ADAPTING THE DESIGN AND MANAGEMENT OF STORM WATER RELATED INFRASTRUCTURE TO CLIMATE CHANGE

Ken Potter
Department of Civil & Environmental Engineering
University of Wisconsin
Madison, WI
HYDROLOGIC DESIGN

Storm water Conveyance

Wastewater Treatment

Floodplain Management

Detention Basins

River and Stream Crossings
DESIGN STORMS-
INTENSITY-DURATION-
FREQUENCY RELATIONSHIPS

Table 9. Sectional Mean Frequency Distributions for Storm Periods of 5 Minutes to 10 Days
and Recurrence Intervals of 2 Months to 100 Years in Wisconsin

<table>
<thead>
<tr>
<th>Section</th>
<th>Duration</th>
<th>2-month</th>
<th>3-month</th>
<th>4-month</th>
<th>6-month</th>
<th>9-month</th>
<th>1-year</th>
<th>2-year</th>
<th>5-year</th>
<th>10-year</th>
<th>25-year</th>
<th>50-year</th>
<th>100-year</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>10-day</td>
<td>1.90</td>
<td>2.26</td>
<td>2.64</td>
<td>3.10</td>
<td>3.57</td>
<td>3.88</td>
<td>4.79</td>
<td>5.93</td>
<td>6.53</td>
<td>7.63</td>
<td>8.47</td>
<td>9.37</td>
</tr>
<tr>
<td>01</td>
<td>5-day</td>
<td>1.55</td>
<td>1.85</td>
<td>2.00</td>
<td>2.42</td>
<td>2.79</td>
<td>3.03</td>
<td>3.75</td>
<td>4.86</td>
<td>5.35</td>
<td>6.27</td>
<td>7.05</td>
<td>7.90</td>
</tr>
<tr>
<td>01</td>
<td>72-hr</td>
<td>1.39</td>
<td>1.63</td>
<td>1.86</td>
<td>2.14</td>
<td>2.47</td>
<td>2.68</td>
<td>3.31</td>
<td>4.12</td>
<td>4.76</td>
<td>5.59</td>
<td>6.35</td>
<td>7.16</td>
</tr>
<tr>
<td>01</td>
<td>48-hr</td>
<td>1.10</td>
<td>1.34</td>
<td>1.59</td>
<td>1.86</td>
<td>2.14</td>
<td>2.37</td>
<td>2.95</td>
<td>3.64</td>
<td>4.14</td>
<td>4.64</td>
<td>5.07</td>
<td>5.49</td>
</tr>
<tr>
<td>01</td>
<td>24-hr</td>
<td>1.00</td>
<td>1.23</td>
<td>1.48</td>
<td>1.73</td>
<td>1.99</td>
<td>2.21</td>
<td>2.65</td>
<td>3.15</td>
<td>3.55</td>
<td>4.05</td>
<td>4.54</td>
<td>5.00</td>
</tr>
<tr>
<td>01</td>
<td>12-hr</td>
<td>1.00</td>
<td>1.24</td>
<td>1.48</td>
<td>1.73</td>
<td>1.99</td>
<td>2.21</td>
<td>2.65</td>
<td>3.15</td>
<td>3.55</td>
<td>4.05</td>
<td>4.54</td>
<td>5.00</td>
</tr>
<tr>
<td>01</td>
<td>6-hr</td>
<td>0.91</td>
<td>1.08</td>
<td>1.26</td>
<td>1.43</td>
<td>1.61</td>
<td>1.79</td>
<td>2.18</td>
<td>2.58</td>
<td>3.02</td>
<td>3.45</td>
<td>3.88</td>
<td>4.30</td>
</tr>
<tr>
<td>01</td>
<td>3-hr</td>
<td>0.78</td>
<td>0.91</td>
<td>1.06</td>
<td>1.23</td>
<td>1.41</td>
<td>1.56</td>
<td>1.85</td>
<td>2.22</td>
<td>2.62</td>
<td>3.07</td>
<td>3.54</td>
<td>4.02</td>
</tr>
<tr>
<td>01</td>
<td>2-hr</td>
<td>0.71</td>
<td>0.83</td>
<td>0.99</td>
<td>1.16</td>
<td>1.34</td>
<td>1.49</td>
<td>1.77</td>
<td>2.14</td>
<td>2.51</td>
<td>2.98</td>
<td>3.42</td>
<td>3.88</td>
</tr>
<tr>
<td>01</td>
<td>1-hr</td>
<td>0.57</td>
<td>0.67</td>
<td>0.83</td>
<td>1.00</td>
<td>1.18</td>
<td>1.35</td>
<td>1.62</td>
<td>1.99</td>
<td>2.36</td>
<td>2.72</td>
<td>3.12</td>
<td>3.52</td>
</tr>
<tr>
<td>01</td>
<td>30-min</td>
<td>0.45</td>
<td>0.52</td>
<td>0.67</td>
<td>0.84</td>
<td>1.01</td>
<td>1.19</td>
<td>1.48</td>
<td>1.86</td>
<td>2.22</td>
<td>2.61</td>
<td>3.00</td>
<td>3.46</td>
</tr>
<tr>
<td>01</td>
<td>15-min</td>
<td>0.33</td>
<td>0.39</td>
<td>0.46</td>
<td>0.63</td>
<td>0.81</td>
<td>1.00</td>
<td>1.29</td>
<td>1.67</td>
<td>2.04</td>
<td>2.43</td>
<td>2.81</td>
<td>3.21</td>
</tr>
<tr>
<td>01</td>
<td>10-min</td>
<td>0.28</td>
<td>0.33</td>
<td>0.40</td>
<td>0.56</td>
<td>0.74</td>
<td>0.93</td>
<td>1.23</td>
<td>1.62</td>
<td>2.01</td>
<td>2.43</td>
<td>2.81</td>
<td>3.21</td>
</tr>
<tr>
<td>01</td>
<td>5-min</td>
<td>0.15</td>
<td>0.17</td>
<td>0.21</td>
<td>0.28</td>
<td>0.37</td>
<td>0.47</td>
<td>0.60</td>
<td>0.75</td>
<td>0.85</td>
<td>1.01</td>
<td>1.13</td>
<td>1.26</td>
</tr>
</tbody>
</table>

Rainfall (inches) for given recurrence interval

• Physical principles and climate models indicate that the magnitude of large rainfalls will increase.

• Historical data indicate that increases have already occurred.

• But the current models and historical data do not yet provide a sufficient basis for hydrologic design.
However, we can do the following:

- Use the latest rainfall statistics
- Use climate scenarios to evaluate vulnerabilities
- Make greater use of continuous hydrologic simulation
- Re-evaluate design criteria
- Design based on risk-based design, incorporating uncertainty
Physical principles and climate models indicate that increasing concentrations of greenhouse gases will cause increases in the magnitude of large rainfall events over most of the world.
Projected changes in the intensity of precipitation, displayed in 5% increments, based on a suite of models and three emission scenarios.

Figure courtesy of Michael Wehner.
In fact, the magnitude of large rainfalls appears to have been increasing over the last several decades.
## NOAA ATLAS 14 VS. TP-40
### 100-YEAR RECURRENCE INTERVAL

<table>
<thead>
<tr>
<th></th>
<th>1-hour (%)</th>
<th>6-hour (%)</th>
<th>12-hour (%)</th>
<th>24-hour (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illinois n = 43</td>
<td>5.9 (-7.7; 15.4)</td>
<td>9.9 (-2.2; 45.8)</td>
<td>5.6 (-5.4; 37.8)</td>
<td>7.0 (-7.9; 46.2)</td>
</tr>
<tr>
<td>Indiana  n = 24</td>
<td>7.0 (-5.5; 15.4)</td>
<td>11.7 (-1.2; 23.3)</td>
<td>6.5 (-7.2; 21.2)</td>
<td>9.4 (-2.2; 28.2)</td>
</tr>
<tr>
<td>Kentucky n = 15</td>
<td>2.9 (-1.7; 8.7)</td>
<td>5.3 (-4.0; 13.2)</td>
<td>3.5 (-6.8; 8.1)</td>
<td>9.4 (-2.2; 20.9)</td>
</tr>
<tr>
<td>Ohio   n = 32</td>
<td>3.5 (-3.3; 9.4)</td>
<td>9.8 (0.2; 22.1)</td>
<td>5.4 (-4.8; 18.2)</td>
<td>11.3 (-1.8; 26.0)</td>
</tr>
</tbody>
</table>

Largest Daily Rainfall
Madison, WI

Year

Rainfall (inches)
Sum of 5 Largest Daily Rainfalls
Madison, WI

Year
Rainfall (inches)
Number of Exceedances of 2 Inches in 5-Year Increments
Madison, WI

Number

Mid-Year

Number of Exceedances of 3 Inches in 5-Year Increments
Madison, WI

Number of Exceedances

Mid-Year

1871-1876
1881-1886
1891-1896
1901-1906
1911-1916
1921-1926
1931-1936
1941-1946
1951-1956
1961-1966
1971-1976
1981-1986
1991-1996
2001-2006

Number

0 1 2 3 4 5 6
IMPLICATIONS FOR DESIGN

Although the historical data indicates increases in the magnitude of large rainfalls, statistical analyses have not supported inclusion of trends in the calculation of new intensity-duration-frequency relationships recently developed by the National Weather Service.
LIMITATIONS OF CLIMATE MODELS

• There are dozens of legitimate climate models and their predictions vary widely and depend on the degree to which CO₂ increases.

• Global model results have coarse spatial resolution and must be “downscaled” either statistically or by use of regional models.
  – There are many different ways to downscale global models.
Change in **Wisconsin** temperature and precipitation predicted by 15 climate models (2080-2099 minus 1980-1999).

The average model change is shown by the thick black line.

*Note the wide variation between models results.*

[Graphs showing temperature and precipitation changes from 2080-2099 compared to 1980-1999.]
LIMITATIONS OF CLIMATE MODELS

Do not capture long-term variability observed in actual rainfall data.
Annual Precipitation
Madison, WI
1869-2008

Year

Rainfall (inches)

1860 1880 1900 1920 1940 1960 1980 2000 2020

10 20 30 40 50 60
Mississippi River at Clinton

Discharge (cfs) vs. Year

Year:
- 1880
- 1900
- 1920
- 1940
- 1960
- 1980
- 2000

Discharge (cfs):
- 0
- 20000
- 40000
- 60000
- 80000
- 100000

The graph shows the discharge of the Mississippi River at Clinton from 1880 to 2000, with a trend line indicating a slight increase in discharge over time.
DESIGN ISSUES

• At this time, climate models should not be directly used to estimate operational intensity-duration-frequency relationships.

• Analyses of historical rainfall data are not currently capturing the effects of climate change, and are conducted infrequently.

• What should we do to adapt hydrologic design to present and future climate change?
ADAPTING HYDROLOGIC DESIGN TO CLIMATE CHANGE

• Use the latest rainfall statistics (e.g. not TP-40)

• Use climate scenarios to evaluate vulnerabilities of existing infrastructure

• Make greater use of continuous hydrologic simulation and coupled models (e.g., surface and ground water)

• Re-evaluate design criteria (e.g. detention basins)

• Design based on risk-based design, incorporating uncertainty
RISK-BASED DESIGN

• Risk-based design is commonly used in decision making when benefits and/or costs are uncertain.

• Flood-risk management is often conducted this way.
  – The expected benefit of a given project is the difference between the expected flood damages with and without the project.
RISK-BASED DESIGN

• The Federal Highway Administration developed a risk-based approach for designing stream and river crossings.


RISK-BASED DESIGN

There are two sources of uncertainty that should be considered in risk-based design:

– Uncertainty due to natural variability (aleatory). This uncertainty cannot be reduced.

– Uncertainty due limited knowledge and information (epistemic). This uncertainty can be reduced through data collection, modeling, and research.
RISK-BASED DESIGN

Modern design incorporates both aleatory and epistemic uncertainty. Examples include

– Levee freeboard design by USACOE (Risk Analysis and Uncertainty in Flood Damage Reduction Studies, 2000, National Academy Press, Washington D.C.)

RISK-BASED DESIGN

An early example of the incorporation of epistemic uncertainty in hydrology design is the use of “expected probability”, proposed by Leo Beard.

EXPECTED PROBABILITY

• Standard statistical analysis of flood data produces flood quantiles (e.g. 100-year flood discharge) that are unbiased.

• However, the exceedance probability associated with the resulting quantile is biased low due to sampling uncertainty.
Ratio of Expected Probability to Nominal Probability

More probable

More data
EXPECTED PROBABILITY

• Beard recommended using quantiles for which the associated exceedance probabilities were the desired probabilities.

• This recommendation is discussed in Bulletin 17B, the current federal guidelines for conducting flood frequency analysis in the United States.
Note that the same issue arises for flood quantiles that are estimated using the USGS regional flood frequency equations.
The expected probability is the integral of the products of the two functions, and in this case equals \(0.0165\).
RISK-BASED DESIGN

• Risk-based design can easily incorporate epistemic uncertainty, such as sampling uncertainty or uncertainty about the magnitude of future rainfalls.

• For large projects (such as the design of a large bridge), the uncertainty can be explicitly included in the design analysis.
RISK-BASED DESIGN

• For smaller projects, the uncertainty can be accounted for in the estimation of rainfall or discharge quantiles.
  – That is the quantiles (e.g 100-year, 24-hour rainfall intensity) can be computed so that the expected exceedance probability is the desired probability.
  – This would lead to increased quantiles, that would decrease as information about future rainfalls improves.
RECOMMENDATIONS

• Use the latest rainfall statistics
• Use climate scenarios to evaluate vulnerabilities
• Make greater use of continuous hydrologic simulation
• Re-evaluate design criteria
• Design based on risk-based design, incorporating uncertainty
QUESTIONS?