HEC 17:
Highways in the River Environment
::
Floodplains, Extreme Events, Risk and Resilience

Webinar C: Chapters 7 and 8
Presenters: Joe Krolak, Brian Beucler, Rob Kafalenos, Cynthia Nurmi, Rob Hyman
Webinar Logistics

**Mute Phone**
- Press *6

**Questions During Presentation**
- Type in Chat Box
- Designated times

**Presentation Recorded**
- Slides available at end of webinar
- Posted to FHWA site
Webinar A: Introduction, Floodplains, Riverine Flood Events, Non-Stationarity (Chapters 1-4)
January 25, 2017, 10 am to 12 pm (Eastern Std Time)
https://www.fhwa.dot.gov/engineering/hydraulics/media.cfm

Webinar B: Climate Modeling and Risk and Resilience (Chapters 5 & 6)
February 8, 2017, 11 am to 1 pm (Eastern Std Time)
https://www.fhwa.dot.gov/engineering/hydraulics/media.cfm

Webinar C: Analysis Framework and Case Studies (Chapters 7 & 8)
February 22, 2017, 11 am to 1 pm (Eastern Std Time)
https://www.fhwa.dot.gov/engineering/hydraulics/media.cfm
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Authors to Acknowledge

- Roger T. Kilgore
  - *Kilgore Consulting & Management*
- George (Rudy) Herrmann
  - *Desert Sky Engineering and Hydrology*
- Wil Thomas
  - *Michael Baker International*
- David B. Thompson
  - *Thompson Hydrologics*
Peer Exchange Panel

- Karen Metchis & Chris Weaver
  - USEPA
- Kate White & Jeff Arnold
  - USACE
- Robert Mason, Robert Hirsch & Tim Cohn
  - USGS

Helped to inform FHWA on Federal insights ...
Why HEC-17?

Intent

- **Provide**
  - Best currently available science, technology and information
  - National consistency and relevance to our highway programs

- **Focus Areas**
  - Floodplains
  - Extreme Events
  - Risk
  - Resilience

- **Assist**
  - Our transportation partners
  - FHWA
  - Other agencies
Why the River Environment?

614,387 Bridges
509,358 over water
≈ 485,000 in River Environment

Source: 2016 NBI

Missing: nationally applicable riverine information on focus areas
What Do We Know?

What Don’t We Know?
Pulling It All Together

- **Floodplain Policy**
  - *Best actionable engineering / science methods and data*  (Chapter 2)

- **Riverine Flooding**
  - *Traditional hydrologic approaches*  (Chapter 3)

- **Nonstationarity**
  - *Sources of nonstationarity*  (Chapter 4)

- **Climate Science and Modeling**
  - *Weather vs Climate, scenarios, ensembles, uncertainty*
  - *Large scale models driven by greenhouse gas forcings*
  - *Downscaling required, FHWA CMIP tool recommended*  (Chapter 5)

- **Risk and Resilience**
  - *Risk “evolution”, exceeding design criteria vs damage*
  - *Resilient designs*  (Chapter 6)
Chapter 7

Analysis Framework
Before we Begin...

- **Observations vs Projections**
  - Observations are measurements taken looking back in time
  - Projections are future estimates of “observations yet to occur”
  - Observations are of fine spatial/temporal scale
  - Projections are of coarse spatial/temporal scale

- **Precipitation vs Flow**
  - Precipitation falls from the sky onto watersheds...GCMs give precip
  - Flow determined by conditions in watersheds...we need flow
  - Chapter 7 deals mainly with precipitation nonstationarity

- **Climate Science vs Hydrology**
  - Climate science set up to answer broader global longer term questions
  - Hydrology focuses on specific sites, answers specific local questions
  - Both fields work with uncertainty
Analysis Framework

- Recognizes Uncertainties
  - Data uncertainty (variability and emissions scenarios)
  - Model uncertainty (hydrologic and GCM’s)

- Levels of Analysis
  - Historic observations vs future projections
  - Effort grows and shifts to projections as risk increases
  - Incorporation of projections into various hydrologic models
  - Watershed size vs level of analysis
  - Service life considered using confidence intervals
  - Skillset/membership of design teams shifts as risk increases

- Programmatic Information
  - How to approach multitudes of assets
  - Regional studies can lead to simplifying assumptions
Five Levels of Analysis

1. Historical Discharges
2. Historical Discharges + Confidence Limits
3. Precipitation Projection Trend Test
4. Projected Discharges using CMIP tool
5. Customized Projected Discharges w/Climate Scientist
Let’s Run through an Example
Snider Creek Culvert

Looking US

Looking DS
Snider Creek Culvert Stats

- Upper Hoh Road crosses an alluvial fan
- Emergency-funded construction 2007, replaced 36 inch culvert
- 16.5 ft x 11.0 ft structural plate arch
- Oversized to provide debris and sediment passage
- Embedded to mitigate for long term degradation
- Upstream slope 5%, downstream slope 3%
- Active channel width 16 ft, bankfull depth 3 ft
- Drainage area 1.1 square miles
StreamStats Results

StreamStats Version 3.0
Flow Statistics Ungaged Site Report

Date: Mon Feb 20, 2017 3:44:12 PM GMT-5
Study Area: Washington
NAD 1983 Latitude: 47.8438 (47 50 38)
NAD 1983 Longitude: -123.9671 (-123 58 02)
Drainage Area: 1.1 mi²

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<th>Parameter</th>
<th>Value</th>
<th>Regression Equation Valid Range</th>
<th>M.A.P.</th>
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<td>0.15 to 1294</td>
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<tr>
<td>Mean Annual Precipitation (inches)</td>
<td>141</td>
<td>45 to 201</td>
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<table>
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<th>Statistic</th>
<th>Value</th>
<th>Unit</th>
<th>Standard Error (percent)</th>
<th>Equivalent years of record</th>
<th>90-Percent Prediction Interval</th>
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<td>516</td>
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</table>

- **Q50** = 371 cfs
- **Std Error** = 36%
- **M.A.P.** = 141 inches
- **HW/D < 1**
- **Note the reference document**

# Hydraulic Results

<table>
<thead>
<tr>
<th>Hydraulic Parameters</th>
<th>Design Flow Q50</th>
<th>Q50 + 20%</th>
<th>Q50 + 50%</th>
<th>Flow at Barrel Top</th>
<th>Roadway Overtops</th>
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</thead>
<tbody>
<tr>
<td>Flow in cfs</td>
<td>371</td>
<td>445</td>
<td>557</td>
<td>760</td>
<td>860</td>
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<tr>
<td>Headwater Elevation (ft)</td>
<td>2004.9</td>
<td>2005.6</td>
<td>2006.6</td>
<td>2008.6</td>
<td>2010.0</td>
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<tr>
<td>Headwater Depth (ft)</td>
<td>5.1</td>
<td>5.8</td>
<td>6.8</td>
<td>8.8</td>
<td>10.2</td>
</tr>
<tr>
<td>Clearance / Freeboard (ft)</td>
<td>1.8 / 5.1</td>
<td>1.1 / 4.4</td>
<td>0.1 / 3.4</td>
<td>-1.9 / 1.4</td>
<td>-3.3 / 0</td>
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<tr>
<td>Headwater-to-Diameter Ratio, HW/D</td>
<td>0.74</td>
<td>0.84</td>
<td>0.99</td>
<td>1.28</td>
<td>1.47</td>
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<tr>
<td>US Bed Elevation @ Invert (ft)</td>
<td>1999.8</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>US Top of Barrel Elevation (ft)</td>
<td>2006.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open Diameter considering Embedment (ft)</td>
<td>6.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- This is a very resilient culvert
- Q50 HW/D = 0.74 < 1, 5.1 ft until road overtops
Performance Curve, $Q_{50}=371$ cfs
2 Determine Confidence Limits

- Confidence Limits for Regression Equations
  - Step 1: Estimate design flow
  - Step 2: Compute log of design flow
  - Step 3: Compute standard error in log units
  - Step 4: Compute confidence limits in log units
  - Step 5: Compute confidence limits in flow units
  - Step 6: Assess/design plan/project

- Assume greater than 75 years remaining service life
  - From Table 7.5, use 90% confidence interval
  - Wide interval reflects larger uncertainty over longer life
Determine Confidence Limits

**Step 1: Estimate design flow**

\[ Q_T = a(A)^b(P)^c, \text{ } A = \text{area}, \text{ } P = \text{M.A.P.}, \text{ } abc = \text{regression coefs} \]

\[ Q_{50} = 0.666(1.1)^{0.921}(141)^{1.26} = 371 \text{ cfs} \]

**Step 2: Compute log of design flow**

\[ Y_T = \log_{10}(Q_T) = \log_{10}(371) = 2.569 \]

**Step 3: Compute standard error in log units**

\[ SE_{\log 10} = \left[ \frac{1}{5.302} \ln \left( \left( \frac{\text{SE}\%}{100} \right)^2 + 1 \right) \right]^{0.5} \]

\[ = \left[ \frac{1}{5.302} \ln \left( \left( \frac{36}{100} \right)^2 + 1 \right) \right]^{0.5} = 0.152 \]
Determine Confidence Limits

- **Step 4: Compute confidence limits in log units**

  Table 7.6: For confidence interval of 90 percent, \( K_c = 1.645 \)

  \[
  Y_{T,U} = Y_T + K_c \cdot SE_{\log_{10}} = 2.569 + 1.645 \cdot (0.152) = 2.819 \\
  Y_{T,L} = Y_T - K_c \cdot SE_{\log_{10}} = 2.569 - 1.645 \cdot (0.152) = 2.319
  \]

- **Step 5: Compute confidence limits in flow units**

  \[
  Q_{T,U} = 10^{Y_{T,U}} = 10^{2.819} = 659 \text{ cfs} \\
  Q_{T,L} = 10^{Y_{T,L}} = 10^{2.319} = 208 \text{ cfs}
  \]

- **Step 6: Assess/design plan/project**

  Go back to Hydraulic Results Table
Confidence Limits Log-Normal
Confidence Limits Log-Log
Hydraulic Results

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- At upper limit Q50 = 659 cfs ...less resilient culvert
- Barrel inundated but no roadway overtopping
- HW/D > 1
Performance Curve, Q50=659 cfs
Precipitation Projection Trend Test

- Projected vs. Historical T-year, 24 hour, Precipitation
  - *If trend weak, stay with level 2*
  - *If trend strong, consider looking at level 4*

- Test requires DCHP precipitation projection data
  - *Step 1: Average the modeled daily precip across all cells*
  - *Step 2: Determine maximum annual value for each year*
  - *Step 3: Select baseline and future periods*
  - *Step 4: Compute baseline & future T-year 24 hr precip per model*
  - *Step 5: Estimate projected T-year 24 hr precip per model*
  - *Step 6: Compute mean for projected T-year 24 hr precipitation*
  - *Step 7: Evaluate for further analyses using Climate Change Indicator*
Precipitation Projection Trend Test

- Using RCP 8.5 and CMIP 5 BCCAv2 daily downscaled data
- We have 20 models

- Step 1: Average the modeled daily precip across all cells
  Used one cell to save time, see next slide

- Step 2: Determine maximum annual value for each year
  Computed w/CMIP tool for calendar yrs 1950 to 2000

- Step 3: Select baseline and future periods
  Baseline 1950-2000, Future 2050-2099
3

Downscaled CMIP3 and CMIP5
Climate and Hydrology Projections
### Precipitation Projection Trend Test

**Step 4: Find baseline & future T-year 24 hr precip per model**

Fitted AMS to Log Pearson Type III distribution (vs GEV)

This sheet provides a time series of annual maximum daily precipitation amounts from 1950-2099. See file 'CMIP5 1950-2099 Precipitation Data' for underlying calculation.

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<th>Year</th>
<th>Annual Maximum 24 hr Precipitation (in)</th>
<th>Multi-Mo</th>
<th>access1-0</th>
<th>bcc-csm1-1</th>
<th>canesm2-1</th>
<th>cccsm4-1nr</th>
<th>cesm1-bgc</th>
<th>cnrm-cm5</th>
<th>csiro-mk3</th>
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<td>3.66</td>
<td>3.76</td>
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</tr>
</tbody>
</table>
Step 5: Estimate projected T-year 24 hr precip per model

- Compute difference between future and baseline T-year, 24 hr precip per model
- Add this difference to the observed T-year 24 hr precip for each model

Step 6: Compute mean for projected T-year 24 hr precipitation

- Compute mean of projected T-year 24 hr precip from all the models (in our case 20 models)
- This is your $P_{24,T,P}$ term
3

Climate Change Indicator

\[ CCI = \frac{P_{24,T,P} - P_{24,T,O}}{P_{24,T,O,U} - P_{24,T,O}} \]

- If CCI < 0.4, trend is weak, historic OK
- If CCI > 0.8, trend is strong, consider further analysis w/ future projections
Projected Discharges and Confidence Limits

- Projected discharges explicitly incorporate future precipitation projections
  - Methods vary for rainfall/runoff vs statistical
- Will temperature will shift fraction of snow vs rain?
- Consider other sources of nonstationarity
  - Landuse: Database of impervious areas from EPA
- Calculate and evaluate projected confidence limits
  - Compare to historical confidence limits from Level 2
- Though not required climate scientist and hydrologist can help
Incorporating projections into rainfall/runoff hydrology

- For precip inputs with sub-daily durations, may use historic ratio of daily, T-year precipitation to sub-daily T-year precipitation from NOAA Atlas 14
- Minnesota Pilot project (to be described later) demonstrates rainfall runoff methods

Our example uses statistical hydrology

- Regression equation with precipitation variable (M.A.P.)

Steps to our Level 4 analysis

- Step 1: Determine future mean annual precipitation (M.A.P.)
- Step 2: Check regression equation limitations
- Step 3: Compute future discharge (incl. other nonstationarities)
- Step 4: Compute and evaluate projected confidence limits
### Step 1: Determine future mean annual precipitation (M.A.P.)

Determine from CMIP tool output

<table>
<thead>
<tr>
<th></th>
<th>Observed Value</th>
<th>Modeled Value</th>
<th>Projected Value</th>
<th>Change from Baseline</th>
<th>% Change from Observed</th>
<th>Model Uncertainty Range (100% Confidence Interval)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>2050-2099 (2050-2099)</td>
<td></td>
<td></td>
<td>Low</td>
</tr>
<tr>
<td><strong>Average Total Annual Precipitation</strong></td>
<td>147.6 inches</td>
<td>147.1 inches</td>
<td>157.1 inches</td>
<td>9.5 inches</td>
<td>6%</td>
<td>151.1 inches</td>
</tr>
<tr>
<td><strong>&quot;Very Heavy&quot; 24-hr Precipitation Amount</strong> (defined as 95th percentile precipitation)</td>
<td>2.0 inches</td>
<td>1.7 inches</td>
<td>2.1 inches</td>
<td>0.1 inches</td>
<td>5%</td>
<td>2.0 inches</td>
</tr>
<tr>
<td><strong>&quot;Extremely Heavy&quot; 24-hr Precipitation Amount</strong> (defined as 99th percentile precipitation)</td>
<td>3.4 inches</td>
<td>2.8 inches</td>
<td>3.6 inches</td>
<td>0.3 inches</td>
<td>8%</td>
<td>3.4 inches</td>
</tr>
<tr>
<td><strong>Precipitation Events per Year (2.0 inches in 24 hrs)</strong></td>
<td>13.6 times</td>
<td>17.7 times</td>
<td>17.9 times</td>
<td>4.3 times</td>
<td>31%</td>
<td>16.0 times</td>
</tr>
<tr>
<td><strong>Precipitation Events per Year (3.4 inches in 24 hrs)</strong></td>
<td>2.7 times</td>
<td>3.6 times</td>
<td>4.8 times</td>
<td>2.1 times</td>
<td>77%</td>
<td>4.0 times</td>
</tr>
</tbody>
</table>

---

**Projected Discharges and Confidence Limits**

- **Click column headings for additional info**
- **Observed Value**: Historical data
- **Modeled Value**: Predicted data
- **Projected Value**: Future projection
- **Change from Baseline**: Difference between observed and projected values
- **% Change from Observed**: Percentage change from observed to projected values
- **Model Uncertainty Range (100% Confidence Interval)**: Low to High values
Projected Discharges and Confidence Limits

Step 2: Check regression equation limitations

From StreamStats output and State regression manual:
45 inches > 157.1 inches > 201 inches

Step 3: Compute future discharge (incl. other nonstationarities)

From WFL report (Hamlet et. al. 2013): Snider Creek is a rain dominant basin and will remain so in the future
Olympic National Park not expected to see significant land use changes (exception would be wildfire...a short term situation)

\[ Q_T = a(A)^b(P)^c, \quad A = \text{area}, \quad P = \text{M. A. P.}, \quad abc = \text{regression coefs} \]

\[ Q_{50} = 0.666(1.1)^{0.921}(157.1)^{1.26} = 425 \text{ cfs} \]
Find Projected Confidence Limits

- **Step 4a: Estimate design flow**

\[ Q_{50} = 0.666(1.1)^{0.921}(157.1)^{1.26} = 425 \text{ cfs} \]

- **Step 4b: Compute log of design flow**

\[ Y_T = \log_{10}(Q_T) = \log_{10}(425) = 2.628 \]

- **Step 4c: Compute standard error in log units**

\[ SE_{\log_{10}} = \left[ \frac{1}{5.302} \ln \left( \frac{(SE\%)}{100} \right)^2 + 1 \right]^{0.5} \]

\[ = \left[ \frac{1}{5.302} \ln \left( \frac{36}{100} \right)^2 + 1 \right]^{0.5} = 0.152 \]
Determine Confidence Limits

Step 4d: Compute confidence limits in log units

Table 7.6: For confidence interval of 90 percent, $K_c = 1.645$

$Y_{T,U} = Y_T + K_c SE_{log10} = 2.628 + 1.645(0.152) = 2.878$

$Y_{T,L} = Y_T - K_c SE_{log10} = 2.628 - 1.645(0.152) = 2.378$

Step 4e: Compute confidence limits in flow units

$Q_{T,U} = 10^{Y_{T,U}} = 10^{2.878} = 755 \text{ cfs}$

$Q_{T,L} = 10^{Y_{T,L}} = 10^{2.378} = 239 \text{ cfs}$

Step 4f: Assess/design plan/project

Go back to Hydraulic Results Table
## Hydraulic Results

- **At upper limit Q50 = 755 cfs ...even less resilient**
- **Barrel inundated, roadway closer to overtopping**
- **If no precip. term in regression?...consider Level 5**

<table>
<thead>
<tr>
<th>Hydraulic Parameters</th>
<th>Design Flow Q50</th>
<th>Q50 + 20%</th>
<th>Q50 + 50%</th>
<th>Flow at Barrel Top</th>
<th>Roadway Overtops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow in cfs</td>
<td>371</td>
<td>445</td>
<td>557</td>
<td>760</td>
<td>860</td>
</tr>
<tr>
<td>Headwater Elevation (ft)</td>
<td>2004.9</td>
<td>2005.6</td>
<td>2006.6</td>
<td>2008.6</td>
<td>2010.0</td>
</tr>
<tr>
<td>Headwater Depth (ft)</td>
<td>5.1</td>
<td>5.8</td>
<td>6.8</td>
<td>8.8</td>
<td>10.2</td>
</tr>
<tr>
<td>Clearance / Freeboard (ft)</td>
<td>1.8 / 5.1</td>
<td>1.1 / 4.4</td>
<td>0.1 / 3.4</td>
<td>-1.9 / 1.4</td>
<td>-3.3 / 0</td>
</tr>
<tr>
<td>Headwater-to-Diameter Ratio, HW/D</td>
<td>0.74</td>
<td>0.84</td>
<td>0.99</td>
<td>1.28</td>
<td>1.47</td>
</tr>
<tr>
<td>US Bed Elevation @ Invert (ft)</td>
<td>1999.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>US Top of Barrel Elevation (ft)</td>
<td>2006.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open Diameter considering Embedment (ft)</td>
<td>6.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Note:** The table includes various hydraulic parameters such as flow rates, elevations, and clearances. The parameters are compared at different flow stages (Q50, Q50 + 20%, Q50 + 50%) and their impacts on the roadways are discussed.
Performance Curve, Q50=755 cfs
Level 5 Example: Iowa DOT

Iowa Bridge and Roadway Vulnerability Assessment Pilot (2015)
Project Partners

- **Lead: Iowa DOT**
  *Dave Claman, Hydraulic Engineer*

- **Iowa State University**
  *(Christopher J. Anderson, Eugene S. Takle)*
  - Climate science and climate projections expertise
  - Lead and contributing authors to IPCC AR4, NCA Agriculture

- **University of Iowa IIHR**
  *(Witold F. Krajewski, Ricardo Mantilla)*
  - Hydrology and hydraulics engineering and modeling
  - Iowa Flood Center: [ifis.iowafloodcenter.org](http://ifis.iowafloodcenter.org)
What makes this a Level 5?

- Climate scientist

- Advanced hydrologic modeling
  - Selected alternative climate data sets
    - Asynchronous Regional Regression Model (ARRM)
  - CUENCAS hydrological model, distributed rainfall-runoff hillslope model
  - Limited to flood season
Two river basins examined: Cedar, South Skunk
Modeling

- Linked precipitation projections to streamflow in Skunk and Cedar River Basins

- Generated continuous 140 year streamflow simulation (1960-2100)

- Modeled projected 100-yr flood levels for 6 locations
Flood Frequency Curves

![Flood Frequency Curves](image)

**Cedar River Basin**

**South Skunk River Basin**

Return period (yr):

- 1960 – 2009
- 1960 – 2059

Discharge (m³/sec):

- 2000
- 1500
- 1000
- 500
- 0
Insights

- Determined using this type of climate data was best for basins 250 km² and greater

- Four of six locations found vulnerable to future flooding (100-yr flows)

- Flood projections are more model-specific than emission scenario-specific
Questions?
Chapter 8

Case Studies
Case Studies

- Bridge 02315 (Barkhamsted, Connecticut)
- USGS Regression Analysis for New York and Vermont
- Minnesota Pilot Project
- Gulf Coast 2: Airport Boulevard Culvert (Mobile, AL)
- Cedar and South Skunk River Iowa Pilot Project
Minnesota Pilot Project

High Level System-wide Assessment

• Metrics to qualitatively assess
  • Sensitivity
  • Exposure
    • Adaptive Capability
• Ranked assets
• Team

Case Studies

• MN 61 Culvert #5648
• US 63 Culvert #5722
MN61 Culvert 5648 over Silver Creek
Watershed
Existing Culvert

- 2 10’x10’ by 90’ long
- Built 1936
- Cracks, Spalling, Exposed Rebar
Hydrologic Methods

- NRCS Method
- USGS Regression
NRCS Input

- Precipitation
- Curve Number
- Time of Concentration
Precipitation

NOAA Atlas 14

- Best available and actionable historic data

Climate Projections
## Precipitation

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>GCMs</th>
<th>Output</th>
<th>Time Period</th>
<th>Bias Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Low emissions scenario: RCP4.5</td>
<td>• 22 models</td>
<td>• 24 hour precipitation depths</td>
<td>• 2040</td>
<td>• Compare historical rainfall and climate projections</td>
</tr>
<tr>
<td>• Medium emissions scenario: RCP6.0</td>
<td></td>
<td></td>
<td>• 2070</td>
<td></td>
</tr>
<tr>
<td>• High emissions scenario: RCP8.5</td>
<td></td>
<td></td>
<td>• 2100</td>
<td></td>
</tr>
</tbody>
</table>
### Table 4: 24-Hour Precipitation Depths at Culvert 5648, Low Scenario

<table>
<thead>
<tr>
<th>24-Hour Storm Return Period</th>
<th>Atlas 14 Precipitation Depth (in)(^1)</th>
<th>Low Scenario Precipitation Depth (in)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Increase</td>
<td>Depth</td>
<td>% Increase</td>
<td>Depth</td>
<td>% Increase</td>
</tr>
<tr>
<td>2-year storm</td>
<td>3.08%</td>
<td>2.56</td>
<td>4.72%</td>
<td>2.60</td>
<td>5.48%</td>
</tr>
<tr>
<td>5-year storm</td>
<td>3.12%</td>
<td>3.36</td>
<td>4.77%</td>
<td>3.42</td>
<td>5.55%</td>
</tr>
<tr>
<td>10-year storm</td>
<td>3.22%</td>
<td>4.02</td>
<td>4.93%</td>
<td>4.08</td>
<td>5.74%</td>
</tr>
<tr>
<td>25-year storm</td>
<td>3.43%</td>
<td>4.96</td>
<td>5.25%</td>
<td>5.05</td>
<td>6.11%</td>
</tr>
<tr>
<td>50-year storm</td>
<td>3.63%</td>
<td>5.73</td>
<td>5.55%</td>
<td>5.84</td>
<td>6.46%</td>
</tr>
<tr>
<td>100-year storm</td>
<td>3.85%</td>
<td>6.55</td>
<td>5.90%</td>
<td>6.68</td>
<td>6.86%</td>
</tr>
<tr>
<td>500-year storm</td>
<td>4.47%</td>
<td>8.63</td>
<td>6.85%</td>
<td>8.83</td>
<td>7.96%</td>
</tr>
</tbody>
</table>

\(^1\)Source: NOAA, 2014b
Land Use

Existing

- National Land Cover Database
- CN = 75

Future

- Current zoning
- CN = 77
Time of Concentration

Existing

- 9 hours

Future

- 9 hours
## Flows

### Table 8: TR-20 Projected Peak Flows at Culvert 5648

<table>
<thead>
<tr>
<th>24-Hour Storm Return Period</th>
<th>Existing Discharges (cfs)</th>
<th>Low Scenario Discharges</th>
<th>Medium Scenario Discharges</th>
<th>High Scenario Discharges</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2040 (cfs)</td>
<td>2070 (cfs)</td>
<td>2100 (cfs)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2040 (cfs)</td>
<td>2070 (cfs)</td>
<td>2100 (cfs)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2040 (cfs)</td>
<td>2070 (cfs)</td>
<td>2100 (cfs)</td>
</tr>
<tr>
<td>2-year storm</td>
<td>770</td>
<td>1070</td>
<td>1100</td>
<td>1120</td>
</tr>
<tr>
<td>5-year storm</td>
<td>1350</td>
<td>1760</td>
<td>1810</td>
<td>1830</td>
</tr>
<tr>
<td>10-year storm</td>
<td>1880</td>
<td>2360</td>
<td>2420</td>
<td>2450</td>
</tr>
<tr>
<td>25-year storm</td>
<td>2690</td>
<td>3260</td>
<td>3350</td>
<td>3390</td>
</tr>
<tr>
<td>50-year storm</td>
<td>3370</td>
<td>4010</td>
<td>4120</td>
<td>4170</td>
</tr>
<tr>
<td>100-year storm</td>
<td>4140</td>
<td>4810</td>
<td>4940</td>
<td>5000</td>
</tr>
<tr>
<td>500-year storm</td>
<td>6090</td>
<td>6870</td>
<td>7060</td>
<td>7150</td>
</tr>
</tbody>
</table>
Design Limitations

- Headwater
- Upstream Properties
- Fish Passage
- Outlet Velocities
Culvert Design Options

- 14x14 2-cell Culvert
- 16x14 2-cell Culvert
- 52-foot long single span bridge
- 57-foot long single span bridge
Economic Analysis

Table 13: Projected Life Cycle Costs for Culvert 5648 Adaptation Options With Social Costs, Medium Scenario

<table>
<thead>
<tr>
<th></th>
<th>Period 1 2025-2055</th>
<th>Period 2 2056-2085</th>
<th>Period 3 2086-2100</th>
<th>Initial Construction Costs</th>
<th>Total Damage/Repair Costs by 2100</th>
<th>Total Life Cycle Cost by 2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case: Replace in Kind</td>
<td>122,352</td>
<td>111,568</td>
<td>40,147</td>
<td>$643,069</td>
<td>$274,067</td>
<td>$917,136</td>
</tr>
<tr>
<td>Option 1: Two Cell Culvert</td>
<td>18,226</td>
<td>9,041</td>
<td>14,708</td>
<td>$697,413</td>
<td>$41,975</td>
<td>$739,388</td>
</tr>
<tr>
<td>Option 2: 52-Foot Bridge</td>
<td>72,592</td>
<td>55,207</td>
<td>30,455</td>
<td>$1,023,476</td>
<td>$158,254</td>
<td>$1,181,730</td>
</tr>
<tr>
<td>Option 3: 57-Foot Bridge</td>
<td>25,839</td>
<td>11,130</td>
<td>3,808</td>
<td>$1,095,934</td>
<td>$40,777</td>
<td>$1,136,711</td>
</tr>
</tbody>
</table>

Note: Options with the best life cycle cost-effectiveness are highlighted in green.

Table 14: Projected Life Cycle Costs for Culvert 5648 Adaptation Options With Social Costs, High Scenario

<table>
<thead>
<tr>
<th></th>
<th>Period 1 2025-2055</th>
<th>Period 2 2056-2085</th>
<th>Period 3 2086-2100</th>
<th>Initial Construction Costs</th>
<th>Total Damage/Repair Costs by 2100</th>
<th>Total Life Cycle Cost by 2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case: Replace in Kind</td>
<td>290,776</td>
<td>125,251</td>
<td>46,990</td>
<td>$643,069</td>
<td>$463,017</td>
<td>$1,106,086</td>
</tr>
<tr>
<td>Option 1: Two Cell Culvert</td>
<td>20,990</td>
<td>111,568</td>
<td>36,756</td>
<td>$697,413</td>
<td>$169,314</td>
<td>$866,727</td>
</tr>
<tr>
<td>Option 2: 52-Foot Bridge</td>
<td>58,740</td>
<td>26,785</td>
<td>41,520</td>
<td>$1,023,476</td>
<td>$127,045</td>
<td>$1,150,521</td>
</tr>
<tr>
<td>Option 3: 57-Foot Bridge</td>
<td>27,913</td>
<td>23,937</td>
<td>39,611</td>
<td>$1,095,934</td>
<td>$91,461</td>
<td>$1,187,395</td>
</tr>
</tbody>
</table>

Note: Options with the best life cycle cost-effectiveness are highlighted in green.
Questions?
Next Steps

❖ HEC-17 2nd Edition is evolving document
  ❖ Science and climate modeling continues to advance
  ❖ Methods will evolve with the science
  ❖ HEC-17 represents attempt to modify current practice, rather than start from scratch
New Research in Progress

- Updating Precipitation Frequency Estimates under Non-Stationary Climate Conditions
  - Develop methods to integrate non-stationary climate effects into precipitation frequency estimates (like NOAA Atlas 14)
  - NWS/FHWA
- Flood Frequency Estimation for Hydrologic Design under Changing Conditions
  - Adjust flood-frequency analysis for observed and projected change for rivers showing trends in peak flows
  - USGS/FHWA
- Potential Impact of Climate Change on US Precipitation Frequency Estimates
  - Examine historical trends in exceedances of precipitation frequency thresholds in different regions
  - Bonnin & Co. LLC
More Research In Progress

- Climate Change Effects on Stream Geomorphology: Maple River Stream Instability Study
  - Evaluate future channel instability at site in Iowa given historic instability and climate change
  - TetraTech

- Sensitivity of Drainage Infrastructure to Climate Change
  - Hydraulic analysis of increased precipitation on drainage infrastructure, including quantifying cost of inaction
  - FHWA Federal Lands Highway Divisions
Even More Research!

- NCHRP 15-61: Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure
  - Design guide of national scope
  - Provide hydraulic engineers with the tools needed to amend practice to account for climate change
  - Builds on HEC-17
  - Completion 2018
Links to Other Resilience Related Work

- Transportation Engineering Approaches to Climate Resilience (TEACR)
- Hurricane Sandy project
- Green Infrastructure Pilots
- Adaptation Pilots
- Gulf Coast 2 Study

Questions?