Culvert Design Process

Hydrology
  ↓
  Site Assessment
  ↓
  Alignment and Profile
  ↓
  Bed and Banks
  ↓
  Structure
  ↓
  Sediment Mobility & Stability

Discharge (cfs)

0 200 400 600 800 1000 1200 1400 1600 1800 2000
0 10/1 1/9 4/19 7/28
Presentation outline

• What and Why?

• General hydrology - Minnesota

• Estimating peak flood flows: $Q_{1.5} - Q_{100}$

• Bankfull flow and elevation

• Estimating flows for by-pass during construction
Hydrology: why and what

- Hydraulic analysis requires hydrologic data (hydrology part of H&H)
- Two basic types of hydrology data
  - Instantaneous peak flows
  - Average daily flows
- Streamflow data
  - Collected at streamflow gaging stations
  - Used to estimate flows at ungaged sites
Flood frequency terms

100-yr flood ($Q_{100}$) = 0.01 (1%) exceedance probability

2-yr flood ($Q_2$) = 0.50 (50%) exceedance probability
What hydrologic data are needed?
Estimates of flood magnitudes and frequencies

- Peak hydraulic design flow
  - Verify structure has adequate flood capacity
  - Recommended min capacity $Q_{100}$ with HW/D<1
  - Consider checking $Q_{500}$

- Bankfull flow
  - Model hydraulics to help verify bankfull elevation
  - $Q_{1.5}$ or $Q_2$

- Sediment mobility and stability
  - Model hydraulics for bed mobility and stability
  - $<Q_{1.5}$ to $>Q_{100}$
Annual flood peaks:
Swan River Tributary at Warba, MN
05216980, DA=3.95 sq mi, period of record=1961-1985

<table>
<thead>
<tr>
<th>Water Year</th>
<th>Date</th>
<th>Gage Height (ft)</th>
<th>Discharge (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1977</td>
<td>Sep. 09, 1977</td>
<td>5.34</td>
<td>21</td>
</tr>
<tr>
<td>1978</td>
<td>Aug. 23, 1978</td>
<td>6.64</td>
<td>70</td>
</tr>
<tr>
<td>1979</td>
<td>Apr. 21, 1979</td>
<td>7.08</td>
<td>50</td>
</tr>
<tr>
<td>1980</td>
<td>Apr. 12, 1980</td>
<td>5.64</td>
<td>28</td>
</tr>
<tr>
<td>1981</td>
<td>Aug. 05, 1981</td>
<td>6.76</td>
<td>70</td>
</tr>
<tr>
<td>1982</td>
<td>Apr. 15, 1982</td>
<td>7.15</td>
<td>43</td>
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<tr>
<td>1983</td>
<td>Aug. 03, 1983</td>
<td>6.74</td>
<td>74</td>
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<tr>
<td>1984</td>
<td>Jun. 08, 1984</td>
<td>5.83</td>
<td>38</td>
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<tr>
<td>1985</td>
<td>Jul. 18, 1985</td>
<td>6.68</td>
<td>40</td>
</tr>
</tbody>
</table>
What flow data are needed?
Estimates of average daily flows

• Construction flows
  • 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 flows
  • 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 flows
  • Determines the depth threshold for fish passage
  • Exceedance percentage from flow duration curve or the 2-year, 7-day low flow
Average daily flows for 5 sites in N MN

- **Knife n Two Harbors, 84 sq mi, 36 yrs**
- **Prairie n. Taconite, 371 sq mi, 26 yrs**
- **Big Fork n. Big Falls, 1480 sq mi, 75 yrs**
- **Mississippi n. Bemidji, 610 sq mi, 23 yrs**
- **Straight n. Park Rapids, 53 sq mi, 21 yrs**
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Local hydrology: annual precipitation
Local hydrology: annual evapo-transpiration

Local hydrology: annual runoff

## Local hydrology: annual water balance

<table>
<thead>
<tr>
<th>Region</th>
<th>Ppt (in)</th>
<th>ET (in)</th>
<th>RO (in)</th>
<th>RO (cfsm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grand Rapids, MN</td>
<td>27</td>
<td>19</td>
<td>8</td>
<td>0.59</td>
</tr>
<tr>
<td>Duluth, MN</td>
<td>28</td>
<td>16</td>
<td>12</td>
<td>0.89</td>
</tr>
<tr>
<td>N WI</td>
<td>32</td>
<td>20</td>
<td>12</td>
<td>0.89</td>
</tr>
</tbody>
</table>
Sources of flow data: US Geological Survey

  - 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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National Streamflow Statistics (NSS) program

- Summary of flood frequencies at gage stations
- Methods for extrapolating data to ungaged sites
- Regional equations for flood frequencies and other streamflow statistics
- Computer Program: Version 4
  - Download software
  - Technical papers for each State
  - Latest equations for each State

http://water.usgs.gov/software/nss.html
Technical publications for each state

Prepared in cooperation with the Minnesota Department of Transportation and the Minnesota Pollution Control Agency

Techniques for Estimating the Magnitude and Frequency of Peak Flows on Small Streams in Minnesota Based on Data through Water Year 2005

Scientific Investigations Report 2009–5250

U.S. Department of the Interior
U.S. Geological Survey

http://water.usgs.gov/software/nss.html
Unique regional regression coefficients for each region and recurrence interval.

Region B variables: drainage area (sq mi), % lake area, % hydro soil group A and mean annual runoff (in).
Example: Clearwater Cr at Hwy 60
(National Streamflow Statistics Program)

Hydrologic Region B:

\[ Q_{1.5} = 3.44(DA)^{0.067(9.031+\log(DA))}(LK+1)^{-0.368}(SA+1)^{-0.104}(RO)^{0.916} \text{ SE: 33\%} \]

\[ Q_{100} = 87.7(DA)^{0.107(3.959+\log(DA))}(LK+1)^{-0.561}(SA+1)^{-0.198}(RO)^{0.529} \text{ SE: 47\%} \]

Where: regression coefficients vary by region and recurrence interval
DA = drainage area (sq mi) = 60.3 sq mi
LK = lake area (ft) = 22.13 % (above max of 13%)
SA = Hydrologic Soil Group A (%) = 14.16 %
RO = generalized mean annual runoff (in) = 7.81 in

Results:
\[ Q_{1.5} = 104 \text{ cfs (1.7 cfsm)} \]
\[ Q_{100} = 323 \text{ cfs (5.4 cfsm)} \]
Estimated flood frequency curve and prediction error: Clearwater Cr at Hwy 60
StreamStats Example: Clearwater Cr at Hwy 60 Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Regression Equation Valid Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage Area (square miles)</td>
<td>60.3</td>
<td>Min 0.23 Max 1700</td>
</tr>
<tr>
<td>Percent Lakes and Ponds (percent)</td>
<td>22.13</td>
<td>0</td>
</tr>
<tr>
<td>Percent Hydrologic Soil Type A (percent)</td>
<td>14.16</td>
<td>0</td>
</tr>
<tr>
<td>Generalized Runoff (inches)</td>
<td>7.81</td>
<td>Min 3 Max 12.2</td>
</tr>
<tr>
<td>Log of Drainage Area (dimensionless)</td>
<td>1.78</td>
<td>Min -0.6383 Max 3.2305</td>
</tr>
</tbody>
</table>

Warning: Some parameters are outside the suggested range. Estimates will extrapolations with unknown errors.
Regional regression limitations

- Derive input variables using the same methods as those used to develop the equations
- Standard Errors of 22-59%
- Beware extrapolating flood estimates beyond the input data used to develop the equations
  - Typically we need estimates for small watersheds
  - Most of USGS gaging data are from larger watersheds
  - Remember that peak flow per unit area increases in smaller tributary areas (less storage and water gets to the channel faster) so adjust estimates accordingly
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Bankfull discharge and elevation (estimate $Q_{1.5}$ 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 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

Example: Lower Blendon Crossing, OH
Model BF Q to verify BF elevation
Example: Upper Blendon crossing, OH
Model BF Q to verify BF elevation
Example: Upper Blendon crossing, OH
Model BF Q to verify BF elevation
Example: L Willow crossing, WI
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Estimating and designing for by-pass flows

• Determine construction season
• Determine required time for construction
• High base flows/long construction period:
  - Days to weeks
  - Diversion channel or culvert
  - Sized for $Q_2$ or local requirements
• Low flows/short construction period:
  - 1 to a few days
  - By-pass pump opportunity
  - Size capacity for highest average monthly flow or flow duration curve (ex. 50%)
Ave monthly runoff near Green Bay, WI and three flow regimes in N. WI

Construction period

0.26 cfs/sq mi
Ave monthly flows for 5 sites in N MN

- Knife n Two Harbors, 84 sq mi, 36 yrs
- Prairie n. Taconite, 371 sq mi, 26 yrs
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Discharge (cfsm)
By-pass pumping capacity estimate based on average monthly flow

Brookside Cr site, drainage area = 3.91 sq mi

July ave flow = 0.24 cfs/sq mi x 3.91 sq mi = 0.94 cfs or 422 gal/min
By-pass culvert design based on Q2

Brush Cr at FR 1417, WI

17"x02" required with H/W=D=1

2-48" circular culms required with H/W=D=1
By-pass culvert design based on $Q_2$
Brush Cr at FR 1417, WI

- Drainage area = 4.32 sq mi
- 2-yr flood flow est = 135 cfs
- Culvert invert elevations:
  - Upstream = 90.0
  - Downstream = 89.0
- Sheetpiling elevations:
  - Upstream = 94.5
  - Downstream = 93.0
Occurrence of annual flood peaks
Swan River Trib (05216980), Itasca County, MN
Consideration for construction flows