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

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THE UNIVERSITY of WISCONSIN MADISON

WISCONSIN INITIATIVE ON CLIMATE CHANGE IMPACTS

HYDROLOGIC DESIGN

Storm water Conveyance

Floodplain Management

Wastewater Treatment

River and Stream Crossings

Detention Basins

DESIGN STORMS-INTENSITY-DURATION-FREQUENCY RELATIONSHIPS

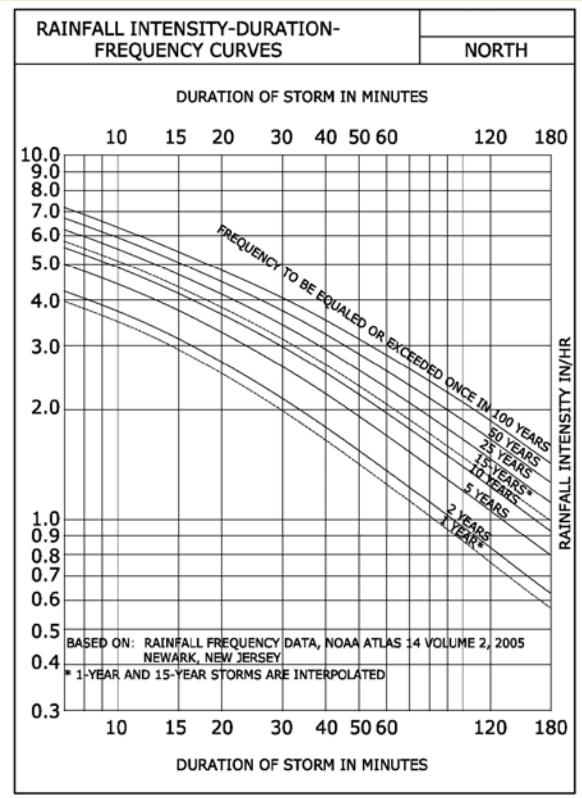


Table 9. Sectional Mean Frequency Distributions for Storm Periods of 5 Minutes to 10 Days and Recurrence Intervals of 2 Months to 100 Years in Wisconsin

Sectional code (see figure 1 on page 4)

01 – Northwest
02 - North Central
03 – Northeast
04 - West Central
05 – Central
06 - East Central
07 - Southwest
08 - South Central
09 - Southeast

Rainfall (inches) for given recurrence interval

Section	Duration	2-month	3-month	4-month	6-month	9-month	1-year	2-year	5-year	10-year	25-year	50-year	100-year
01	10-day	1.90	2.29	2.64	3.10	3.57	3.88	4.78	5.83	6.58	7.63	8.47	9.37
01	5-day	1.55	1.85	2.09	2.42	2.79	3.03	3.75	4.66	5.35	6.27	7.05	7.90
01	72-hr	1.39	1.63	1.85	2.14	2.47	2.68	3.31	4.12	4.78	5.67	6.39	7.16
01	48-hr	1.30	1.53	1.70	1.97	2.26	2.46	3.05	3.82	4.41	5.23	5.88	6.56
01	24-hr	1.22	1.42	1.55	1.80	2.04	2.22	2.77	3.50	4.04	4.79	5.36	5.98
01	18-hr	1.15	1.34	1.46	1.69	1.92	2.09	2.60	3.29	3.80	4.50	5.04	5.62
01	12-hr	1.06	1.24	1.35	1.56	1.78	1.93	2.41	3.05	3.51	4.17	4.66	5.20
01	6-hr	0.91	1.06	1.16	1.34	1.53	1.66	2.08	2.62	3.03	3.59	4.02	4.49
01	3-hr	0.78	0.91	0.99	1.15	1.31	1.42	1.77	2.24	2.59	3.07	3.43	3.83
01	2-hr	0.71	0.83	0.90	1.04	1.19	1.29	1.61	2.03	2.34	2.78	3.11	3.47
01	1-hr	0.57	0.67	0.73	0.84	0.96	1.04	1.30	1.64	1.90	2.25	2.52	2.81
01	30-min	0.45	0.52	0.57	0.66	0.75	0.82	1.02	1.30	1.49	1.77	1.98	2.21
01	15-min	0.33	0.38	0.42	0.49	0.55	0.60	0.75	0.95	1.09	1.29	1.45	1.61
01	10-min	0.26	0.30	0.33	0.38	0.43	0.47	0.58	0.73	0.85	1.01	1.13	1.26
01	5-min	0.15	0.17	0.19	0.22	0.25	0.27	0.33	0.42	0.48	0.57	0.64	0.72

Huff, F. A. and J. Angel, 1992, Rainfall Frequency Atlas of the Midwest, Bulletin 71, Midwestern Climate Center and Illinois State Water Survey, Champaign, Illinois.

OUTLINE

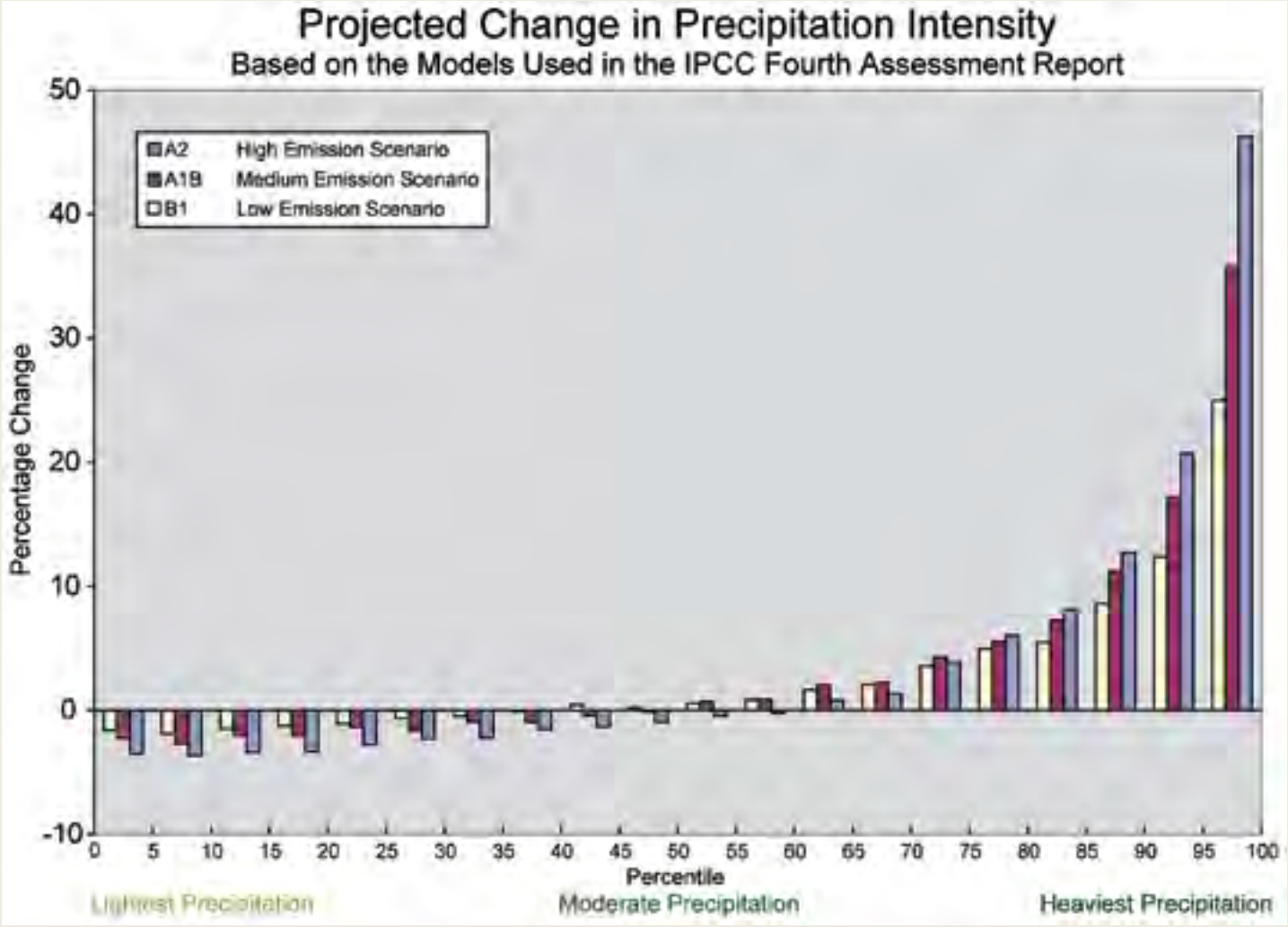
- Physical principles and climate models indicate that the magnitude of large rainfalls will increase.
- Historical data indicate that increases have already occurred.
- But the current models and historical data do not yet provide a sufficient basis for hydrologic design.

OUTLINE

- 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

CLIMATE CHANGE

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.

CLIMATE CHANGE

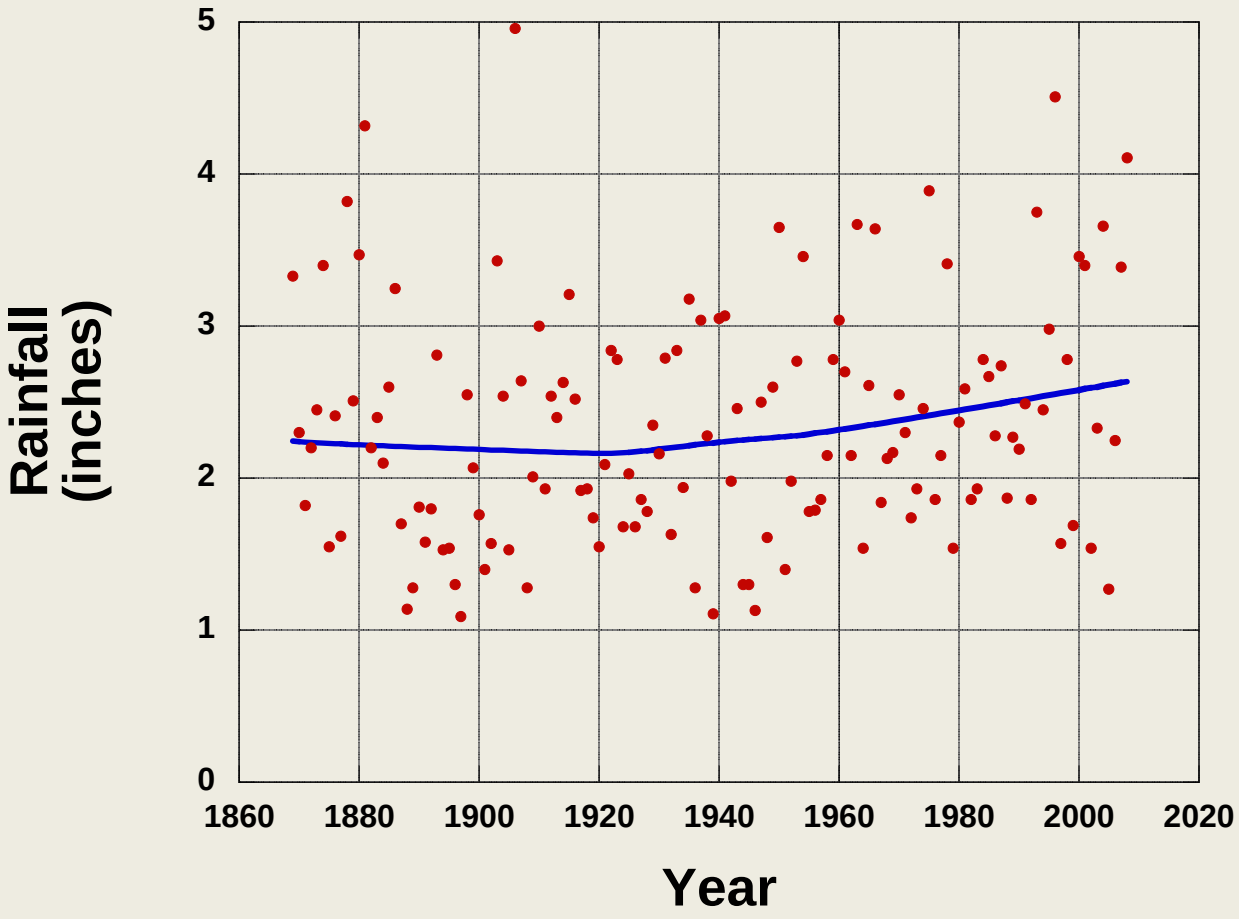
In fact, the magnitude of large rainfalls appears to have been increasing over the last several decades.

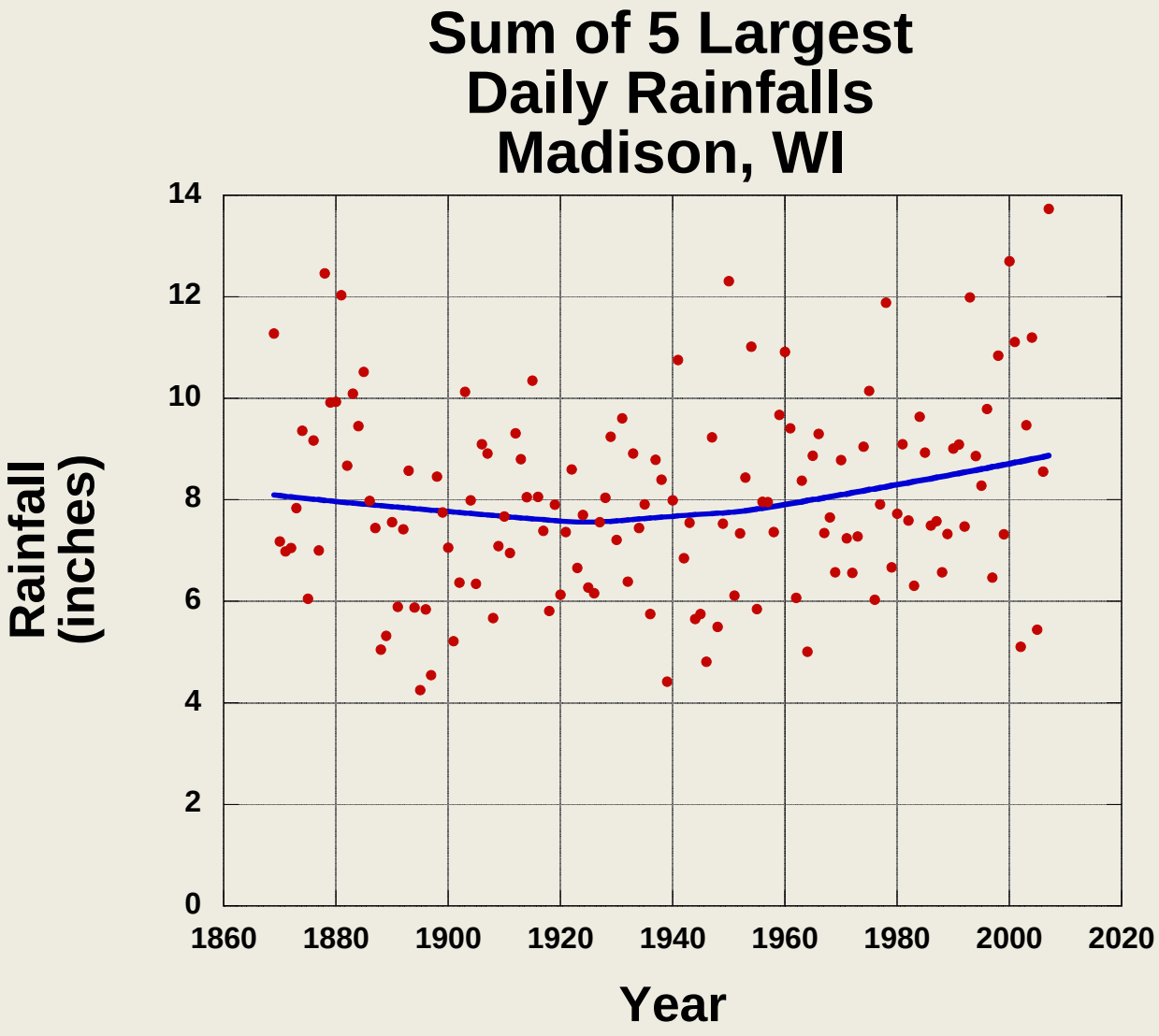
NOAA ATLAS 14 VS. TP-40 100-YEAR RECURRENCE INTERVAL

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

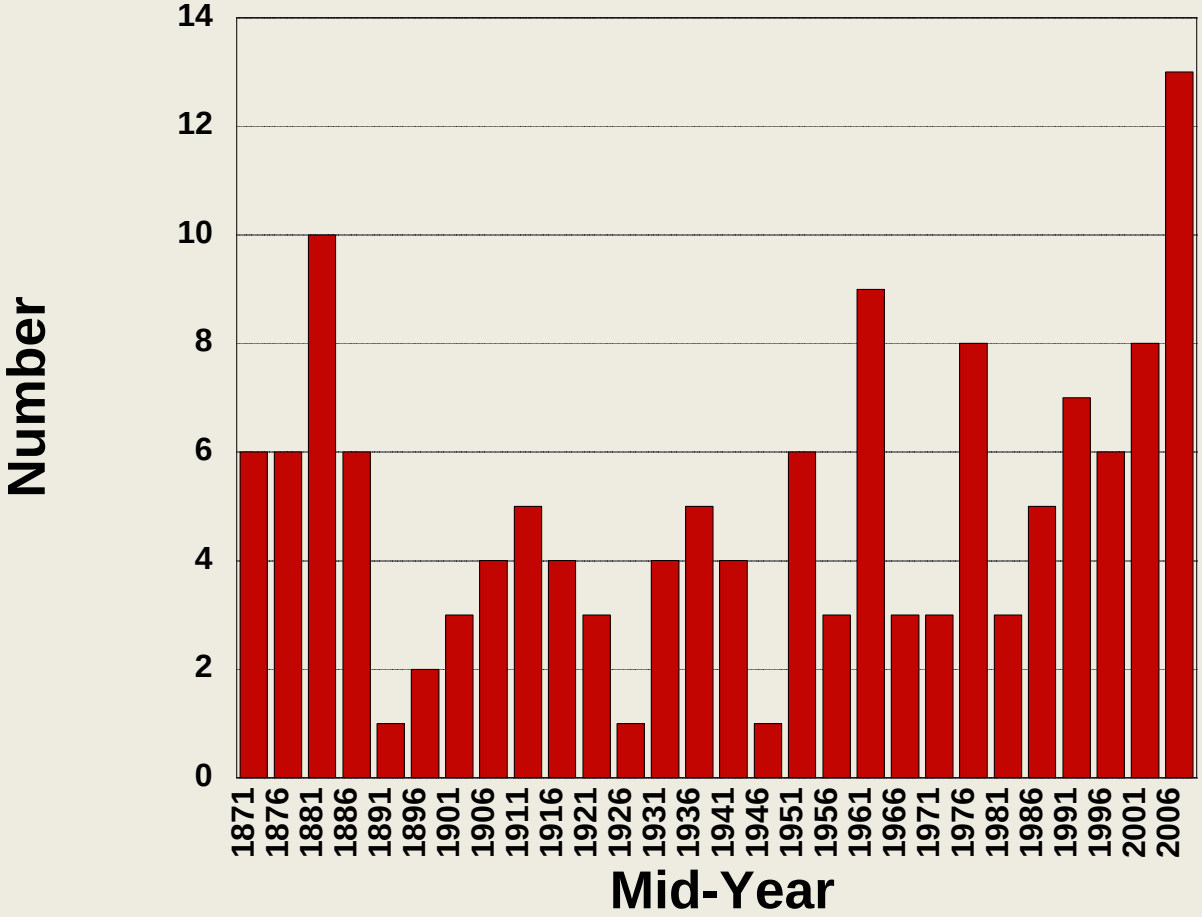
Todd, C. E., J. M. Harbor, and B. Tynor, Increasing magnitudes and frequencies of extreme precipitation events used for hydraulic analysis in the Midwest, 2006, *Journal of Soil and Water Conservation*, 61, 179- 184.

Largest Daily Rainfall
Madison, WI

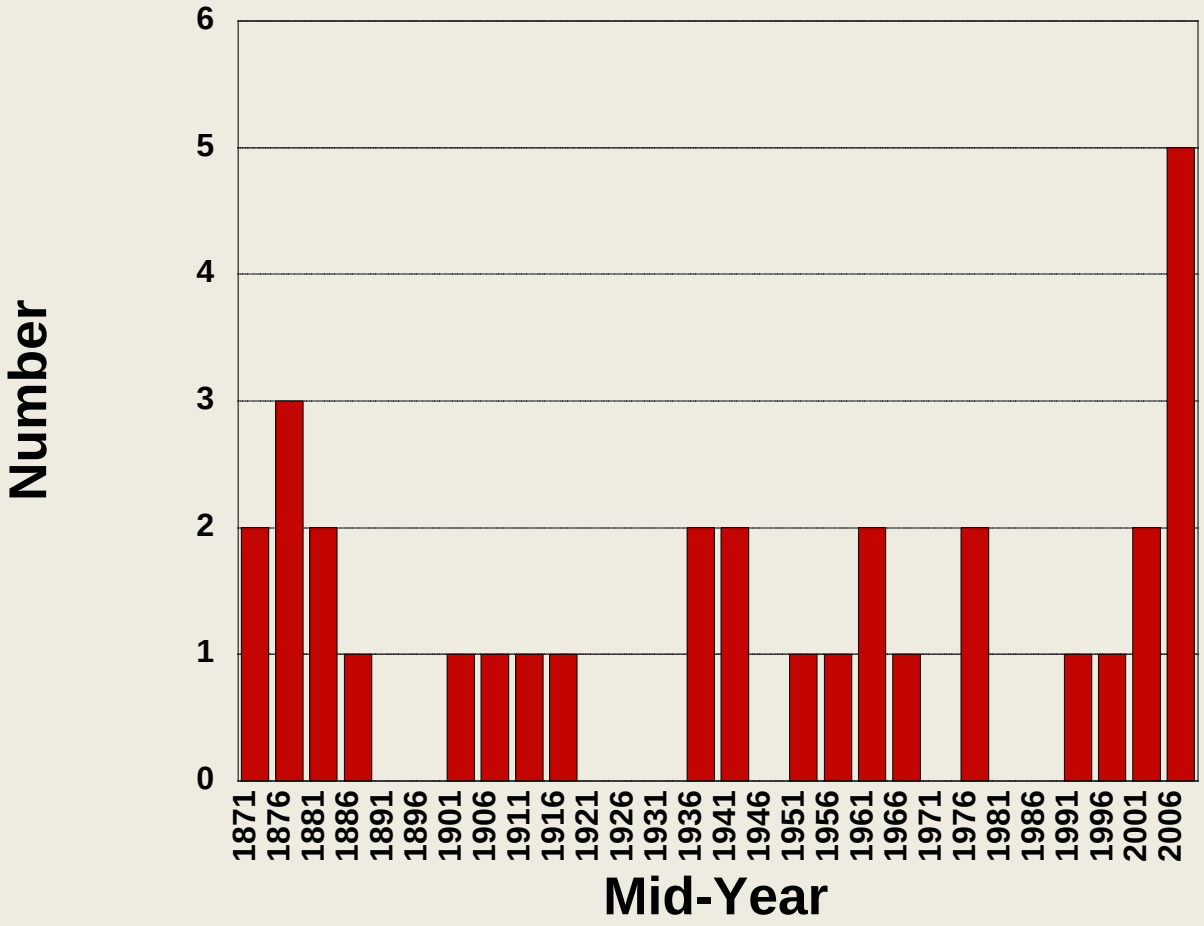



Sum of 5 Largest
Daily Rainfalls
Madison, WI
Rainfall
(inches)
14
12
10
8
6
4
2
0
1860
1880
1900
1920
1940
1960
1980
2000
2020
Year

Number of Exceedances of 2 Inches in 5-Year Increments Madison, WI



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



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 recenty developed by the National Weather Service.

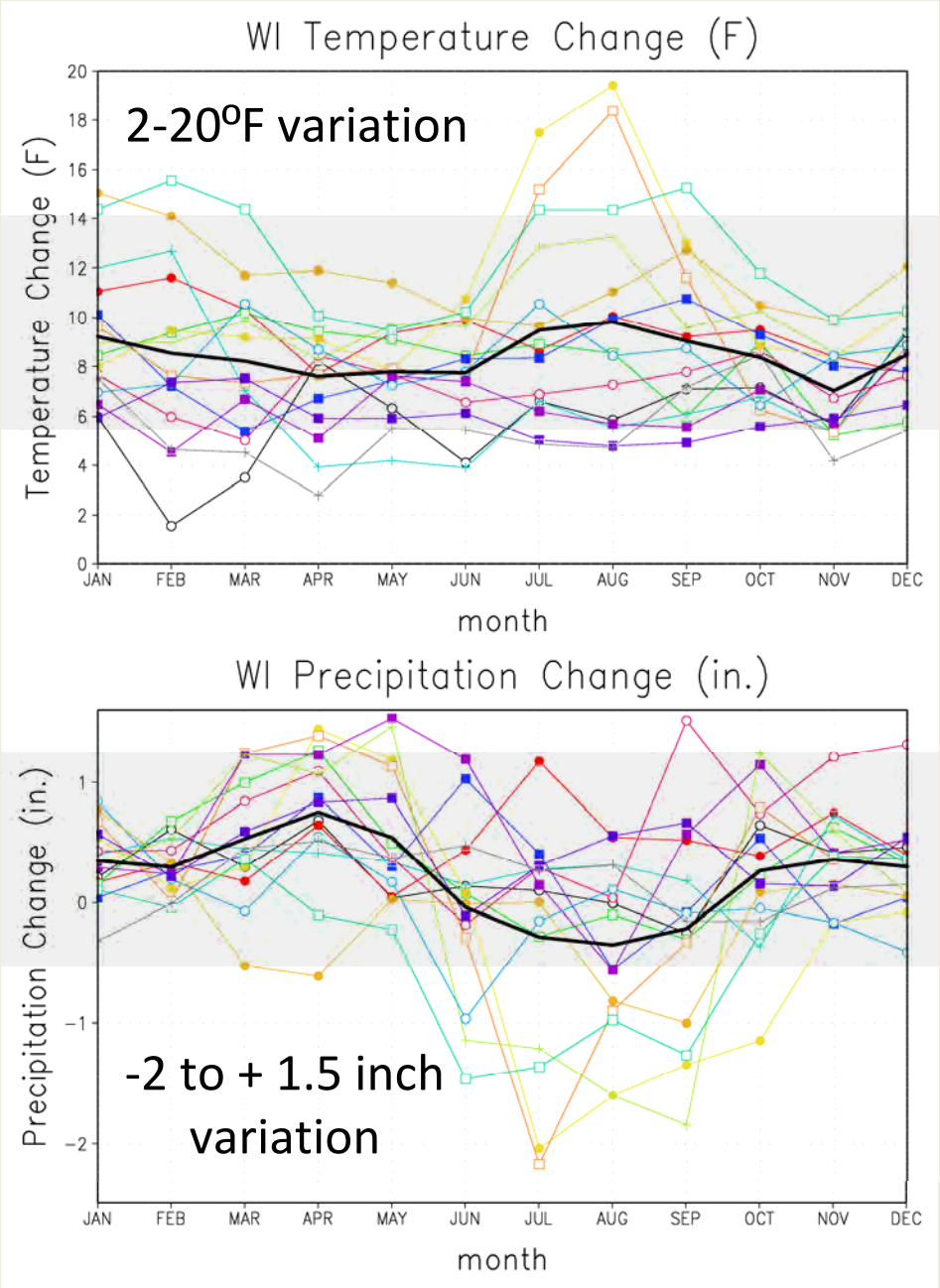
LIMITATIONS OF CLIMATE MODELS

- There are dozens of legitimate climate models and their predictions vary widely and depend on the degree to which CO_2 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.

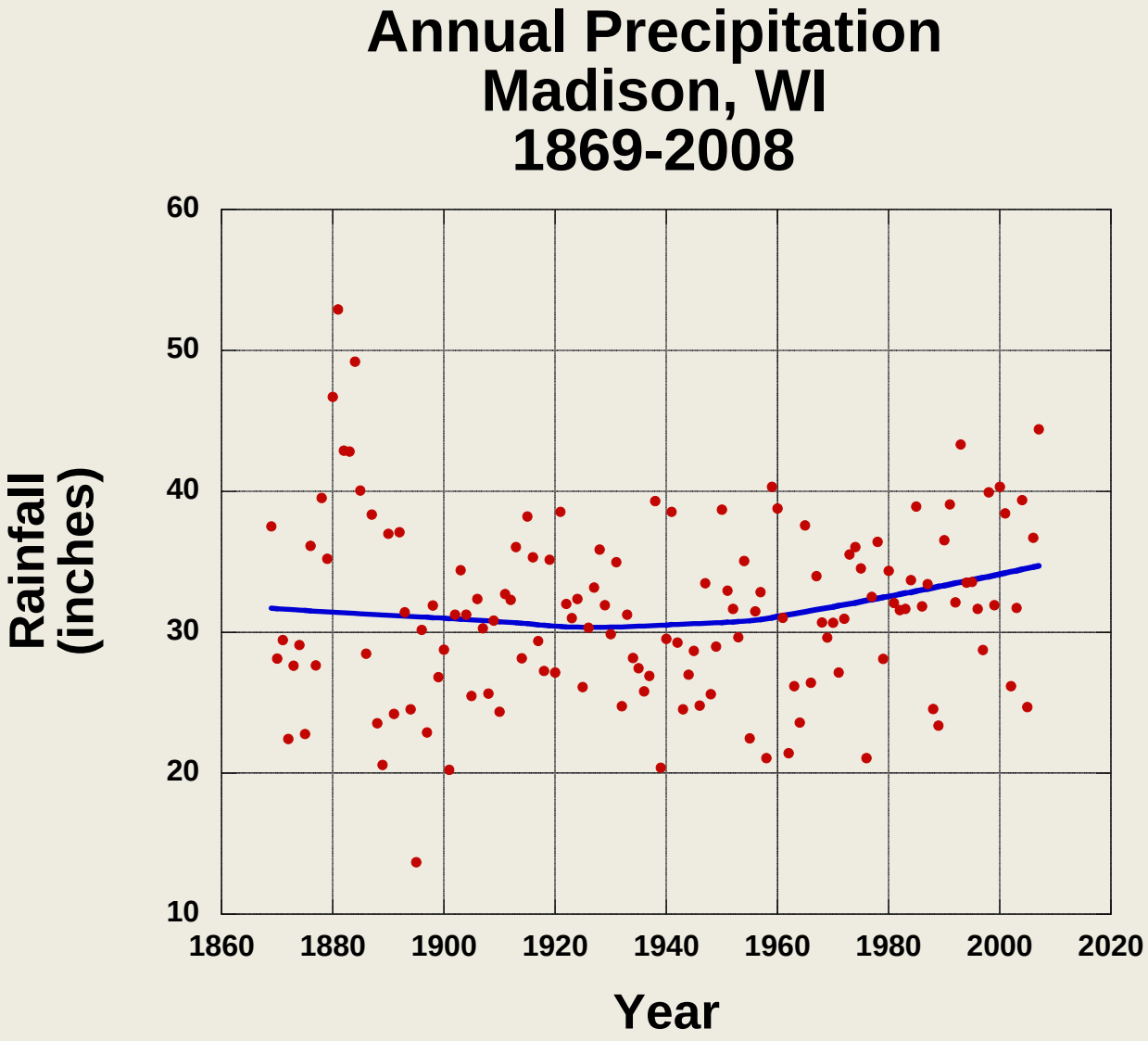
Note the wide variation between models results.



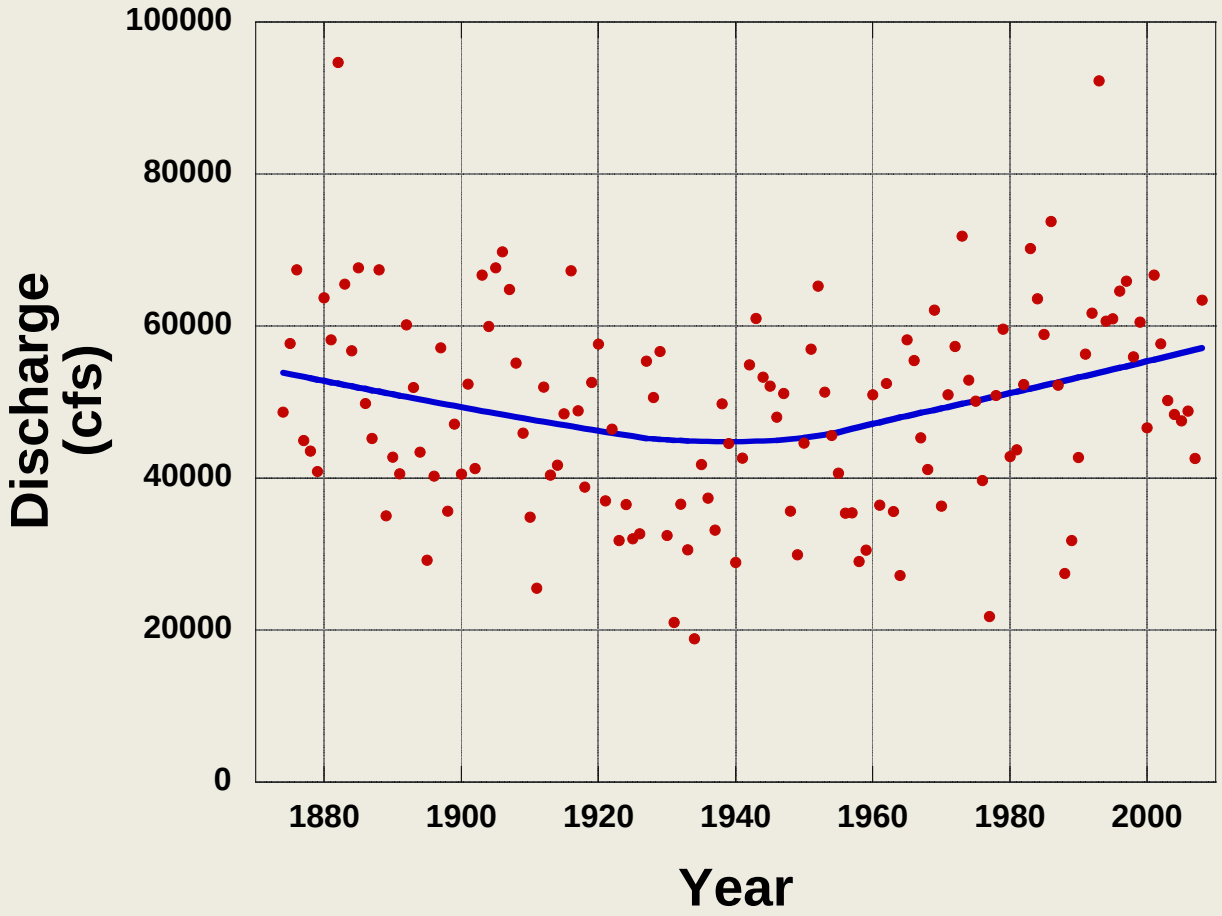
Courtesy of Dave Lorenz

LIMITATIONS OF CLIMATE MODELS

Do not capture long-term variability observed in actual rainfall data.


Annual Precipitation
Madison, WI
1869-2008
Rainfall
(inches)
60
50
40
30
20
10
1860
1880
1900
1920
1940
1960
1980
2000
2020
Year

Mississippi River at Clinton



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.
  - Schneider, V.R. and K.V. Wilson, 1980, *Hydraulic Design of Bridges With Risk Analysis*, U.S. Department of Transportation, FHWA-TS-80-226.
  - Corry, M.L., J.S. Jones, and P.L Thompson, 1981, *The Design of Encroachments on Flood Plains Using Risk Analysis*, U.S. Department of Transportation, Hydraulic Engineering Circular No. 17.

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.)

- Estimation of hurricane flood risk for New Orleans. (http://nolarisk.usace.army.mil/)

RISK-BASED DESIGN

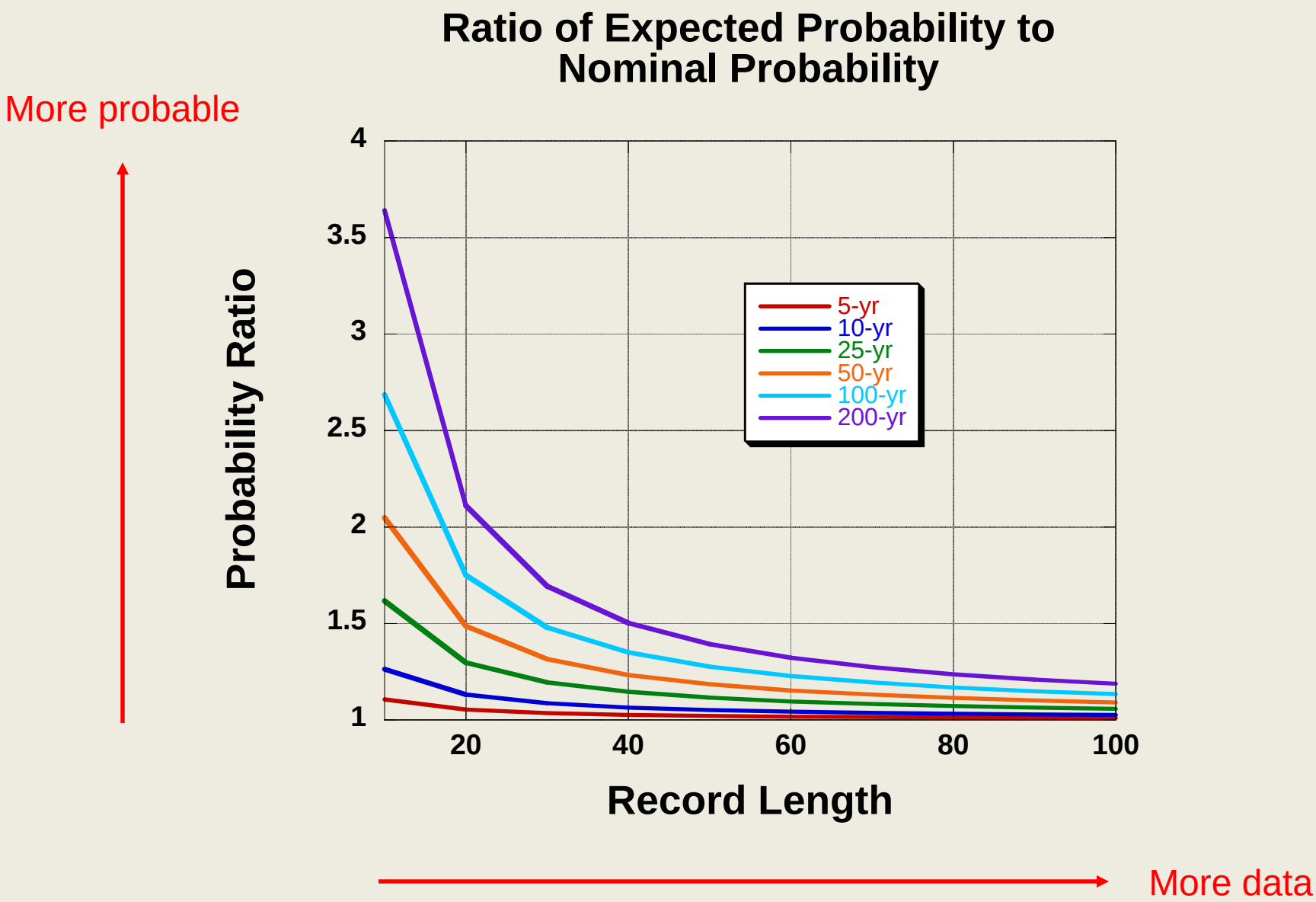
An early example of the incorporation of epistemic uncertainty in hydrology design is the use of “expected probability”, proposed by Leo Beard.

- Beard, L.R., 1960, *Probability estimates based on small normal-distribution samples*, Journal of Geophysical Research, American Geophysical Union, 65(7), 2143-2148.

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
Probability Ratio
4
3.5
3
2.5
2
1.5
1
20
40
60
80
100
Record Length
5-yr
10-yr
25-yr
50-yr
100-yr
200-yr
More data

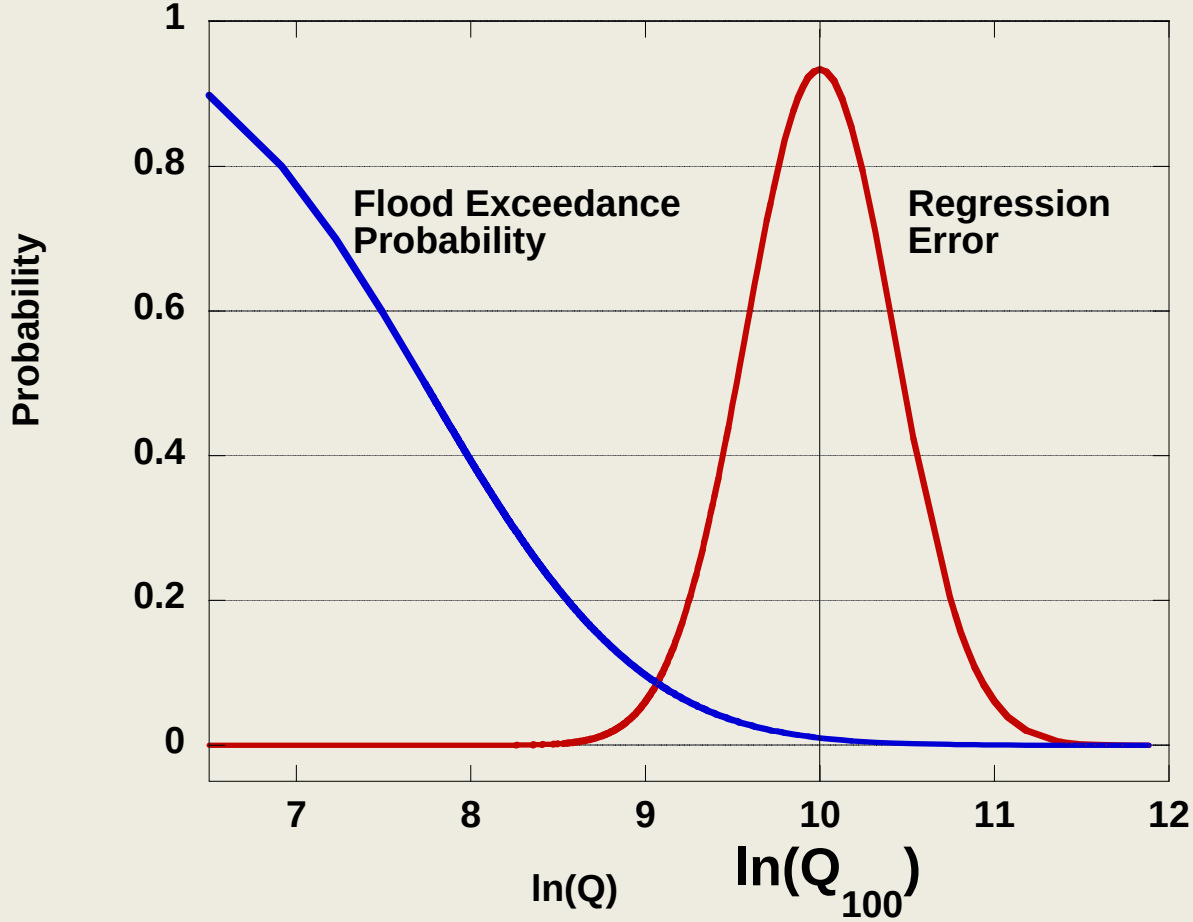
EXPECTED PROBABILITY

- 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.

EXPECTED PROBABILITY

Note that the same issue arises for flood quantiles that are estimated using the USGS regional flood frequency equations.

Expected Probability
Regional Flood Flood Quantile Estimation
Galena River, WI



The expected probability is the integral of the products of the two functions, and in this case equals **.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

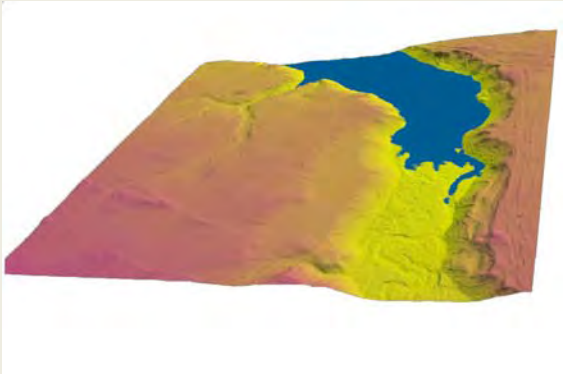
- For smaller projects, the uncertainty can be accounted for in the estimation of rainfall or discharge quantiles.
  - That is the quantiles (e.g 100-year, 24-hour rainfall intensity) can be computed so that the expected exceedance probability is the desired probability.
  - This would lead to increased 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?


Davis Pond
Freshwater Diversion
Project
New Orleans, LA
RIVER
MISSISSIPPI
Union Pacific RR
BN-SF RR
Luling, LA
U.S. HWY 90
Willowdale
Subdivision
Ponding Area
9,300 acres
LAKE CATAOUATCHE
Diversion Structure
Bridge
Outflow Channel
Guide Levee
Pumping Station
Rock Weir




FIRM