A Presentation of the

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November 23, 2010 Owatonna, MN

Late 20th century trends in Iowa watersheds

- an assessment of observed and modeled hydrologic data

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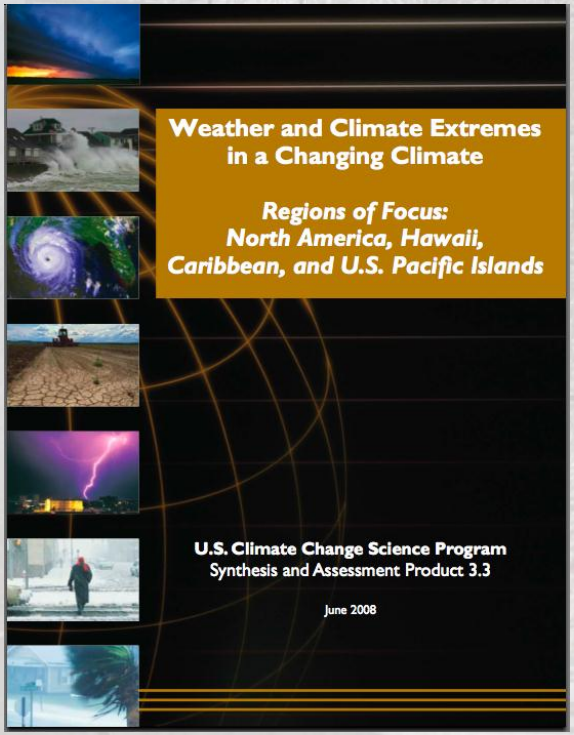
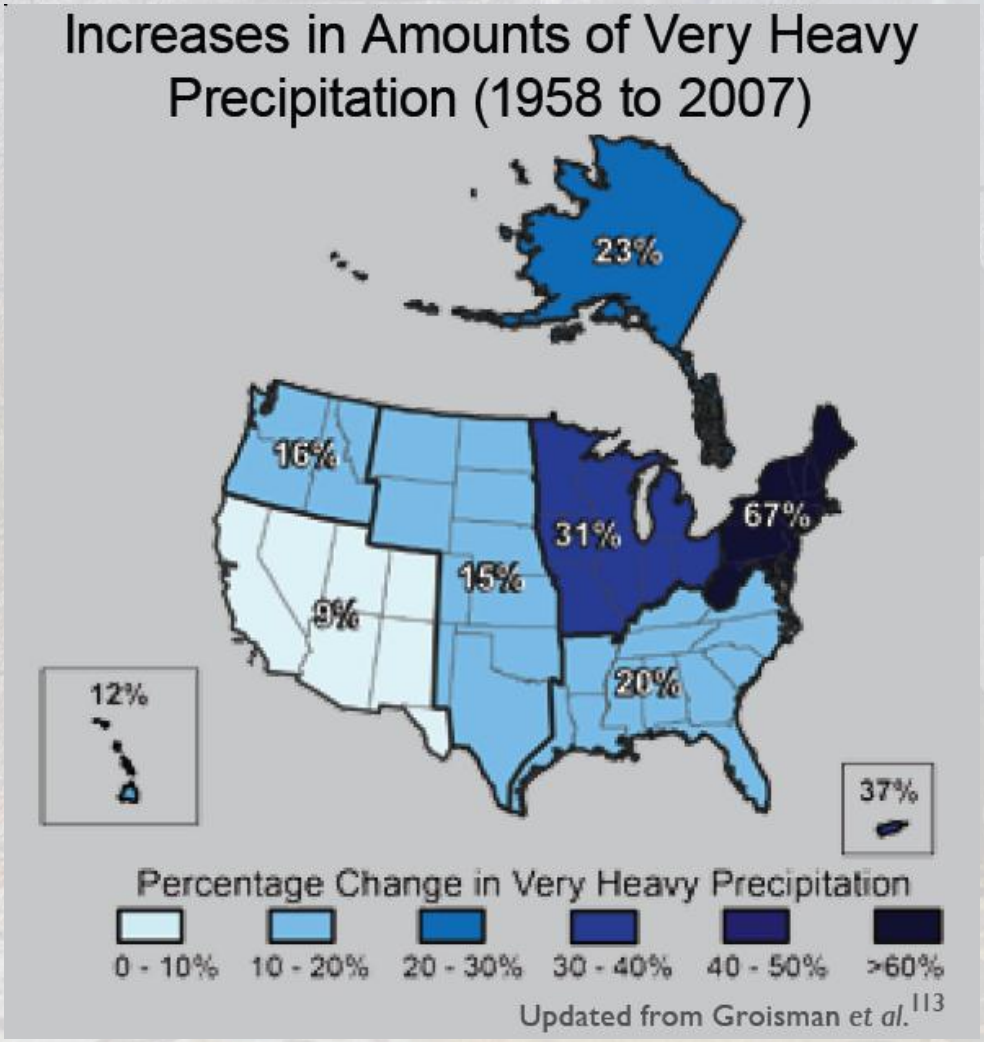
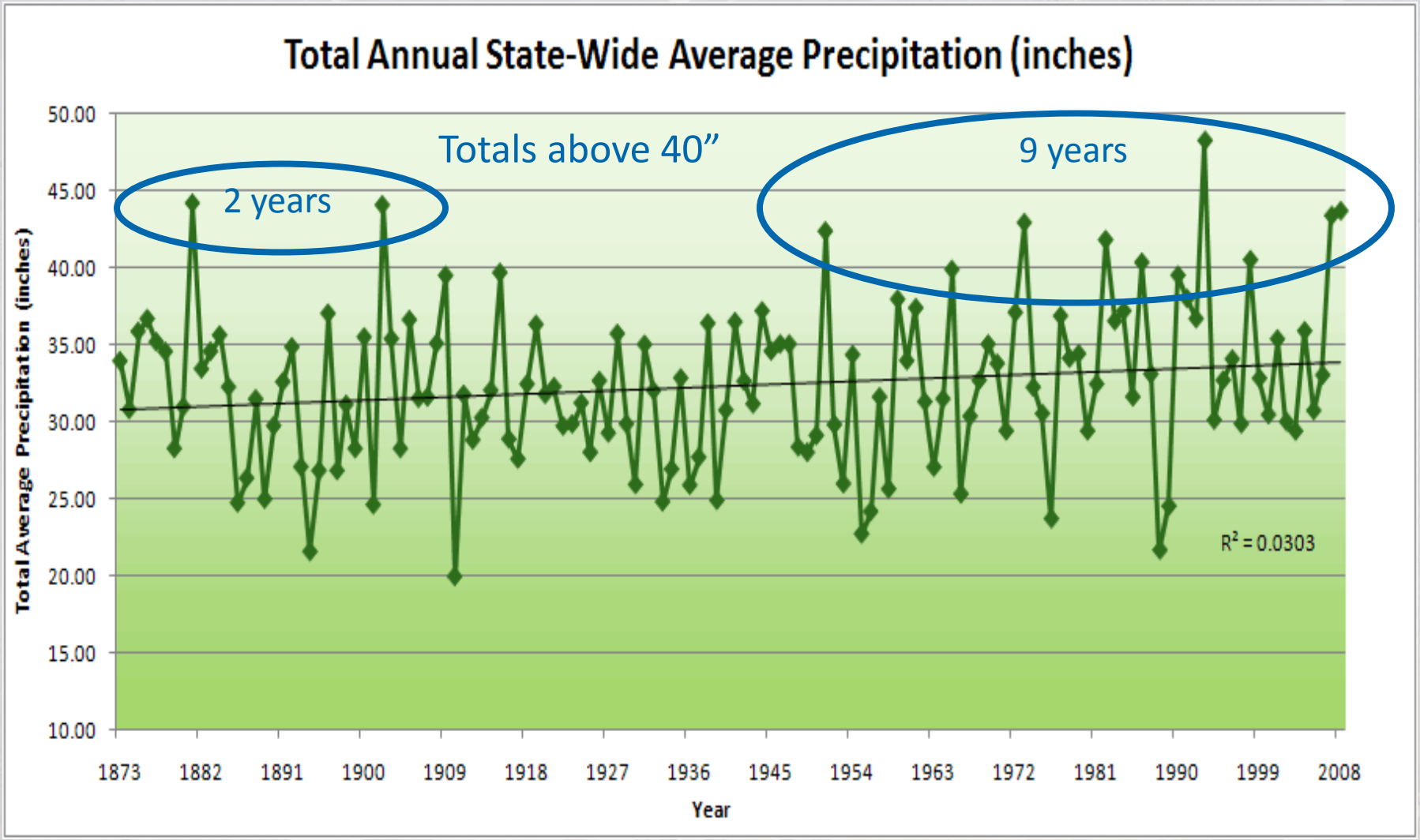
"One of the clearest trends in the United States observational record is an increasing frequency and intensity of heavy precipitation events… this trend is statistically significant."





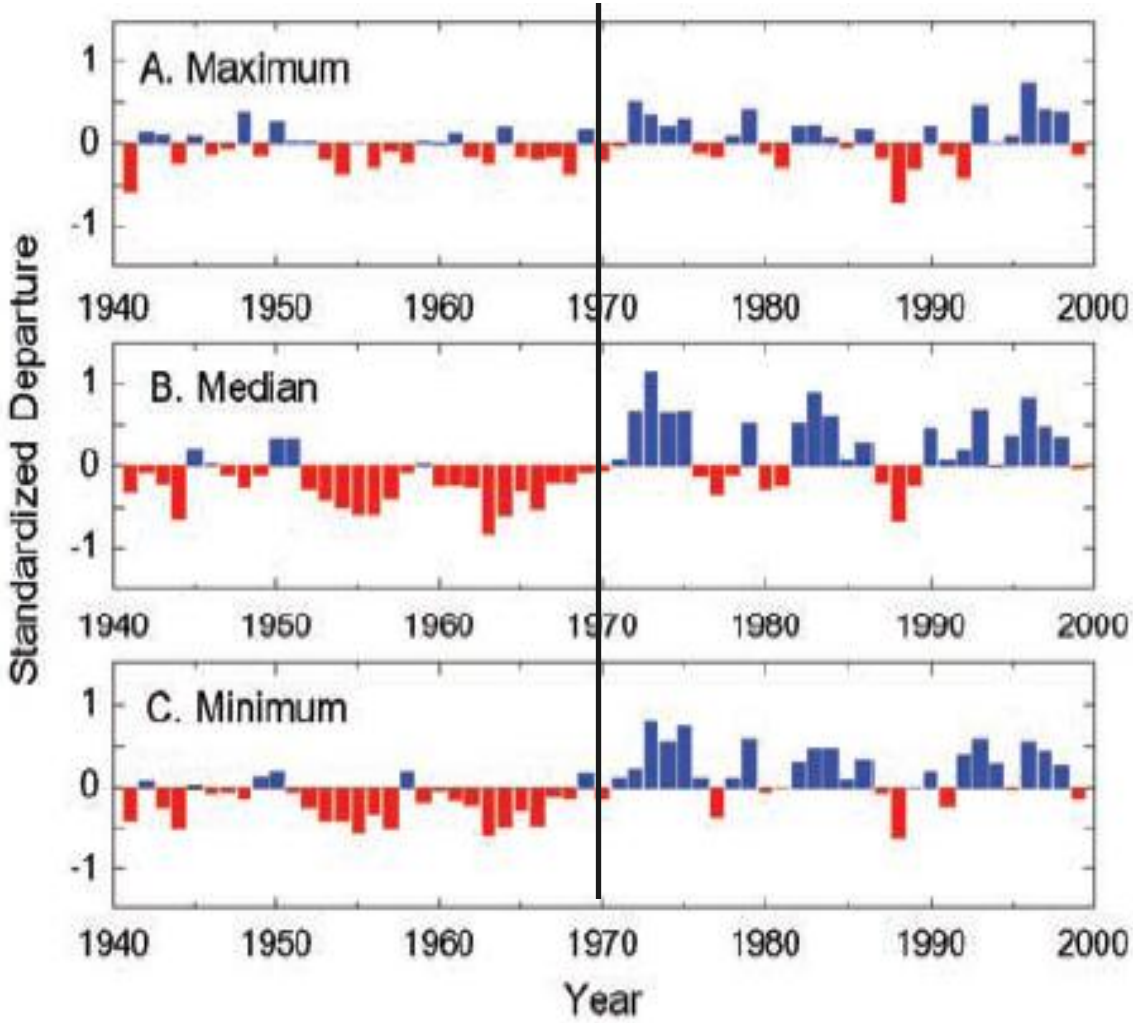
Slide: C. Anderson

Wet Years more common in Iowa since 1950



Slide: C. Anderson

Departures from mean annual streamflow at 400 sites in the U.S. - McCabe and Wolock, 2002



- **50% of the conterminous U.S. exhibited increasing discharge between 1940 and 1999 (most pronounced trends in the central U.S.) - Lins and Slack, 2005**

- **Most notable since 1970s - McCabe and Wolock, 2002**

Objectives

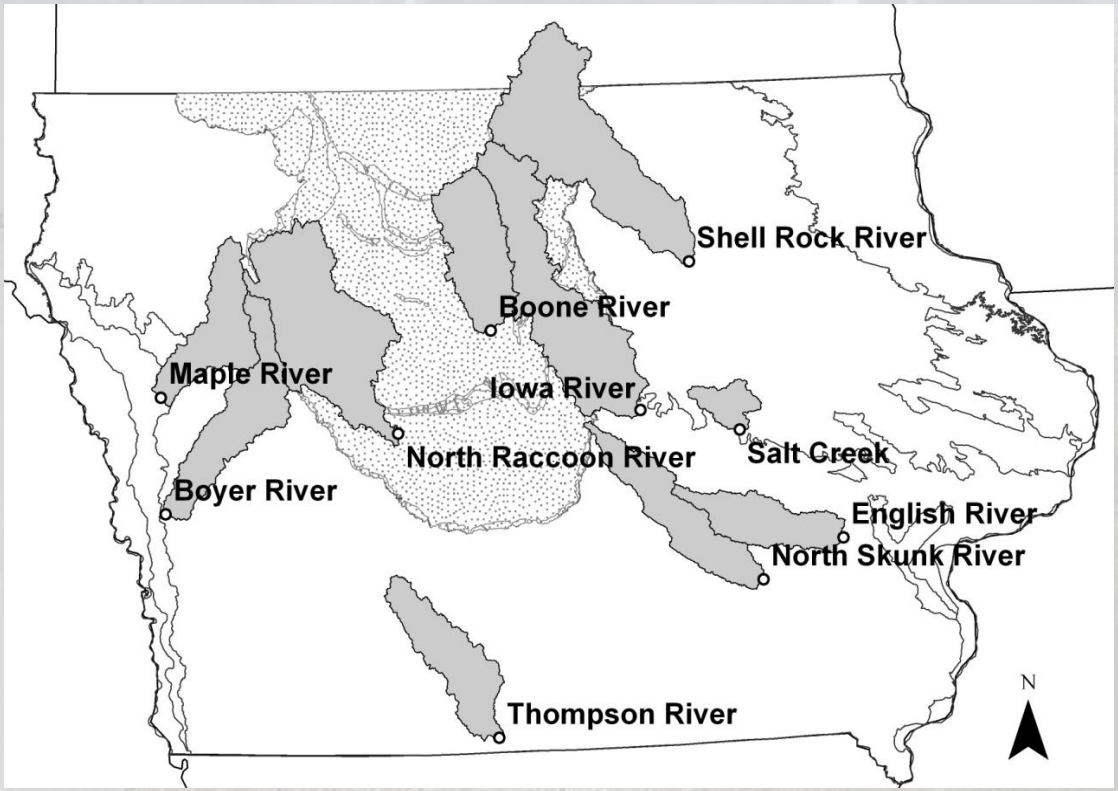
1) To determine trends in hydrologically relevant variables for watersheds in Iowa
   - Streamflow, soil moisture, snow, frozen ground

- *Many hydrologic variables are poorly observed*
- *Can we rely on models to fill in the blanks?*

2) To determine the ability of a commonly used hydrologic forecast model to reproduce observed trends

Methods

10 Iowa study basins



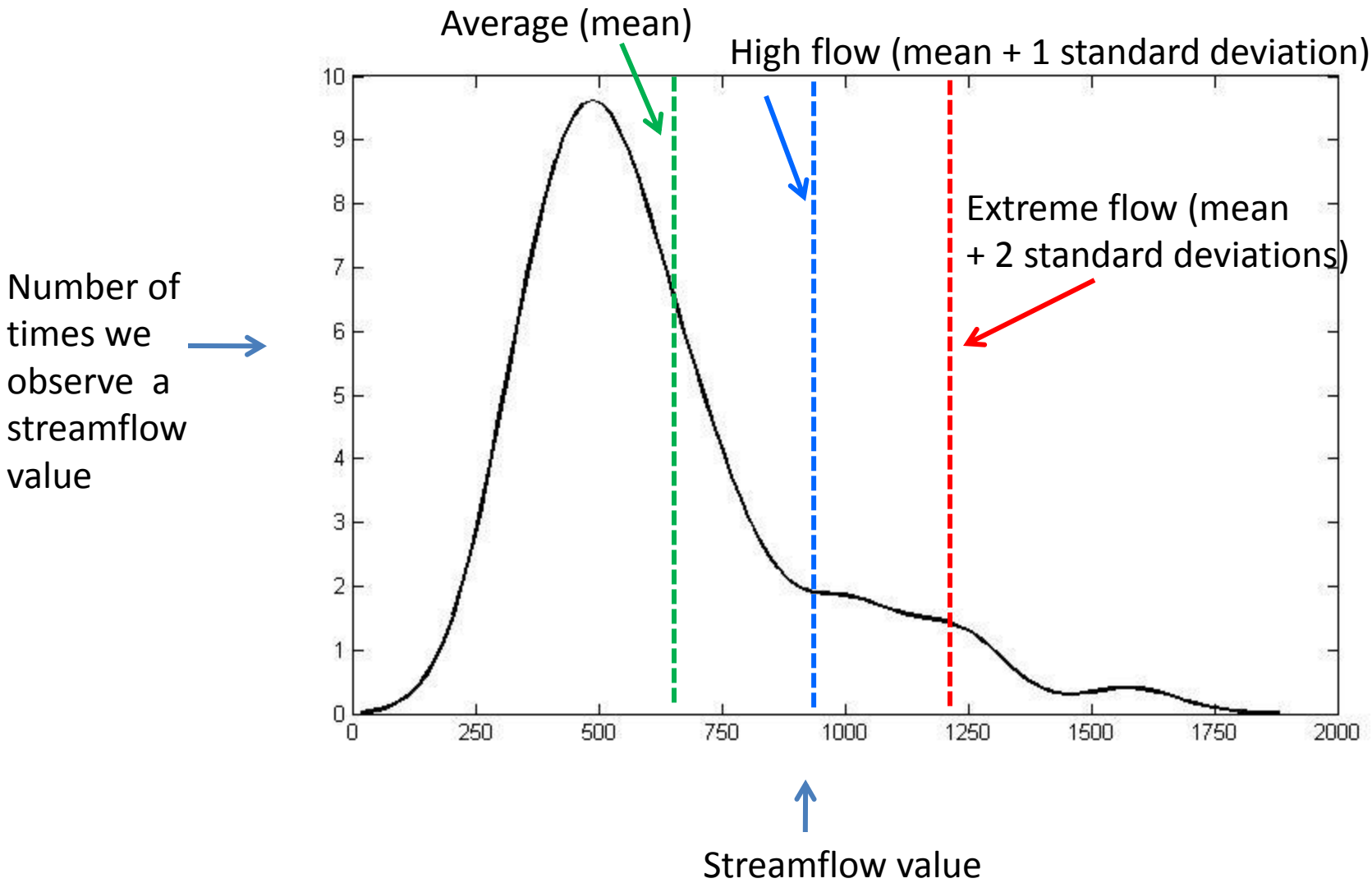
Area (sq. km)	521-7268
Avg. Q (mm/year)	195.12
Avg. Precip (mm/year)	823.28

- **Precipitation, T_{air}, and Discharge data from the MOdel Parameter EXperiment (MOPEX) database (NWS and USGS data)**
- **~ 50 years of data for each site (1948-2003)**

Analyzed observed and modeled (*) data

- Mean daily flows
- 7-day low flows (summer and winter)
  - Lowest flows during 7 consecutive days
- Peak flows from rain and snow
- Number of high flow days
- Number of extreme flow days
- Monthly subsurface moisture storage*
  - As a percent of total
- Occurrence of snow melt*
- Occurrence of frozen ground*

Characteristics of streamflow



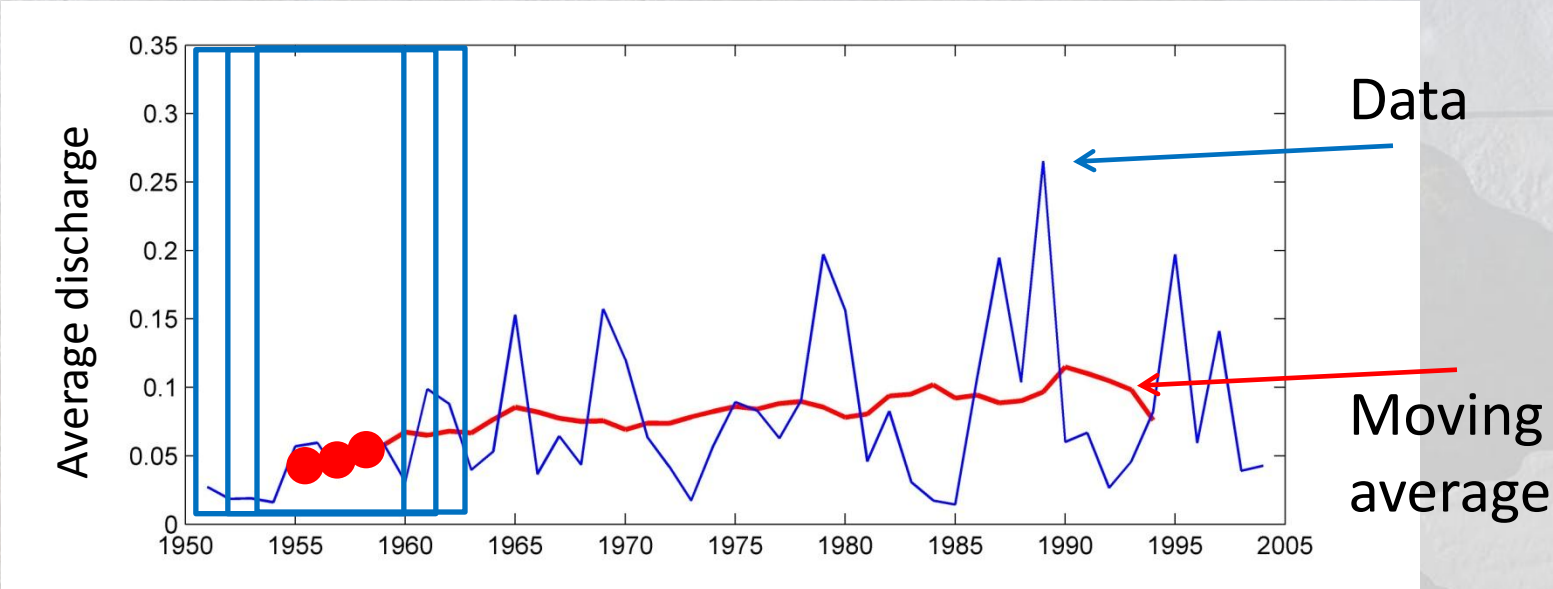
We do not use the term flood

- **Flood: an overflow or inundation that comes from a river or other body of water, and causes or threatens damage.**
  - USGS Professional Paper 1775

- Floods are often a stage measurement, which are difficult to compare across time due to changes in channel

Visual analysis

- Plots of 10-year moving average



- Percent change from start to end

Trend Analysis

- Trend significance: Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975)
  - Extensively used in similar hydrologic studies (Hirsch et al., 1982, Lins and Slack, 1999; Burn et al., 2004)
  - Requires the data be serially independent: Trend-Free Pre Whitening procedure (TFPW)

- MK test with TFPW procedure:
  1. Slope of the data estimated using Thiel-Sen Approach which limits influence of outliers (Thiel, 1950; Sen, 1968)
  2. If slope differs from zero, it is removed from the series
  3. Next, the (lag-1) correlation coefficient is removed from the detrended series
  4. Trend is added back into the data set and the MK test is applied to the blended series

MK Test

Mann-Kendall test

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} Sgn(X_j - X_i)$$

where:

$$Sgn(\theta) = \begin{cases} +1 & \theta > 0 \\ 0 & if\ \theta = 0 \\ -1 & \theta < 0 \end{cases}$$

n = number of values in the data set

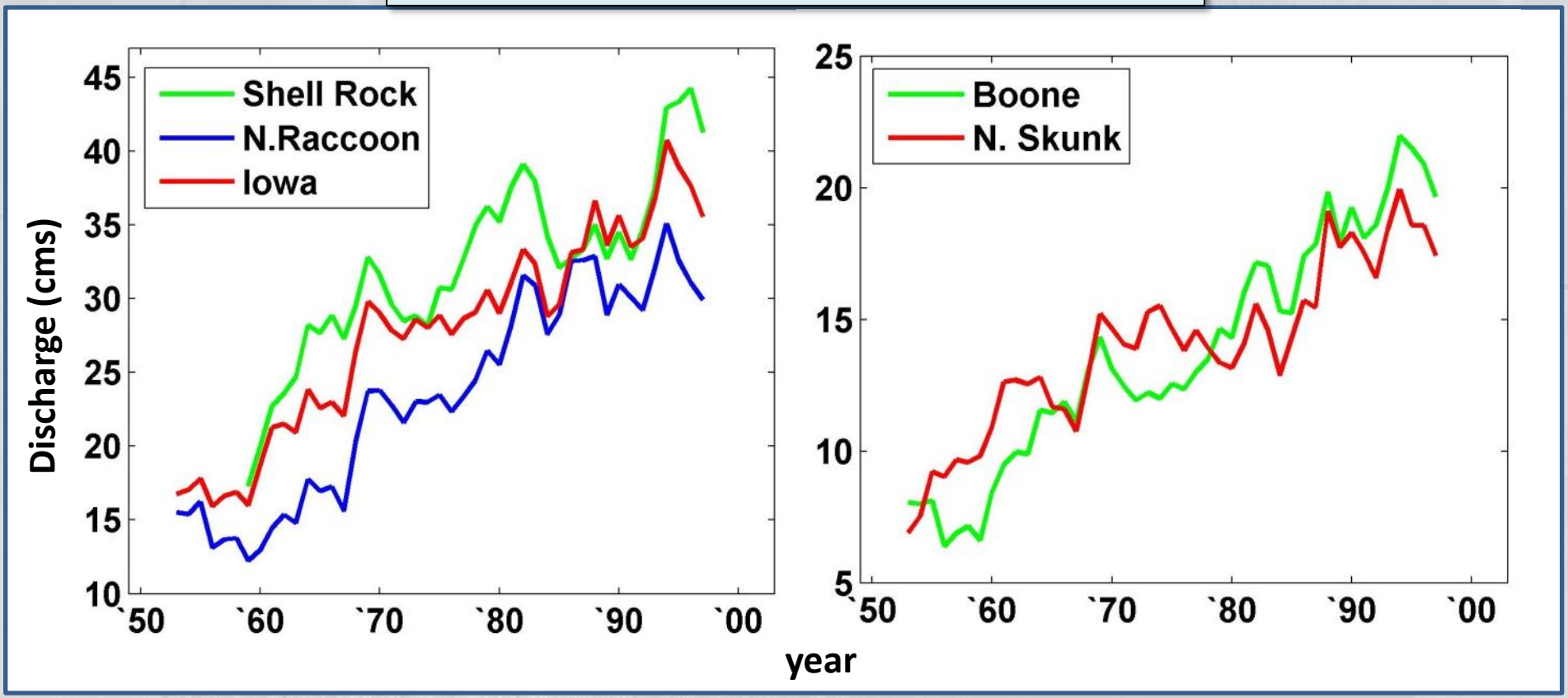
if *n* ≥ 8, S is (approximately) normally distributed allowing for computation of Z:

$$Z_s = \begin{cases} \dfrac{S-1}{\sqrt{var(S)}} & S > 0 \\ 0 & for\ S = 0 \\ \dfrac{S+1}{\sqrt{var(S)}} & S < 0 \end{cases}$$

- Positive(negative) value of Z represents an upward(downward) trend
- If *p*-value ≤ significance level, reject the null hypothesis that a trend does not exist
- Used a significance level of 10%

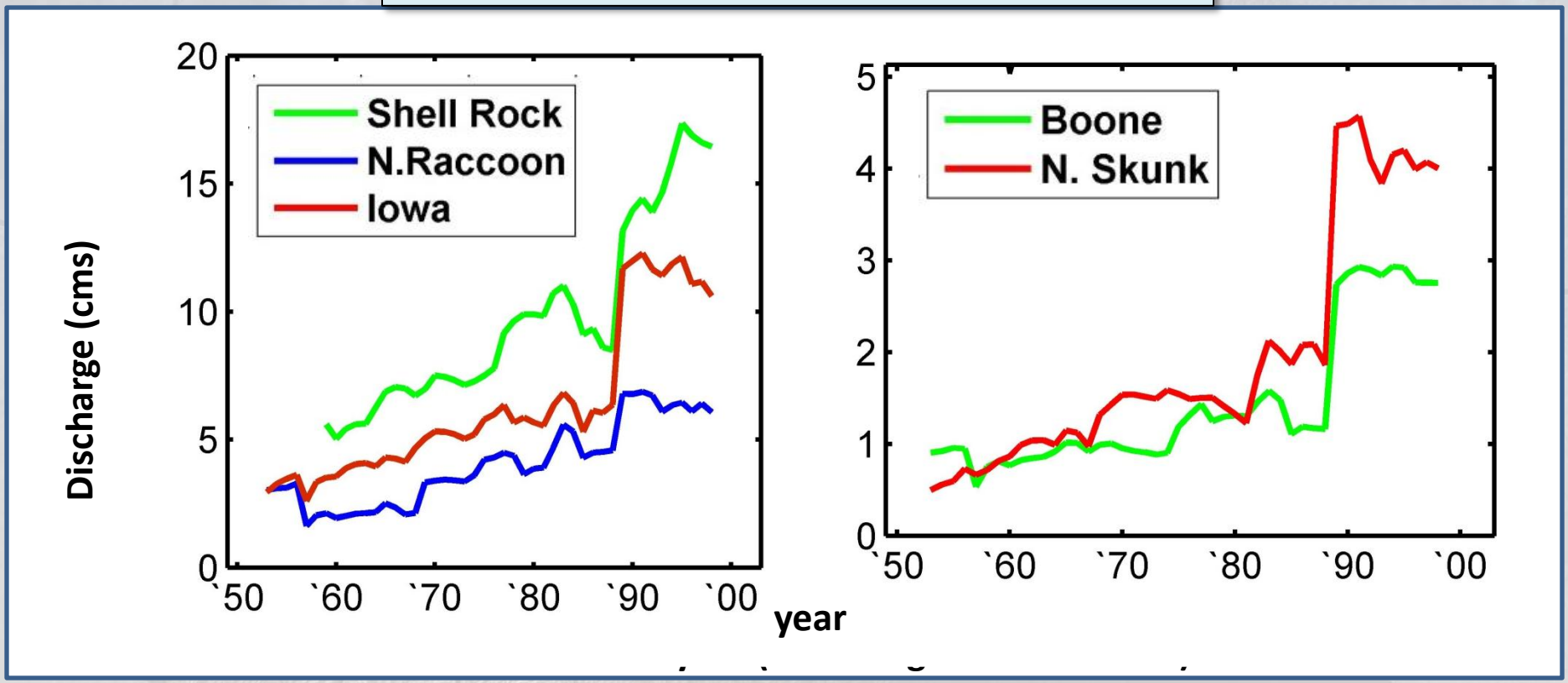
Observed data trends: streamflow

Average daily streamflow



Average daily streamflow +51%
8 sites had positive MK trends

7-day summer low flows



7-day low flows +71% (August-September)
Flood years are influencing this percentage
3 positive MK trends, 7 negative MK trends

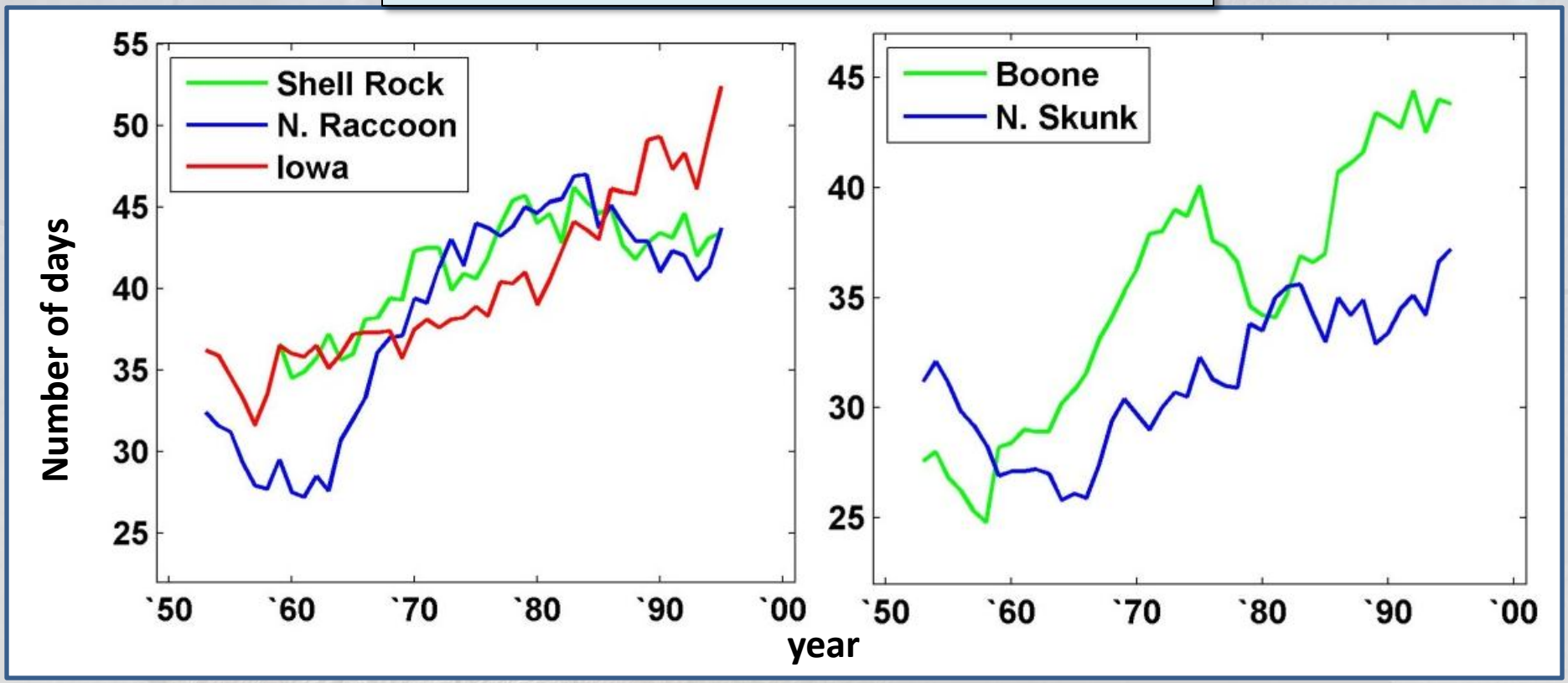
- Winter 7-day low flows increased +63%, but only 2 sites had positive trends

- Low flow results are in contrast to other studies that found significant upwards trends in low flows in the Midwest (Douglas et al., 2000; Schilling and Libra, 2003; Lins and Slack, 2005; Novotny and Stefan, 2006; Juckem et al., 2008).

- Partly due to de-trending procedure. Without it, 5 sites w/positive trends in summer and winter

- Also a lot of variability in low flows due to flood events.

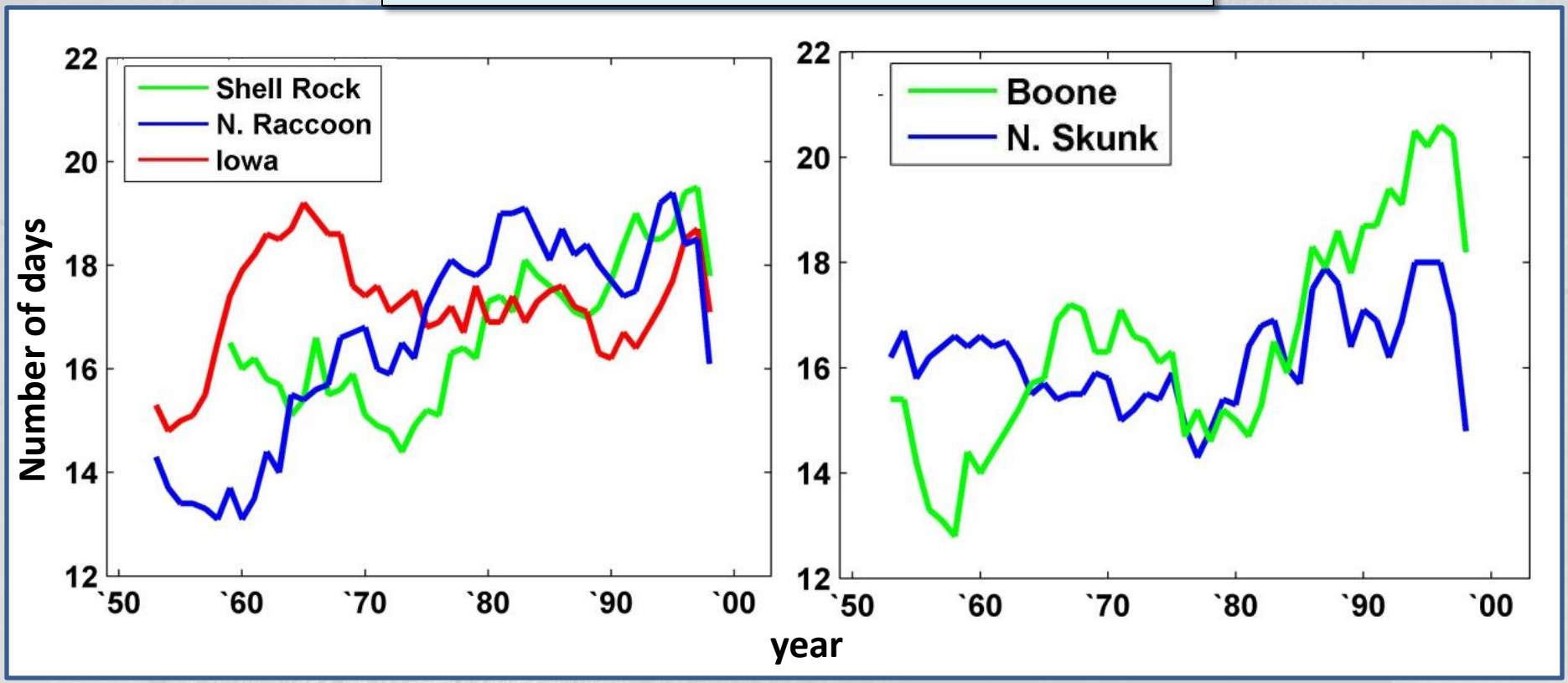
Number of high flow days



+10 high flow days per year

9 positive MK trends, 1 negative MK trend

Number of extreme flow days



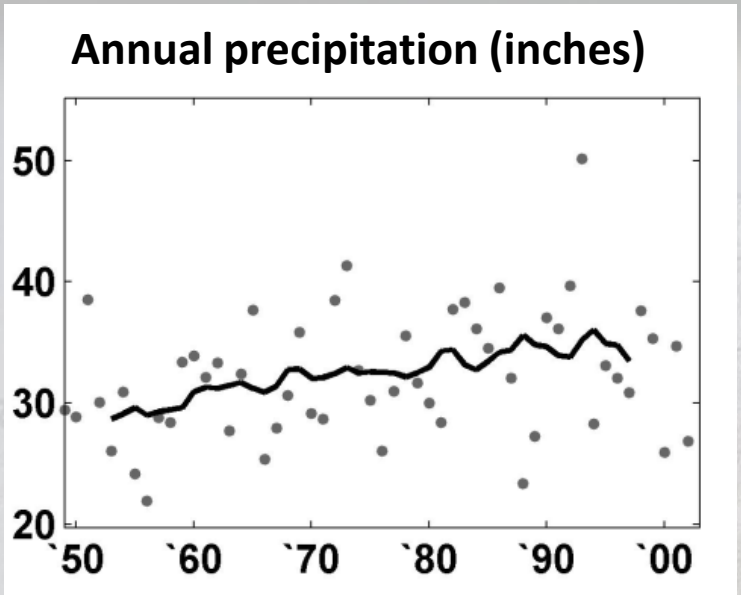
+2.5 extreme flow days per year

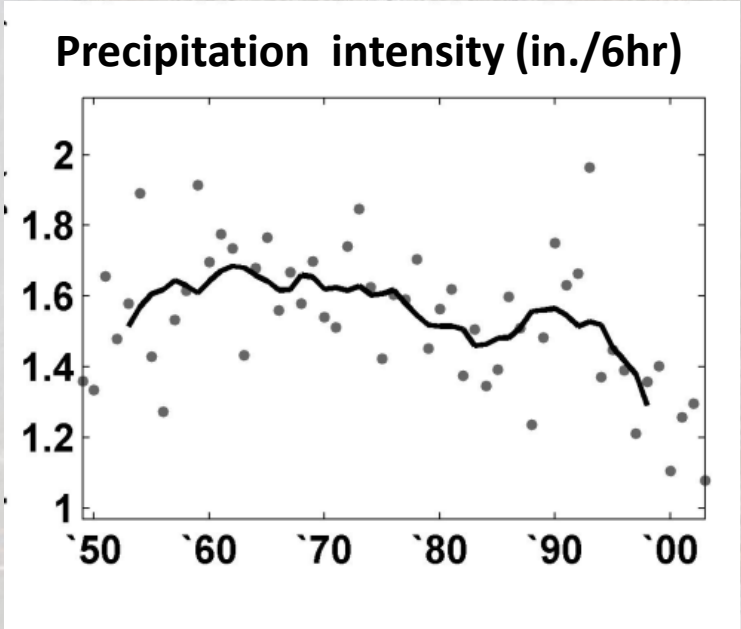
3 positive MK trends, 7 negative MK trends

Summary of MK test for observed streamflow

	Sites with trends	
	positive	**negative**
Mean daily discharge	**8**	**2**
7-day summer low flow	**3**	**7**
7-day winter low flow	**2**	**8**
Peak flow from rain	**8**	**2**
# High flow days	**9**	**1**
# Extreme flow days	**3**	**7**

	Sites with trends		Sites with statistically significant trends	
	positive	negative	positive	negative
Mean daily discharge	8	2	4	0
7-d. summer low flow	3	7	1	5
7-d. winter low flow	2	8	0	5
Peak flow from rain	8	2	2	0
# High flow days	9	1	5	0
# Extreme flow days	3	7	0	1



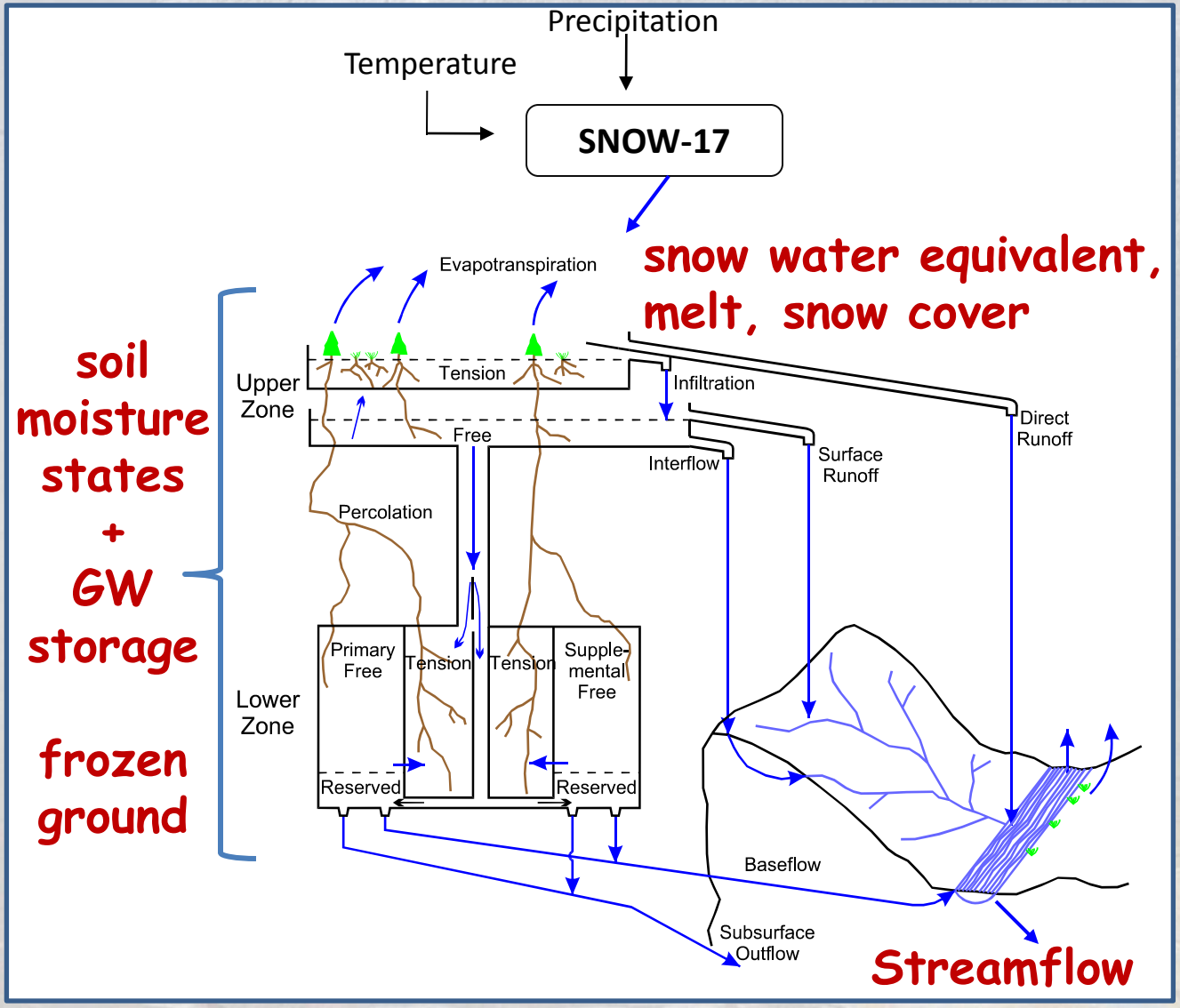


- Results make sense given precipitation observations
  - Increased annual precipitation
  - Declining intensity
  - More days with precipitation

-> all would lead to higher streamflow on average, but not contribute to more extreme flows

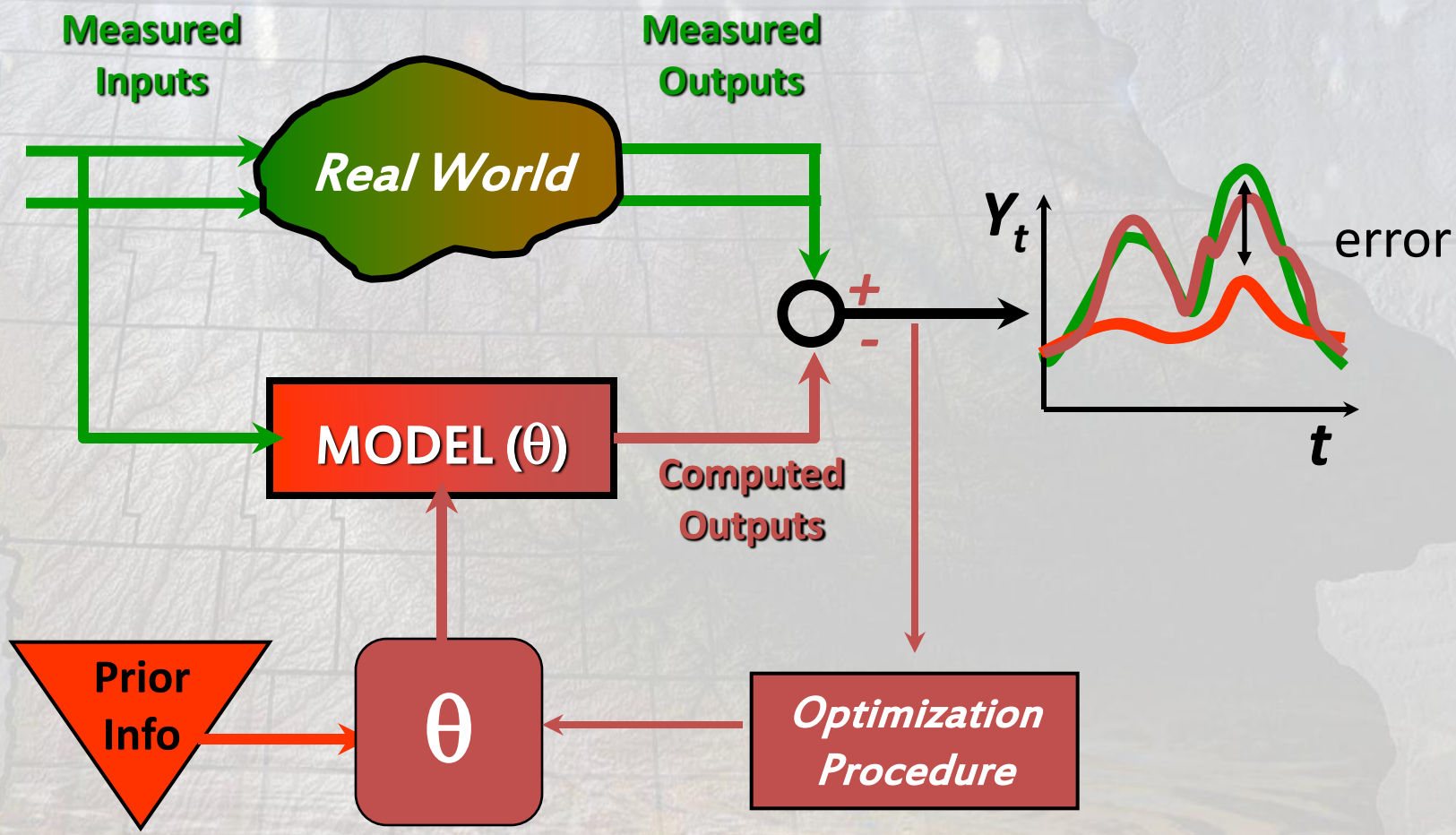
Trends in modeled data

National Weather Service Sacramento Soil Moisture Accounting Model (SAC-SMA) modeling system



- Modeling system used for short- and long-term **streamflow predictions** across US
- Continuous, **conceptual** rainfall-runoff model
  - 2 soil zones
- **Empirically-based** snow model simulates accumulation and melt

Conceptual models require calibration



"Calibration: constraining the model to be consistent with observations"

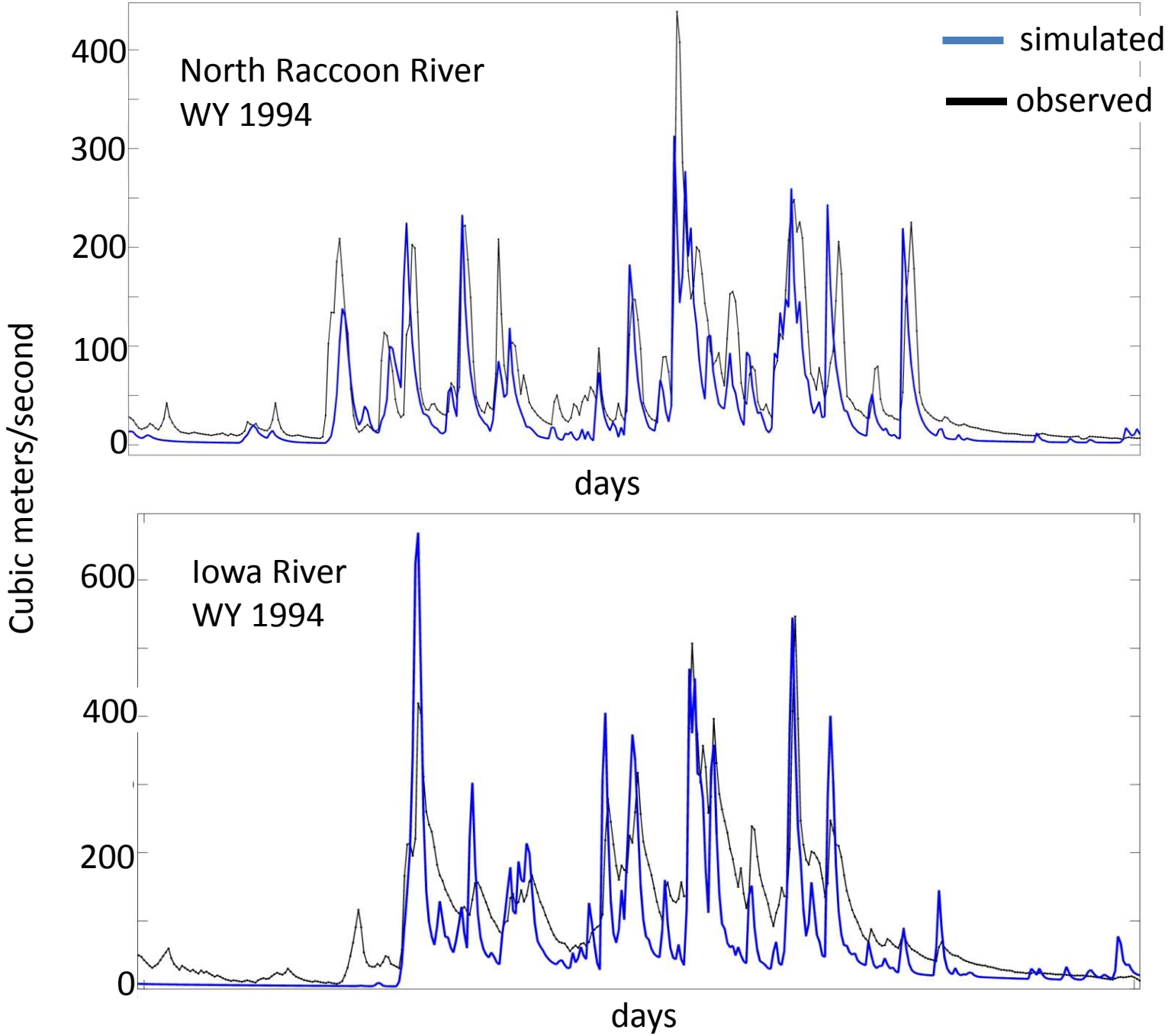
- Parameters are considered to be invariant in time
  - Modeling system cannot account for changes in basin characteristics over time, i.e. land use changes
- Calibrated for 3 periods -> 3 parameter sets:
  - 1958-1970
  - 1970-1982
  - 1988-2000

Model Calibration Results

Mean values

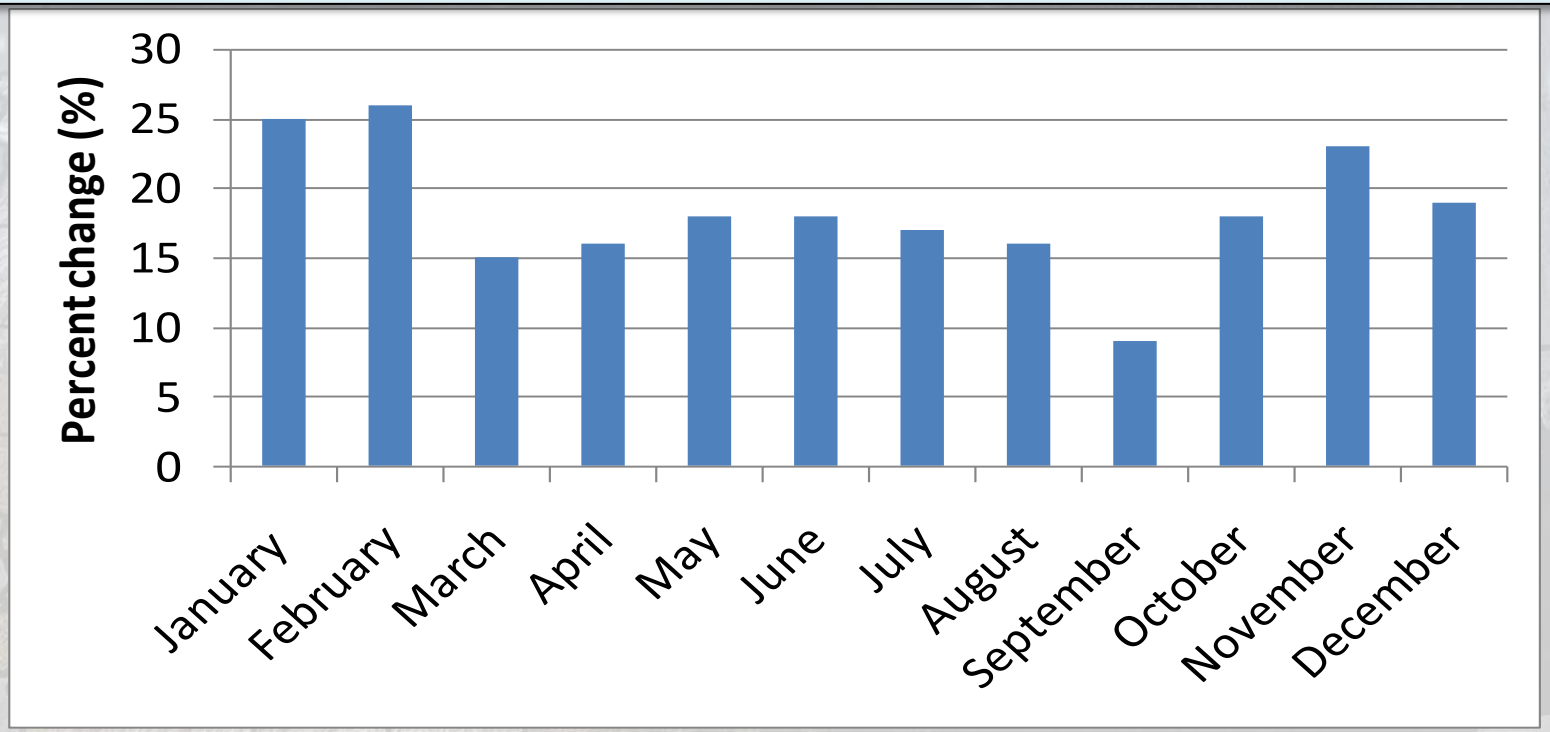
	Root Mean Squared Error (cms)	Percent Bias (%)	Nash Sutcliffe Efficiency
1958-1970	16.8	-7.6	0.64
1970-1982	17.1	-9.6	0.63
1988-2000	16.4	-1.8	0.66

- Ran 3 calibrations
- Results similar for each period
- Model underestimating flow on average
- Nash-Sutcliffe Efficiency is rather low
  -timing of peaks off


North Raccoon River
WY 1994
simulated
observed
400
300
200
100
0
days
Cubic meters/second
Iowa River
WY 1994
600
400
200
0
days

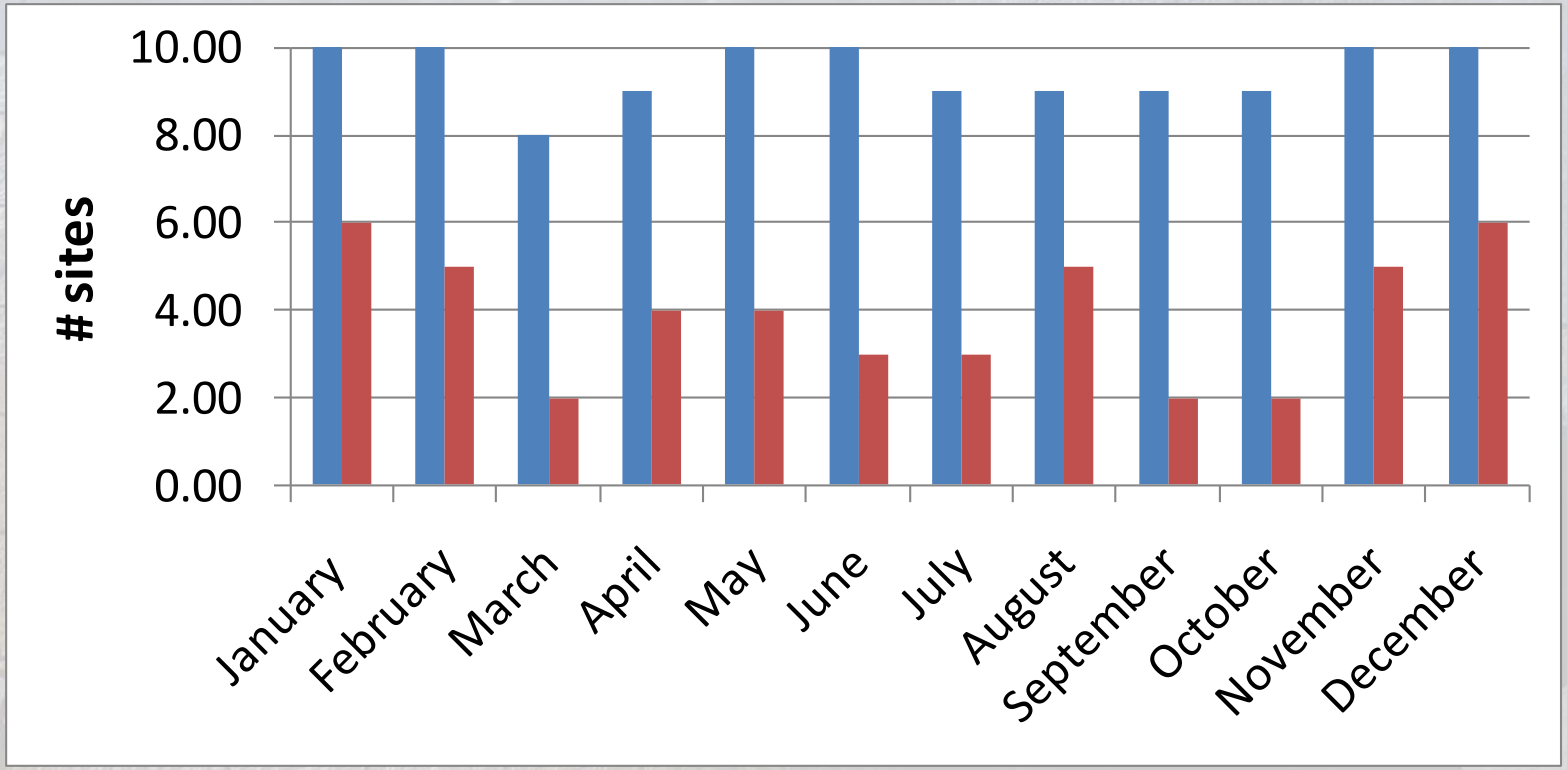
Modeled data trends: subsurface moisture, snow, frozen ground ('58 – 70 calibration)

Mean Monthly Subsurface Moisture – moving average



- Trends follow those found in precipitation analysis for the Midwest (Angel and Huff, 1997; Karl et al., 1995; Davis-Todd et al., 2006)
- Increasing potential for runoff/flooding throughout the year
- All simulations showed increasing subsurface moisture storage

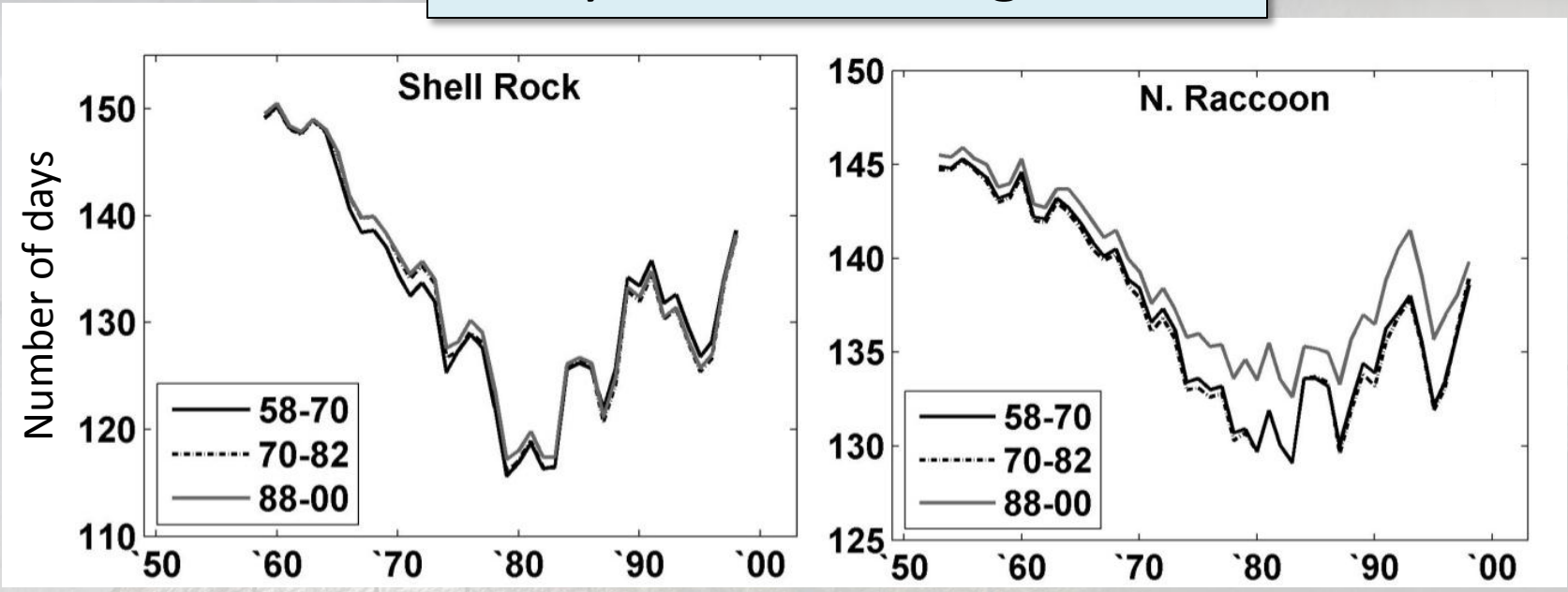
Mean Monthly Subsurface Moisture Trends



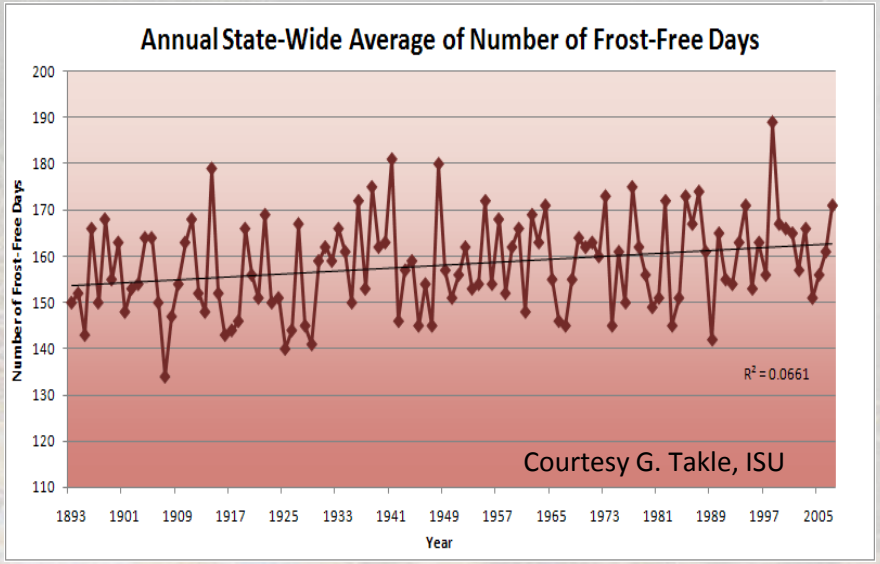
with positive MK trends

with positive and significant MK trends

Days with frozen ground



- -6 fewer days with frozen ground
- Correlates with observed increases in air temp. throughout the winter (Seeley, 2003)
- Could contribute to increased winter low flows or soil moisture



Simulated cold season shifts

	MK trend #pos/#neg	Significant #pos/#neg	Change in running avg
# days frozen ground	0/10	0/10	-6.1 days
First day frozen ground	0/10	0/6	-2.6 days
Last day frozen ground	0/10	0/10	-9.2 days
# snow cover days	3/7	0/0	2.0 days
First day snow cover	0/10	0/10	-11.1 days
Last day snow cover	0/10	0/6	-2.53 days
# bare ground days	8/2	2/0	6.57 days

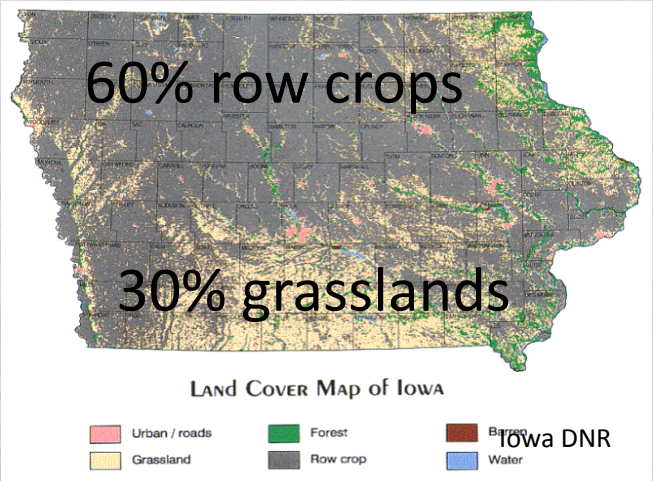
- Trend towards earlier cooling in the fall, earlier warming in the spring

- Frei et al. (1999) that show the snow season is beginning earlier and ending sooner.

Model evaluation

- ***Remember model parameters are considered to be invariant in time (assumes stationarity)***

- Iowa land development
  - 70-80s shift in cropping to mainly soybeans and corn
  - Changes in conservation/land management
  - Artificial drainage



- Changes in land cover and land management shown to impact the hydrologic response of Midwestern watersheds - Tomer et al., 2005; Jukem et al., 2008; Mao and Cherkauer, 2009

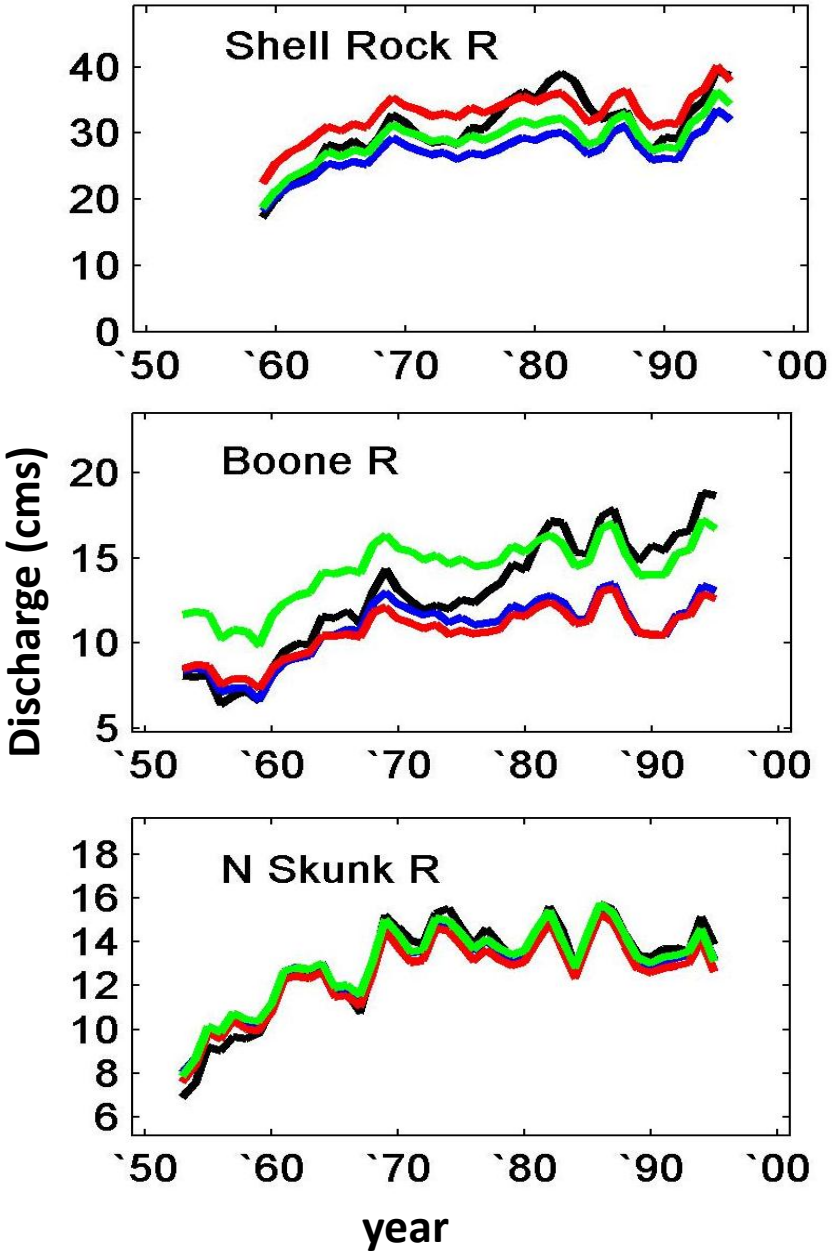
Photo : Mark Tomer, NSTL

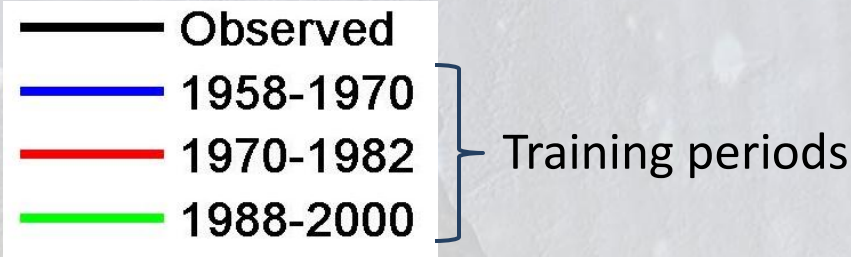
- Our model cannot explicitly account for changes in land use
  - implicitly accounted for in calibration
  - can we use these models to derive land use impacts?

- We ran the model for the historical time period (1948-2003) using each calibrated parameter set:
  - 1958-1970
  - 1970-1982
  - 1988-2000

watershed conditions for these time periods & 1948-2003 climate

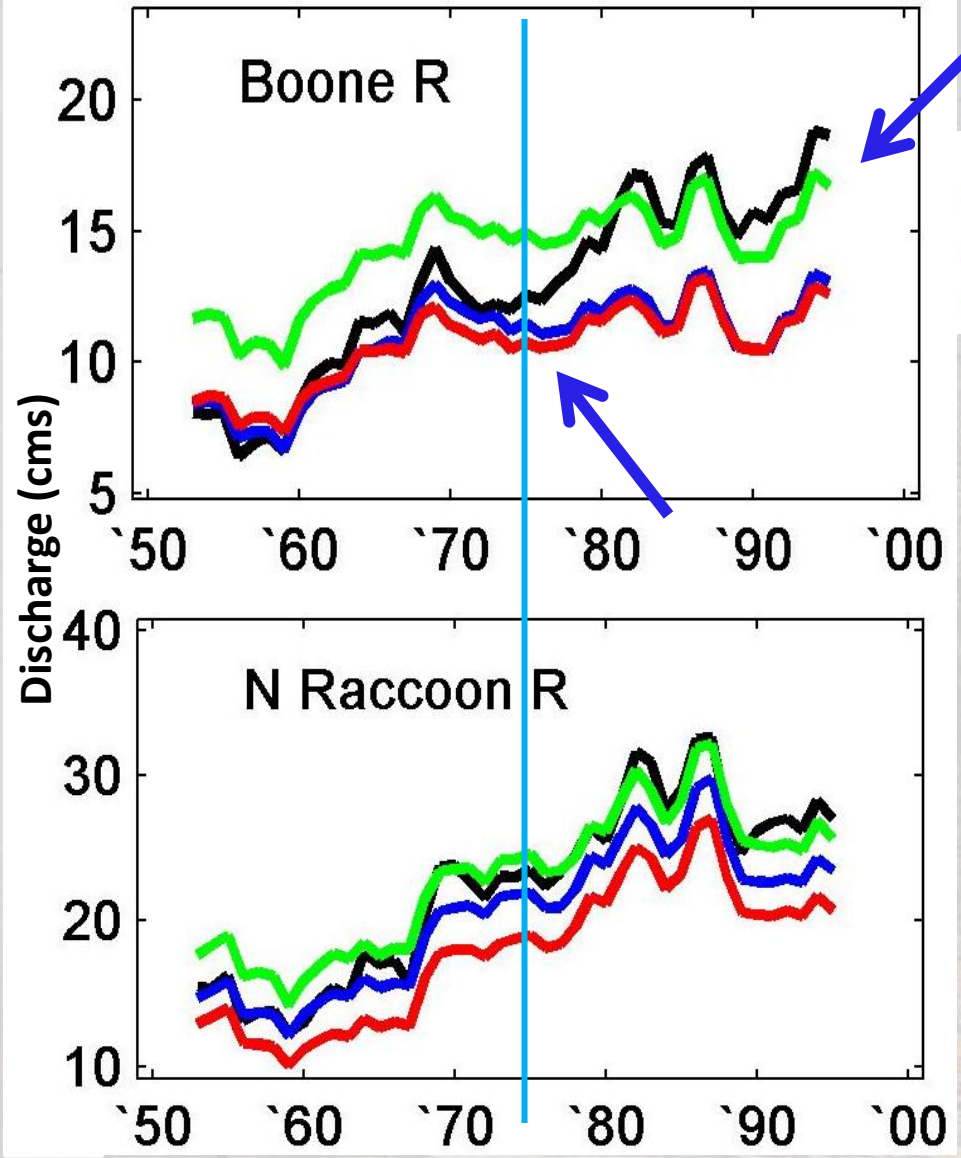
Simulated mean daily discharge





- Each test shows increasing streamflow in response to climate (regardless of training period)
- Different calibration periods shift running averages up and down

Simulated mean daily streamflow



Are we seeing land use impacts?

- Match to observations varies throughout period

  - *We would expect the best match to observations during the calibration period*

- Variations outside of calibration window due to changes in watershed?

Summary of modeled streamflow trends

	Positive MK trend (# sites)			Change in 10-yr running average		
	58-70	70-82	88-00	58-70	70-82	88-00
Mean daily flow	7	8	9	27%	43%	41%
High flow days	3	4	4	+1.5 days	+6 days	+20 days
Extreme fl. days	4	2	4	+1.7 days	+2 days	+19 days

- About as many basins with trends
- Not as many with significant trends
- Model sensitive to calibration period:
  - 88-00 many more extreme flow days
  - Does this indicate that under current watershed conditions we should expect more extreme events?

Summary and conclusions

- Our analysis shows while discharge is increasing, the number of extreme flow days per year is not.
  - Similar results were found for basins in Minnesota - Novotny and Stefan, 2007
  - Only a few U.S. sites had increasing maximum streamflows, more sites had increasing minimum and median streamflows - Lins and Slack, 1999; Douglas et al., 2000; McCabe and Wolock, 2002; Kalra et al., 2008
- We also found that the low flows were increasing
  - The popular idea that extremes in streamflow will become more frequent is **not supported by the evidence** that shows a decrease in the range between low and high flows - Lins and Slack, 2005

- Trends were seen in many of the variables analyzed, although they were not all statistically significant at a 10% level

- The strongest trends found for:
  - Increasing mean annual flow
  - Decreasing number of frozen ground days
  - Shift to earlier dates in cold season onset and conclusion
  - Increasing monthly mean soil moisture (esp. winter/spring)

- MK test did not reveal increasing trend in low flows in these basins
  - High variability
  - Need different statistical approaches?

K. Franz, 2010

- SAC modeling system responsive to long-term climate change
  - Some trends not as strong as in observed
  - Limited treatment of land use and evapotranspiration

- Model was evaluated for three calibration periods
  - Does land use explain some of the trends and discrepancies in observed and simulated streamflow?
  - How much does land use impact the ability to use the model for climate change analysis?
    - Potentially limited application for long-term analysis
  - Caveat: model calibration is sensitive to climate as well

Future Work

- Better correlation between changes in precipitation and streamflow, and land use and streamflow
- Conduct study using an ensemble of hydrologic models to assess the influence of model structure on soil moisture, snow and frozen ground results
- Test alternative methods for evaluating trends
- Investigate relationships between trends (i.e. frozen ground and winter soil moisture)

Acknowledgements

- Kayla Steffens, MS meteorology, 2010
- Center for Global and Regional Environmental Research, University of Iowa
- Iowa State University

Questions?

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