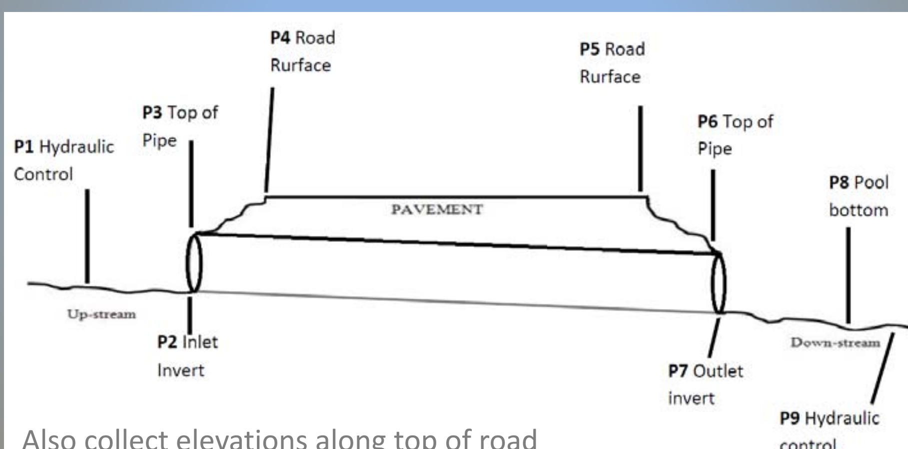






Culvert Data Collection - Profile

P1: Hydraulic Control	**P4**: US Road Surface	**P7**: Outlet Invert
P2: Inlet Invert	**P5**: DS Road Surface	**P8**: Pool Bottom
P3: Inlet Top of Pipe (inside)	**P6:** Outlet Top of Pipe (inside)	**P9**: Hydraulic Control



Also collect elevations along top of road

Additional Geometric Data

- Roadway weir
- Downstream tail water control
  - Downstream riffle cross section estimated as compound trapezoid
  - Tailwater rating curve (FIS, etc.)

Hydrology

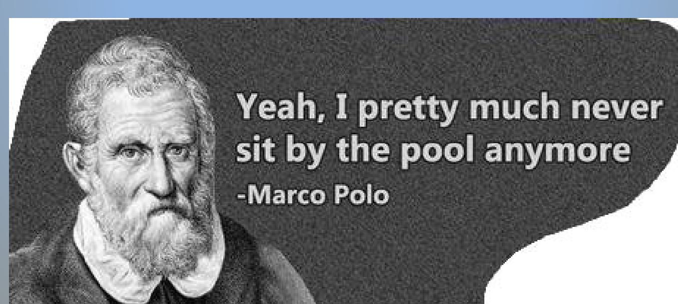
- Simulation (A < 2 mi^2)
  - NRCS
- Regression (A > 2 mi^2)
  - StreamStats

Rao, A.R., 2005, Flood-Frequency Relationships for Indiana: Joint Transportation Research Program, Purdue University, FHWA/IN/JTRP-2005/18, 14 p.

Stream Crossing Hydraulics

General Culvert Hydraulics

- Inlet Control
- Outlet Control
- Weir flow
- Bypass flow



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Overtopping

[redacted]

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Hydraulics

- **USDOT's FHWA's HDS-5 Method**
  - Headwater Depth
    - Inlet
    - Outlet
  - Applicable Equations
    - Unsubmerged
    - Submerged
    - Regression Equations
- **Limitations**
    - Some multiple culverts
    - Inlet grates
    - Buried culverts

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AOP

The AOP Coarse Screen

VT Aquatic Organism Passage Coarse Screen	Full AOP	Reduced AOP	No AOP			
Updated 2/25/2008	for all aquatic organisms	for all aquatic organisms	for all aquatic organisms except adult salmonids		for all aquatic organisms including adult salmonids	
AOP Function Variables / Values	Green (if all are true)	Gray (if any are true)	Orange		Red	
Culvert outlet invert type	at grade **OR** backwatered	cascade	free fall **AND**		free fall **AND**	
Outlet drop (ft)	= 0		> 0 , < 1 ft **OR**		≥ 1 ft **OR**	
Downstream pool present			= yes	(= yes **AND**	= no **OR**	(= yes **AND**
Downstream pool entrance depth / outlet drop			n/m	≥ 1)	n/a	< 1) **OR**
Water depth in culvert at outlet (ft)					< 0.3 ft	
Number of culverts at crossing	1	> 1				
Structure opening partially obstructed	= none	≠ none				
Sediment throughout structure	yes	no				

VT Stream Crossing Protocol

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Example

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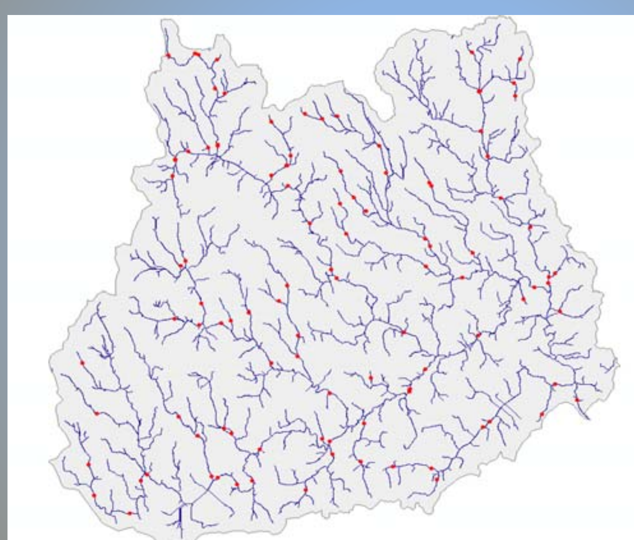
Example: Unnamed Brook on Hayes Road, Madbury

Lat/Long to GIS database
From which watershed
Parameters are obtained
For hydrology

Example Stream Crossings



- **Crossings in red**

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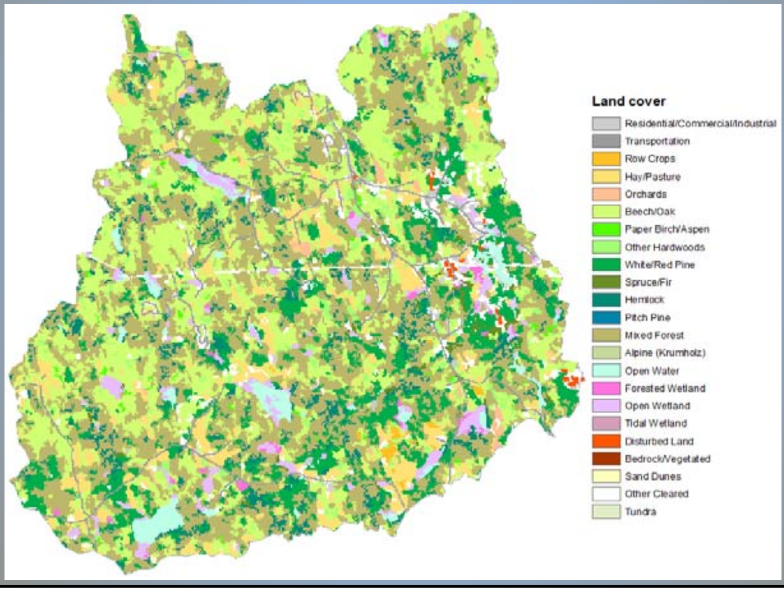
Land Cover



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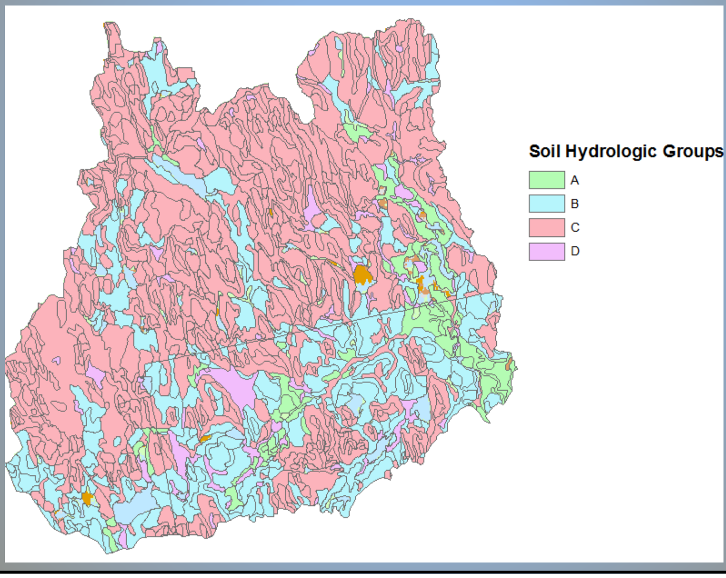
Hydrologic Soils Groups



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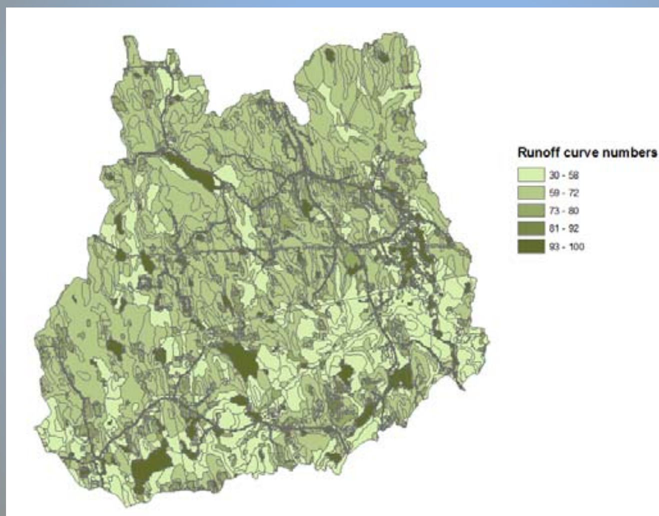
Runoff curve numbers



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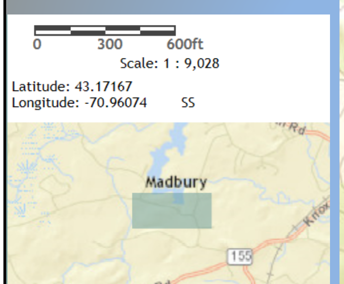
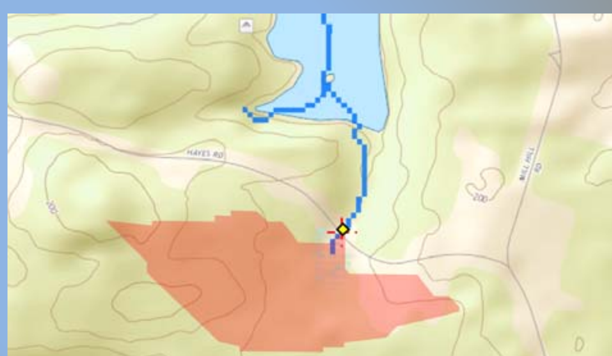
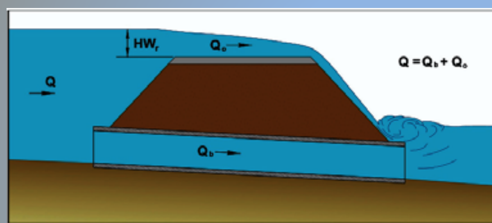
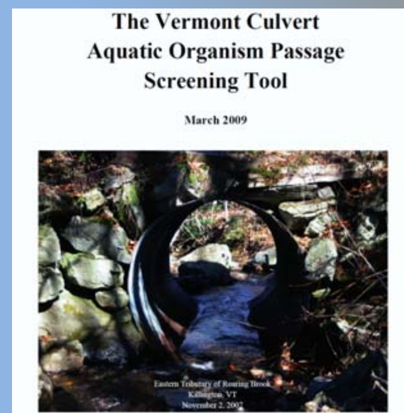
Watershed Delineation





Suggested C-RiSe Classifications

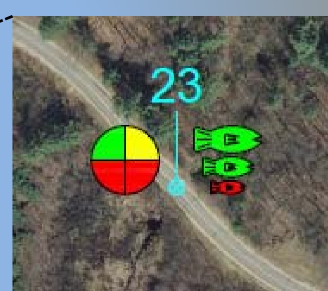



The Vermont Culvert
Aquatic Organism Passage
Screening Tool

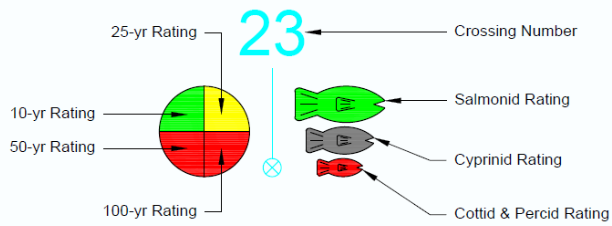
March 2009

- Hydraulics: Top of Culvert and Top of Road
- AOP: NH scheme

Ratings



116



Hydraulic Rating Key

- 10-yr: Rating for the water's surface elevation at the inlet for the 10-yr flood flow
- 25-yr: Rating for the water's surface elevation at the inlet for the 25-yr flood flow
- 50-yr: Rating for the water's surface elevation at the inlet for the 50-yr flood flow
- 100-yr: Rating for the water's surface elevation at the inlet for the 100-yr flood flow

Pass: Headwater stage is below the lowest top of top of culvert at the site

Fail: Headwater stage overtops the road

Transitional: Headwater stage is between the lowest top of culvert and the top of the road

AOP Rating Key

- Top Fish: Salmonids; Salmon, Trout
- Middle Fish: Cyprinids; Carp, Minnow
- Bottom Fish: Cottids & Percids; Sculpin, Walleye, Perch

Pass: Species can navigate the culvert

Fail: Species cannot navigate the culvert

Indeterminate: Insufficient information to determine a rating

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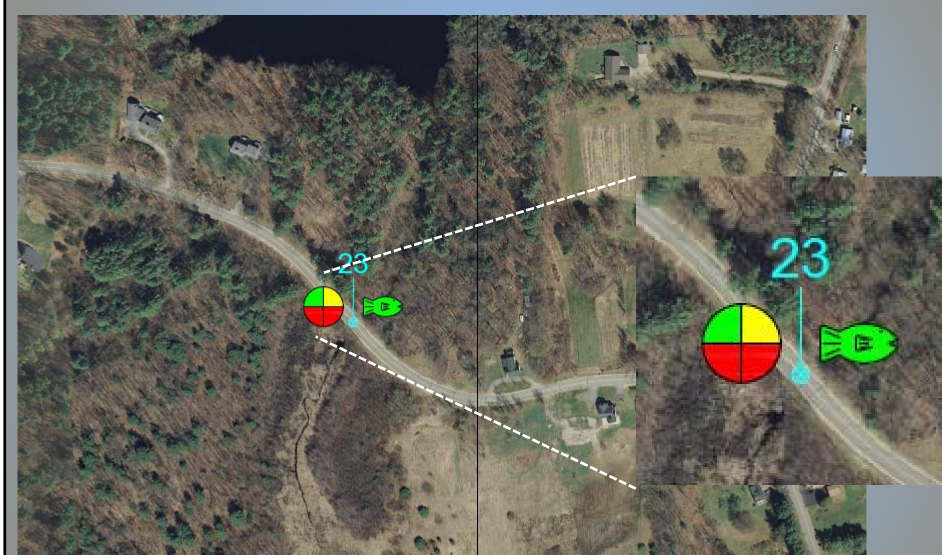

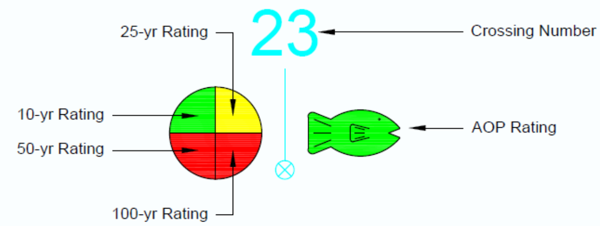

Hydraulic Rating Key

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- 50-yr: Rating for the water's surface elevation at the inlet for the 50-yr flood flow
- 100-yr: Rating for the water's surface elevation at the inlet for the 100-yr flood flow

Pass: Headwater stage is below the lowest top of top of culvert at the site

Fail: Headwater stage overtops the road

Transitional: Headwater stage is between the lowest top of culvert and the top of the road

AOP Rating Key

Rating system performed using the Vermont Culvert Aquatic Organism Passage Screening Tool

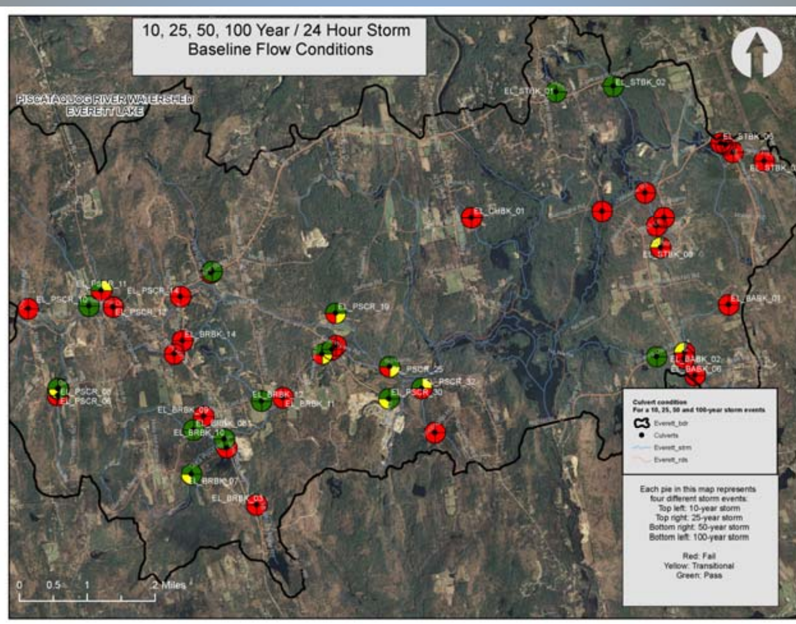
Full AOP: All species can navigate the culvert

Restricted AOP: All species have reduced ability to fully navigate the culvert

No AOP: Impassable by all species other than adult Salmonids

No AOP: Impassable by all species

Community Based Assessment Tool



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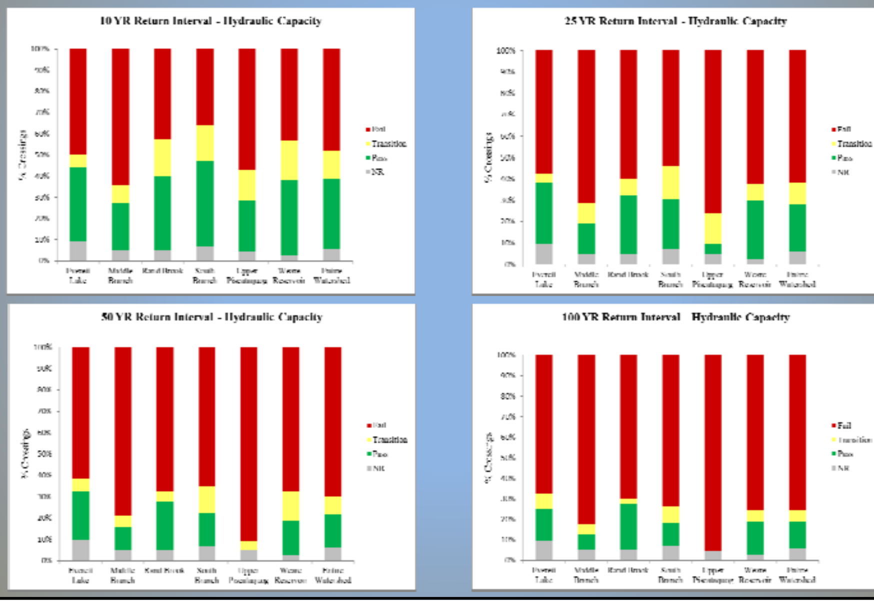
Excel Model - Results



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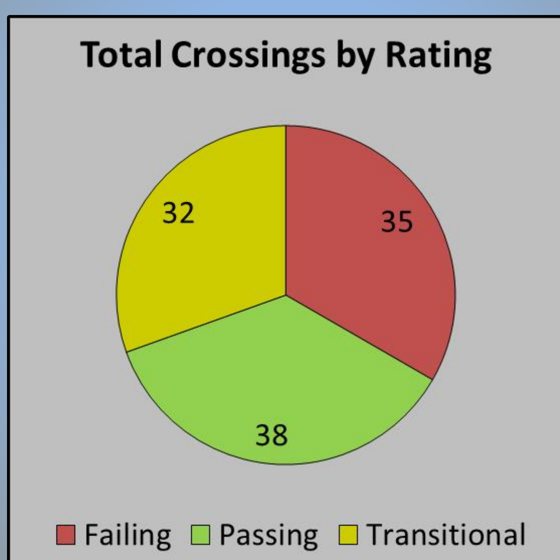
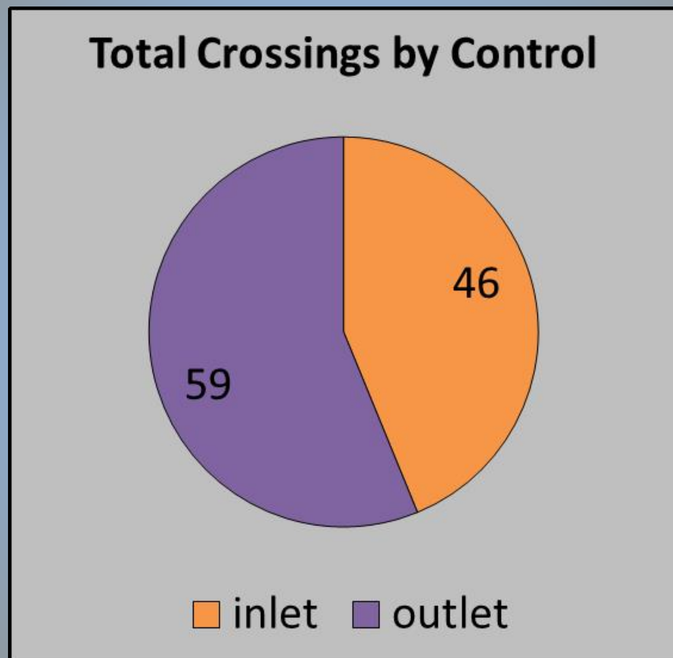
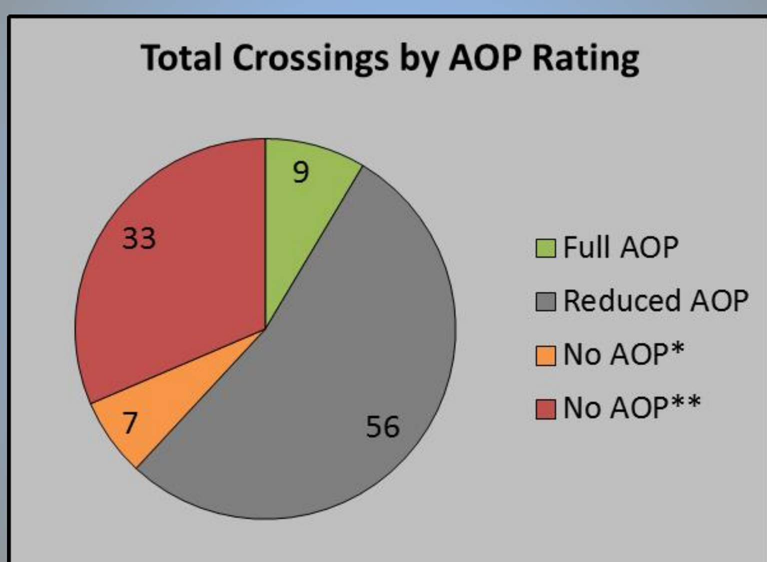
C-RiSE Results



122


Total Crossings by Control
46
59
inlet
outlet

123


Total Crossings by AOP Rating
9
33
7
56
Full AOP
Reduced AOP
No AOP*
No AOP**

124


Really bad star
Nasty star
Death star
BRAINSTORMING
Some of the best ideas were found through it.

End

125