8. Hydrology

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Contributors

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- Mike Furniss (Retired Hydrologist, PNW Research Station)

Successful stream simulation design and construction requires:

- Knowledge of the local hydrology
- An ability to estimate a wide range of flows (transfer data from gaged to ungaged sites)

Presentation Outline

- What and Why?
- General Hydrology – Maine
- Estimating Peak Flood Flows: $Q_{1.5}$ - Q_{100}
- Bankfull Flow and Elevation
- Culvert Hydraulics and Capacity
- Estimating Flows for Fish Passage and Construction

What flow data are needed? Annual Flood Peaks

- Peak hydraulic design flow
  - Determines the peak flow capacity of the structure
  - Flood-frequency analysis for 100-yr flood
  - Consider checking 500-yr flood
- Sediment mobility and stability
  - Model hydraulics to determine bed mobility and stability
  - Flood-frequency analysis for 1.5 to 100-yr flood
- Bankfull flow
  - Model hydraulics to help verify bankfull elevation
  - Flood-frequency analysis for 1.5 or 2-yr flood

Annual Flood Peaks:

Carrabassett River near North Anson, Maine
01047000, DA=353 sq mi, period of record=1926-2012

Water Year	Date	Gage Height (ft)	Discharge (cfs)
2003	Apr 16, 2003	7.29	3,740
2004	Dec 18, 2003	16.57	20,300
2005	Apr 03, 2005	16.70	21,500
2006	Oct 16, 2005	12.97	13,300
2007	Oct 29, 2006	15.71	19,200
2008	Apr 30, 2008	14.17	15,700
2009	Nov 26, 2008	13.58	14,500
2010	Mar 31, 2010	13.36	14,000
2011	Aug 29, 2011	20.53	31,600
2012	Apr 23, 2012	12.03	11,500

Nomenclature

Recurrence Interval:

$$\text{Recurrence Interval} = \frac{1}{\text{Exceedance Probability}}$$

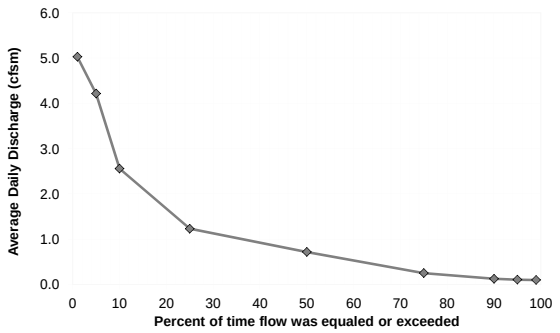
100 yr flood = 0.01 (1%) exceedance probability

2 yr flood = 0.50 (50%) exceedance probability

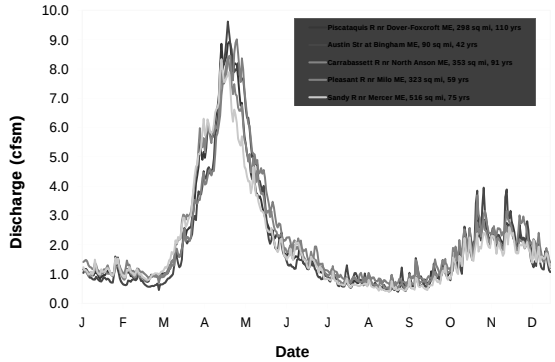
What flow data are needed? Average Daily Flows

- **Construction flow**
  - Determine construction time and duration
  - Average monthly flow for that time period
  - Additional capacity or 2-yr flood for extended construction period (weeks-months, state req.)
- **High fish passage flow**
  - Determines the **velocity threshold** for fish passage
  - Typically an exceedance percentage from flow duration curve (1%-10%) or some percentage of the 2-year flood
- **Low fish passage flow**
  - Determines the **depth threshold** for fish passage
  - Exceedance percentage from flow duration curve or the 2-year, 7-day low flow

Nomenclature - Flow Duration



Average Daily Flows 5 Sites in Maine



Flow data and design methods

Stream Simulation Design Method

- Mimics the natural stream processes within a culvert; culvert functions as a natural channel

Hydraulic Design Method

- Matches the hydraulic performance of a culvert with the swimming capabilities of a target species and age class of fish

Requires **Peak Hydraulic Design Flow** (100-year flood), **Sed Mob/Stability, BF Q Check**, **By-Pass Flows**

Also Requires **High and Low Fish Passage Flows**

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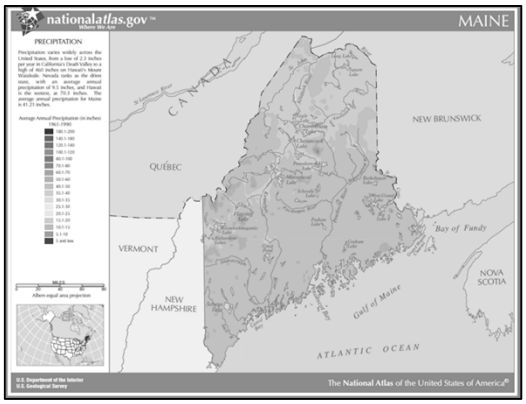
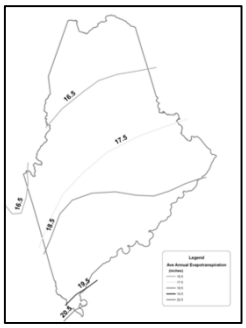
Local Hydrology: Annual Precipitation

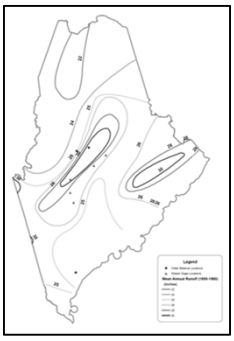


Local Hydrology: Annual Evapotranspiration



(Source: Randall 1996, Mean annual runoff, precipitation and evapotranspiration in the glaciated NE United States, 1951-80. US Geological Survey Open-File Report 96-395, plate 2)

Local Hydrology: Annual Runoff

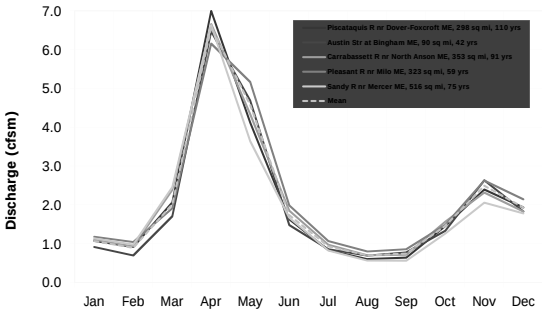


(Source:Gebert, W.A., Graczyk, D.J., and Krug, W.R., 1987, Average annual runoff in the United States, 1951-80: U.S. Geological Survey Hydrologic Investigations Atlas HA-710, 1 sheet, scale 1:7,500,000)

Local Hydrology: Annual Water Balance

Region	Ppt (in)	ET (in)	RO (in)	RO (cfsm)
Gorman Chairback, ME	48	16	32	2.3
Greenville, ME	44	16	28	2.1
Portland, ME	44	19	25	1.8

Average Monthly Flows
5 Sites in Maine



Sources of flow data: US Geological Survey

- Web site – National Water Information Systems (NWIS) (http://water.usgs.gov/nwis/)
  - Instantaneous peak
  - mean daily
  - mean monthly values
- Published data summaries
  - Peak flow T-year return period flows
  - annual and monthly flow with exceedance
- Custom data retrievals
  - Anything you want if you have the money, such as 7-day, 2-year low flow statistics

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Estimating Flood Flows

1. **Gaged sites**
2. **Sites near gaged sites on the same stream**
3. **Ungaged sites: Regional regression equations**

1. Gaged Sites in Virginia

1. Gaged Sites: 65 in Maine

- Use reported data
- Gaging Station Name, Number, Location
- Peak Flow for Given Recurrence Interval

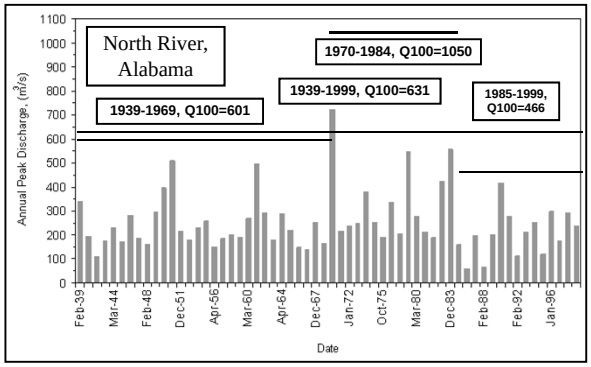
  (2, 5, 10, 25, 50, 100, 500)
- Consider period of record

Table 1. Estimated peak flows and maximum recorded flows for selected U.S. Geological Survey streamflow-gaging stations--Continued

[m^3/s, cubic meters per second; km^2, square kilometers; u, unregulated; r, regulated; nr, nonr]

USGS gaging station number	Gaging station name	Gaging station (G), Regression (R), Weighted (W)[a]	Peak flow (m^3/s) for given recurrence interval							Highest peak flow known				Drainage area (km^2)
			2 years	5 years	10 years	25 years	50 years	100 years	500 years	Date	Flow (m^3/s)	Period of known peak flows[b]	Regulation[c]	
01045000	Dead River at The Forks, Maine	G	294	404	470	547	601	651	758	3-20-1936	813	1903-07, 1911-79	r	2,250
01046000	Austin Stream at Bingham, Maine	G	68.0	108	139	182	218	256	359	11-3-1966	234	1931-69	u	233
		R	64.5	96.5	119	150	173	198	258					
		W	67.8	107	137	179	213	249	344					

Importance of data length



2) Sites near gages – same stream

- **Extrapolate gaged data to ungaged location**
  - Assumes similar topography, geology, vegetation, and other characteristics that may affect flood magnitude
  - Refer to state publication
  - General Rule: Ungaged drainage area should be **50-150% of gaged drainage area**

$$Q_{100(ungaged)} = Q_{100(gaged)} \left(\frac{A_{ungaged}}{A_{gaged}} \right)^X$$

(x = can vary by flood region and recurrence interval)

3) Ungaged Sites: USGS Equations

Publications available from:
U.S. Geological Survey
Publication Distribution Center
(303) 202-4200 or (800) 435-4200
http://water.usgs.gov/osw/streamstats/

The Source in Maine:

Water Resources Investigations Report 99-4008

Estimating the Magnitude of Peak Flows for Streams in Maine for Selected Recurrence Intervals

by Glenn Hodgkins

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY
Water Resources Investigations Report 99-4008

Prepared in cooperation with the
MAINE DEPARTMENT OF TRANSPORTATION

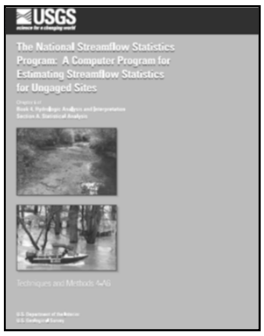
Augusta, Maine
1999

By G. Hidgkins, 1999

National Streamflow Statistics (NSS) Program

- **Regional equations for each state in the United States**
- **Replaced NFF**
- **Computer Program**:
  - Download software
  - Technical papers for each State
  - Latest equations for each State

http://water.usgs.gov/software/NSS/



Ungaged sites – the typical approach

- **USGS regional regression equations**
  - **Available for each State divided into hydrologic regions**
  - **Discharges at gaged sites computed using Log Pearson Type III distribution**
  - **Multiple regression of flow on watershed and climatic characteristics, yielding prediction equations of the form:**

$$Q_T = aA^b B^c \ldots N^n$$

  - **The analysis also provides measure of accuracy; standard errors of the estimate are commonly in the range of ± 30 to 80%**

No Flood Frequency Regions in Maine

Unique regional regression coefficients for each recurrence interval.
Drainage area and wetland are the only significant variables used in the equations.

Sample Predictive Equations for Unregulated Streams in ME

(National Streamflow Statistics Program)

Full Regression Equations (with wetlands):

$Q_2 = (35.31)\ (1.075)\ (A)^{0.686}\ (10^{-0.0286(W)})$ SE: 40.6 to -28.9%

$Q_{100} = (35.31)\ (5.629)\ (A)^{0.771}\ (10^{-0.0258(W)})$ SE: 48.6 to -32.7%

Where: A = drainage area (sq mi),
W = wetland area (%),
regression coefficients vary by recurrence interval,
no statistically significant regions

Henderson Brook Road Crossing in ME

(National Streamflow Statistics Program)

Full Regression Equations (with wetlands):

$Q_2 = (35.31)\ (1.075)\ (A)^{0.686}\ (10^{-0.0286(W)})$ SE: 40.6 to -28.9%

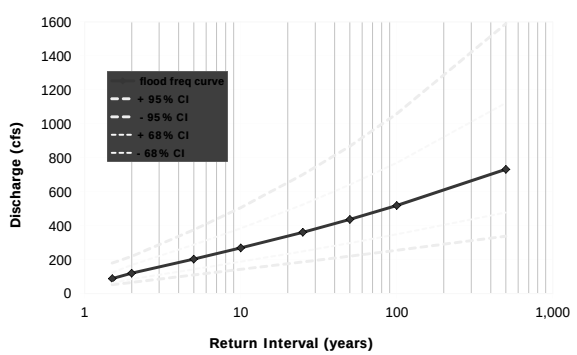
$Q_{100} = (35.31)\ (5.629)\ (A)^{0.771}\ (10^{-0.0258(W)})$ SE: 48.6 to -32.7%

Where: regression coefficients vary by recurrence interval
A = drainage area (sq mi) = 2.07 sq mi
Wetlands = 4.45 percent

Results:

Q_2 = 120 cfs (58 cfsm)
Q_{100} = 519 cfs (251 cfsm)

Estimated Flood Frequency Curve and Prediction Error: Henderson Brk in ME



Shafer Trib Crossing in WA

(National Streamflow Statistics Program)

$Q_2 = 0.350(A)^{0.802}(P)^{1.246}$ SE: 32%

$Q_{100} = 0.745(A)^{0.862}(P)^{1.260}$ SE: 37%

Where: regression coefficients vary by region and recurrence interval
A = drainage area (sq mi) = 1.16 sq mi
P = mean annual precipitation (inches) = 130 inches

Results:

Q_2 = 128 cfs (76 cfsm)
Q_{100} = 349 cfs (301 cfsm)

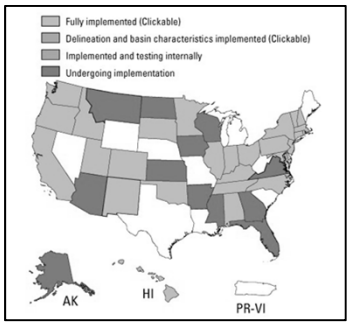
(See page 14-18)

Regional Regression Limitations

- Derive input variables using the same methods as for the equations Standard Errors of -28.9 to 53.5%
- Beware extrapolating flood estimates beyond the input data used to develop the equations
  - drainage area range was 0.91 to 1,653 sq mi
  - wetland area range was 0.7 to 26.7 percent
  - typically need estimates for small watersheds
  - most USGS gage data are from larger watersheds
  - peak flow per unit area increases as drainage area decreases (less storage, water gets to the channel faster)
  - Use full equations rather than simplified in Maine

Developing Stream Stats Technology

Web-based GIS integrated flow prediction

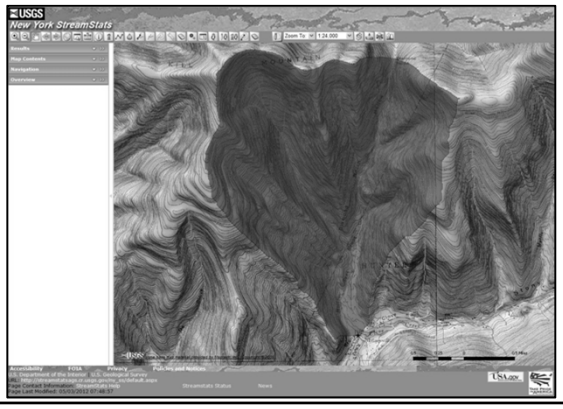


StreamStats

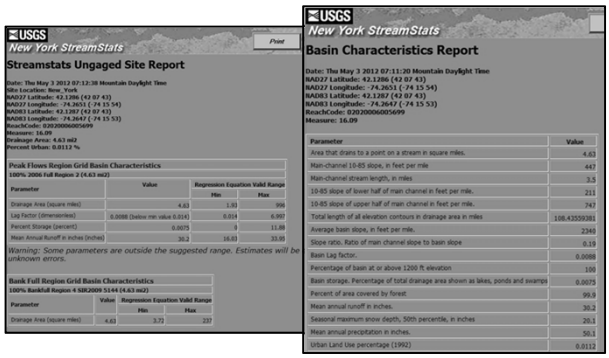
Web/GIS/Database

http://water.usgs.gov/osw/streamstats/

StreamStats Example from NY: Watershed Delineation for Hollow Tree Br at Hwy 214



StreamStats Example from NY: Hollow Tree Br at Hwy 214 Data



StreamStats Example from NY: Hollow Tree Br at Hwy 214 Results

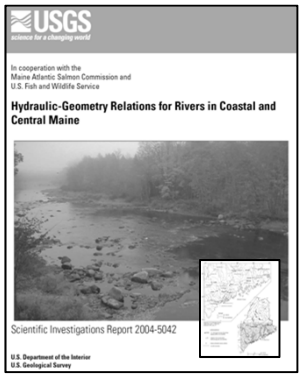
Peak Flows Region Grid Streamflow Statistics

Statistic	Flow (ft^3/s)	Prediction Error (percent)	Equivalent years of record	90-Percent Prediction Interval	
				Minimum	Maximum
PK1_25	221		4.8		
PK1_5	285		4.3		
PK2	380		4.4		
PK5	680		7.3		
PK10	937		10		
PK25	1320		14		
PK50	1650		16		
PK100	2030		18		
PK200	2450		19		
PK500	3090		20		

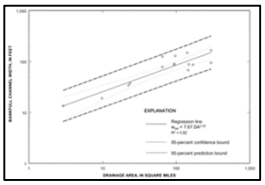
Bank Full Region Grid Streamflow Statistics

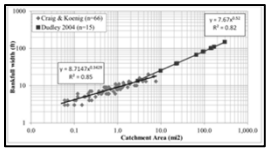
Statistic	Flow (ft^3/s)	Estimation Error (percent)	Equivalent years of record	90-Percent Prediction Interval	
				Minimum	Maximum
BFAREA	58.9	35		12.8	270
BFDPTH	1.73	19		0.41	7.31
BFFLOW	387	59		28.7	5220
BFWDTH	34.6	26		7.96	150

Bankfull Channel Characteristics in Maine

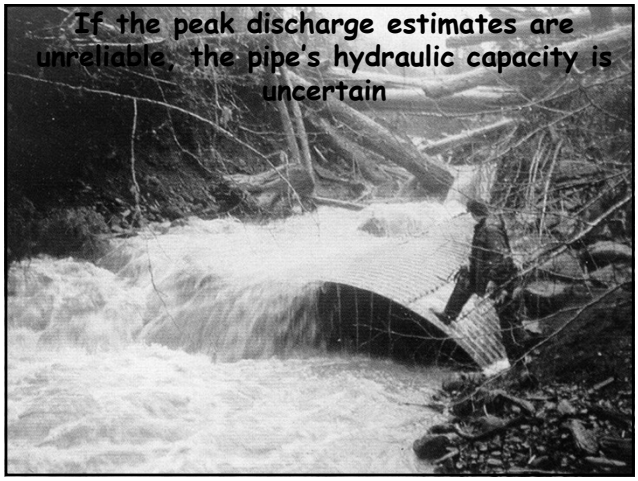


(Dudley, R. W. 2004)





(Koenig, S. and S. Craig, 2009. Restoring Salmonid Aquatic/Riparian Habitat: A Restoration Strategy for the Downeast Maine DPS Rivers. Eastport, ME, Project SHARE and USFWS Maine Fishery Resources Office: 45 p.)



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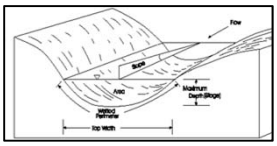
Model Bankfull Discharge (Est $Q_{1.5}$ or Q_2)

- Use results to help identify and verify bankfull elevation (and channel dimensions)
- Where bankfull elevations are good, use analysis to verify the relative accuracy of the regression equations and/or hydraulic model

Model Bankfull Discharge



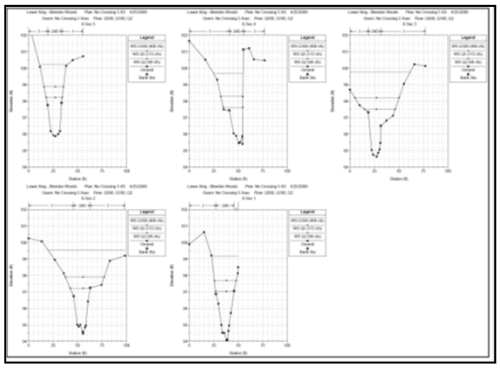
- Model bankfull discharge with Manning's Equation

$$Q_{bf} = \frac{1.49}{n} A_{bf} R_{bf}^{2/3} S^{1/2}$$

- Model bankfull discharge using a cross section analysis tool (e.g., WINXSPRO) or a step-backwater model (e.g. HEC-RAS)

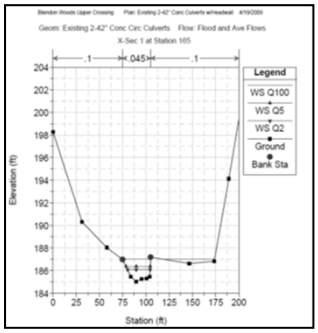
Model BF Q to Verify BF Elevation

Lower Blendon Crossing, OH Example



Model BF Q to Verify BF Elevation

Upper Blendon Crossing, OH Example



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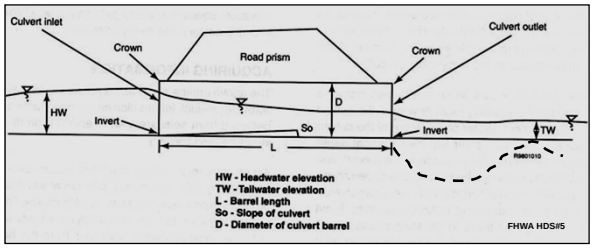
Culvert Hydraulics Terms



- **Invert, Headwater (HW), Tailwater (TW)**
- **Headwater/Depth Ratio (HW/D): HW / pipe diameter or depth**
- **Supercritical Flow: high velocity, shallow water**
- **Subcritical Flow: low velocity, deep water**

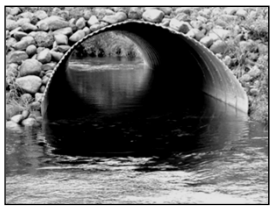
Inlet Control

Culvert Hydraulics

- **Culvert geometry at inlet controls flow**
- **Flow determined by HW elev and inlet characteristics**
- **Flow in culvert is supercritical**
- **Culvert can convey more flow than inlet will accept**

Outlet Control

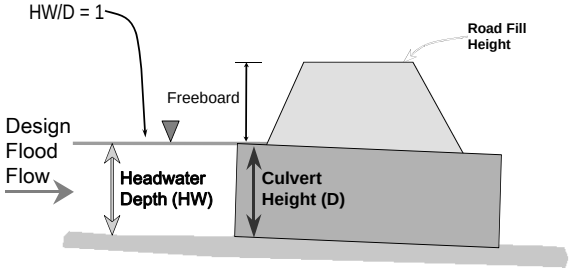
Culvert Hydraulics



- **Tailwater, culvert inlet and barrel characteristics (slope, length, roughness) control flow**
- **Flow in culvert is subcritical or under pressure**
- **Culvert inlet can convey more flow than barrel**

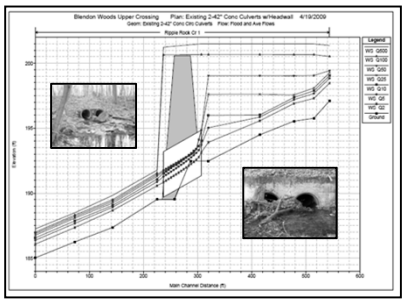
Culvert Capacity

At the design flood flow (Q_{100}), HW/D should be less than 0.8.

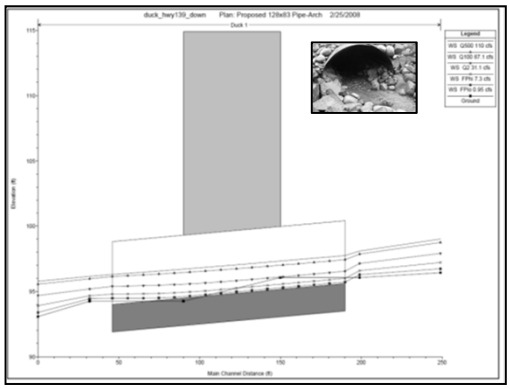


Culvert Hydraulic Models

- **HEC-RAS – USACOE**
- **HY8 – FHWA**
- **Culvert Master – Haestad Methods**
- **FishXing – USFS**



Ex: Stream Simulation Q_{100} Capacity Check with Hec-Ras, Duck Cr at Hwy 139, WI



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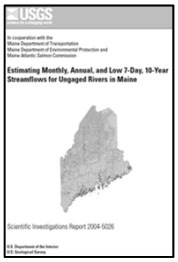
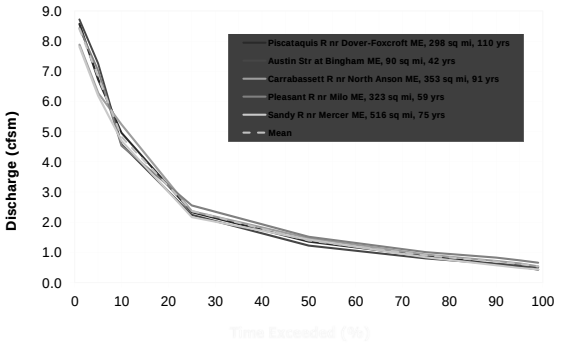
Methods for Estimating Fish Passage and Construction Flows

- High Fish Passage Flow:
  - 1-10% annual exceedance flow
- Low Fish Passage Flow:
  - 90-99% annual exceedance flow
- Construction flows:
  - Short-term (days) - average annual or monthly flow
  - Long-term (weeks) - Q2 (?)



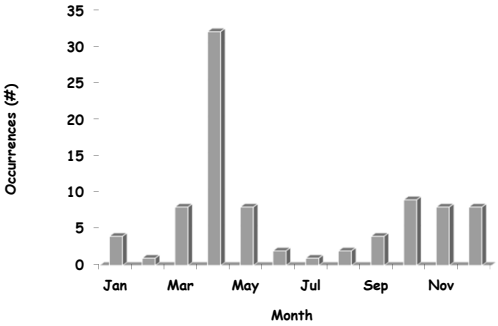
Note: Check state requirements

Flow Duration Curves
5 Sites in Maine

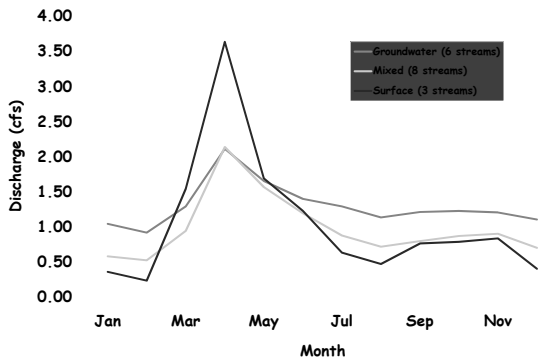


Occurrence of Annual Flood Peaks

Carrabassett River near North Anson, ME (01047000), Somerset County, ME
Methods for Estimating Construction Flows



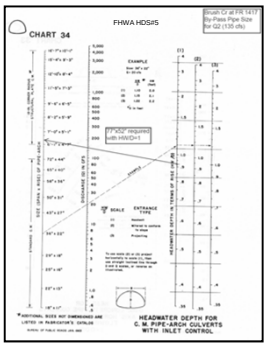
Est Monthly Flows: Brush Cr at FR 1417, WI
Methods for Estimating Construction Flows

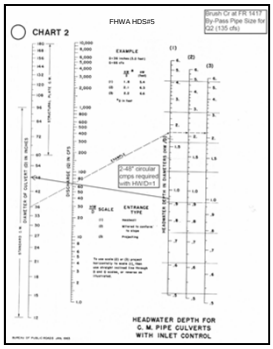


Est Monthly Flows: Brush Cr at FR 1417, WI
Methods for Estimating Construction Flows

- Drainage Area = 4.32 sq mi
- 2-yr Flood Flow Est = 135 cfs
- Construction By-Pass Flows:
  - Baseflow assume 0.4-1.1 cfsm
    - 1.4-4.7 cfs or 760-2,110 gal/min
  - 2-yr flood requires 77"x52" or 2-48" circ
    - Up invert at 90.0, down invert at 89.0
    - Up sheetpile at 94.5, down at 93.0

Est Monthly Flows: Brush Cr at FR 1417, WI
Methods for Estimating Construction Flows





Summary

- Predicted peak discharge estimates using regional regression equations have a degree of uncertainty
- If the peak discharge estimates are unreliable, then the risk of failure increases
- Use field evidence and hydraulic models to verify peak discharge estimates
- The headwater depth to culvert height ratio (HW/D) should be less than 0.80 for the Q_{100} discharge