Does Urbanization Really Diminish Stream Baseflow? An Empirical Analysis for New Jersey

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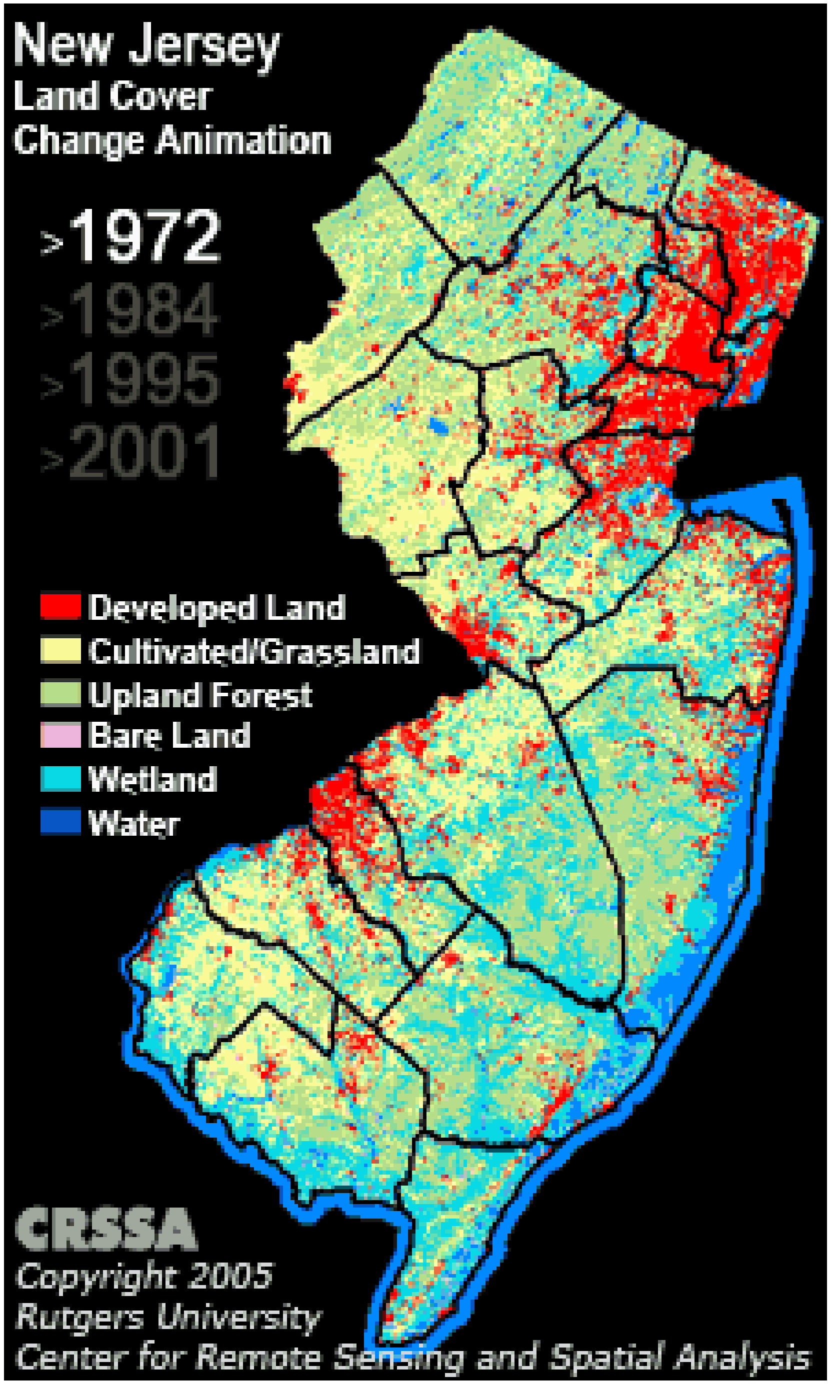
Motivation

- Much of US depends on surface water for water supply
- Droughts are common; perhaps to become more common and/or severe with climate change
- Streams and reservoirs rely on baseflow during drought
- Also, sufficient baseflow is critical to stream ecology
- Historically rural, water-supply watersheds have been/are urbanizing


New Jersey
Land Cover
Change Animation
>1972
>1984
>1995
>2001
Developed Land
Cultivated/Grassland
Upland Forest
Bare Land
Wetland
Water
CRSSA
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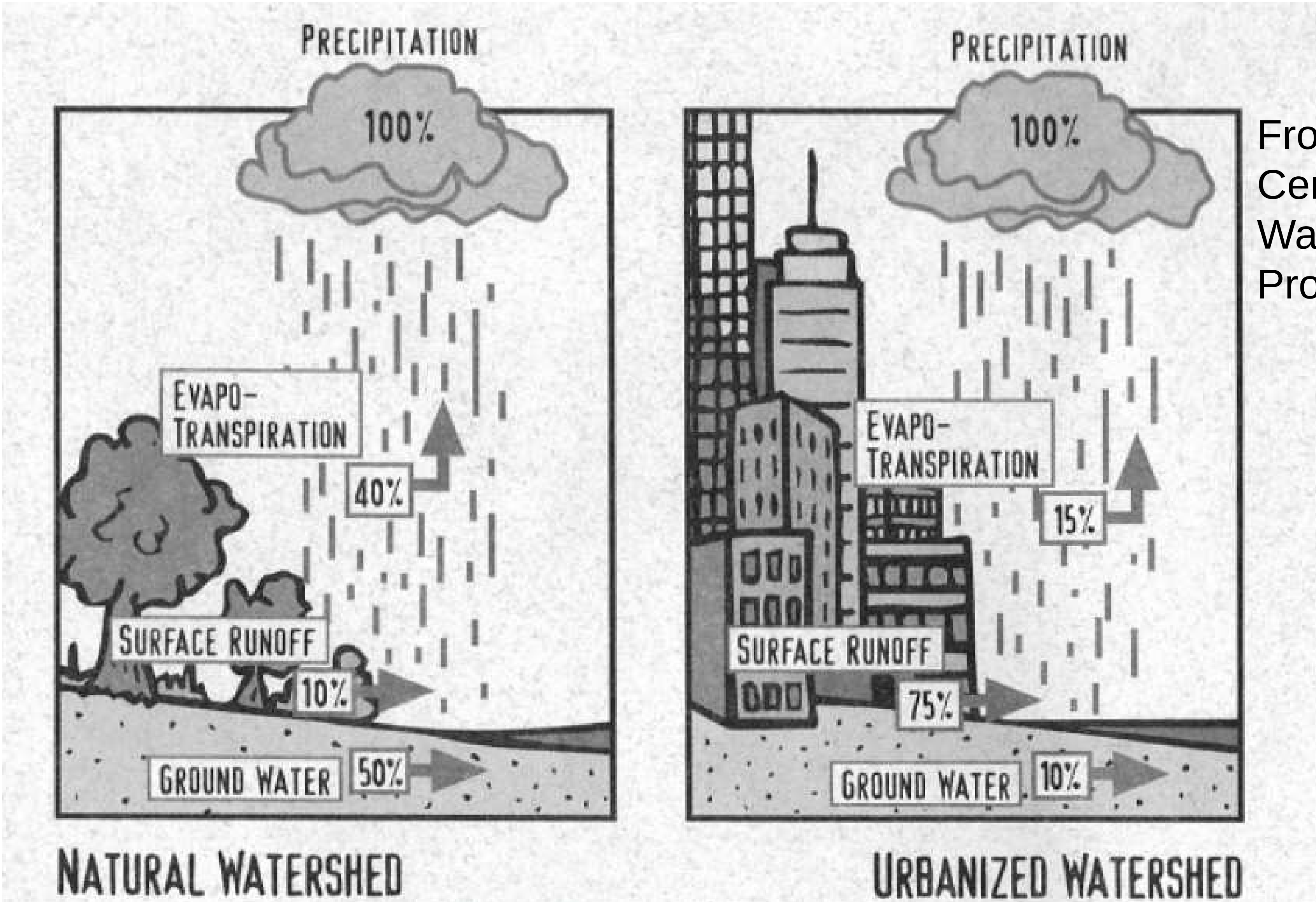
Rutgers University
Center for Remote Sensing and Spatial Analysis

Motivation (cont.)

- **Urbanization (replacing pervious surfaces with impervious, like pavement and rooftops) reduces infiltration, theoretically reducing baseflow**

- **Therefore, urbanization could therefore pose an important threat to surface water supply (and stream ecology), especially during drought**



From Center for Watershed Protection

So it should be a "no brainer" that urbanization is decreasing baseflow, right?

But urbanization is a lot more complex than just paving over the soil!

Several confounders to the theoretical idea urbanization decreases baseflow

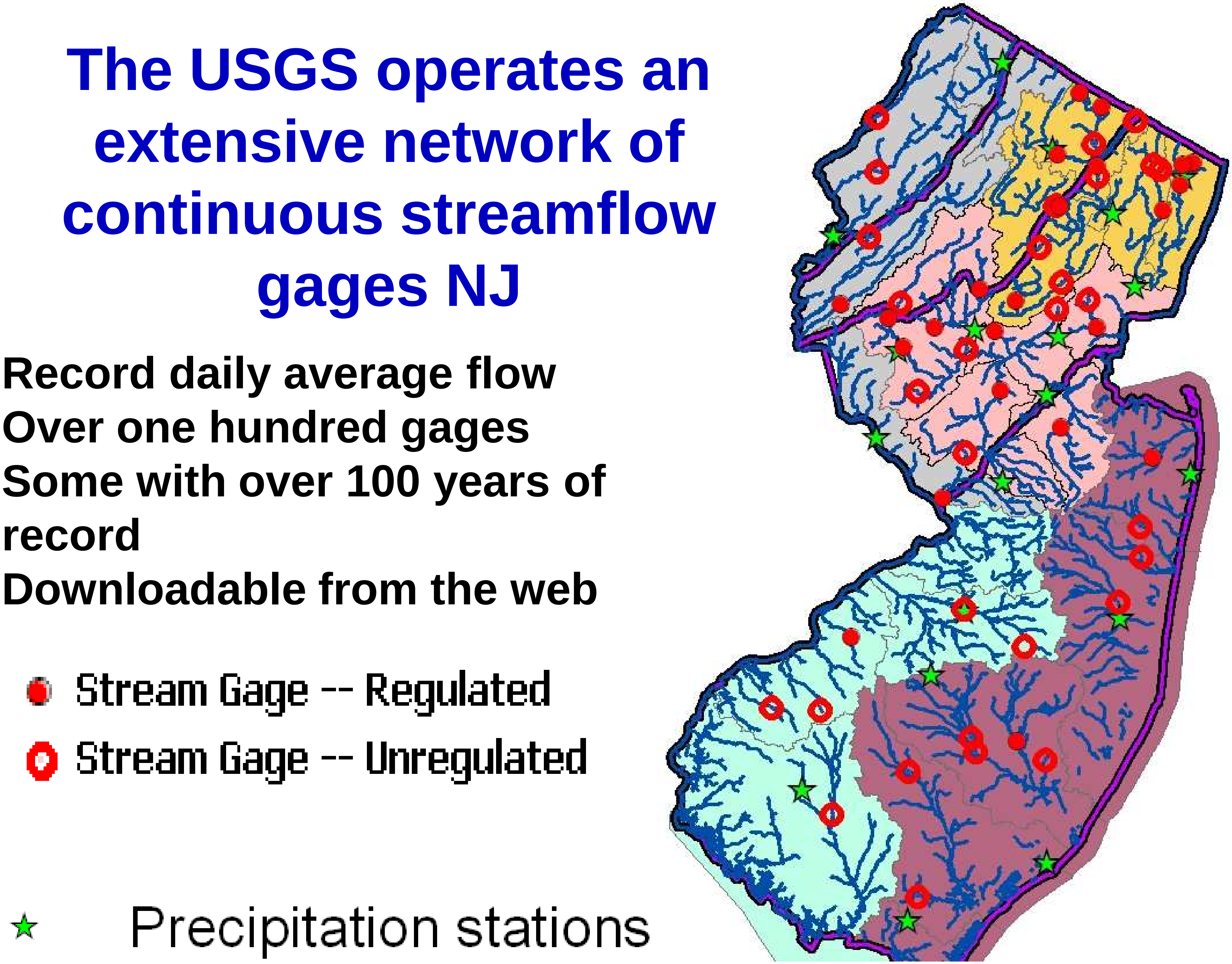
- **Septic systems recharge groundwater and wastewater treatment plant discharge to streams constantly; population growth would increase both**
- **Lawn watering can recharge groundwater; watering is likely to be high during drought**
- **Leaky sewers or water pipes can recharge groundwater**
- **This “artificial recharge” water may have originated from a significant distance (vertically or horizontally) from where it was withdrawn**

So, how can we tell if urbanization really reduces baseflow?

- **One (straightforward, empirical) approach: determine if there is a correlation between baseflow and imperviousness**

The USGS operates an extensive network of continuous streamflow gages NJ

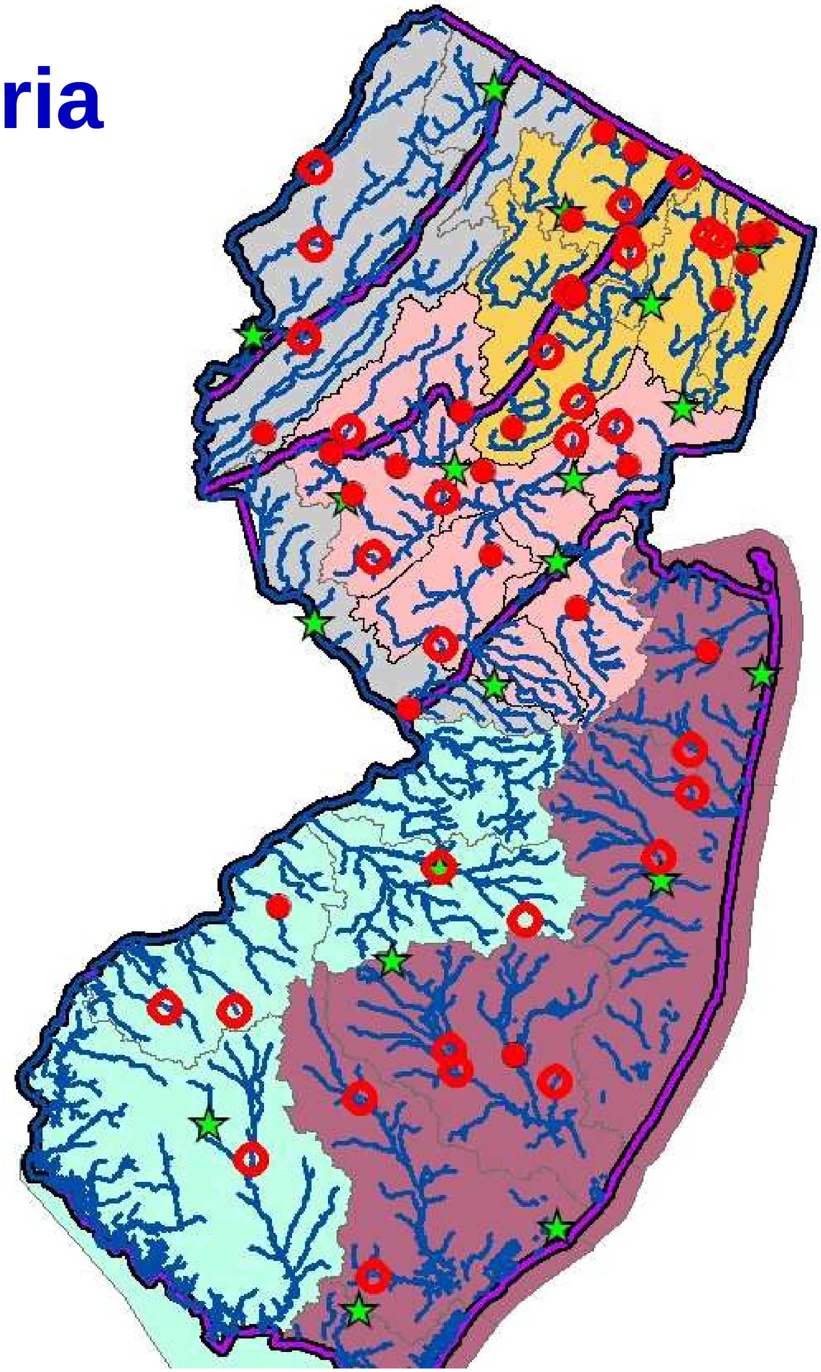
- Record daily average flow
- Over one hundred gages
- Some with over 100 years of record
- Downloadable from the web



Gauge selection criteria

- >25 years of record through 2005
- drainage area <350 sq mi
- 51 gages
  - 31 “unregulated”
  - 20 “regulated”

- 19 long-term precipitation gages

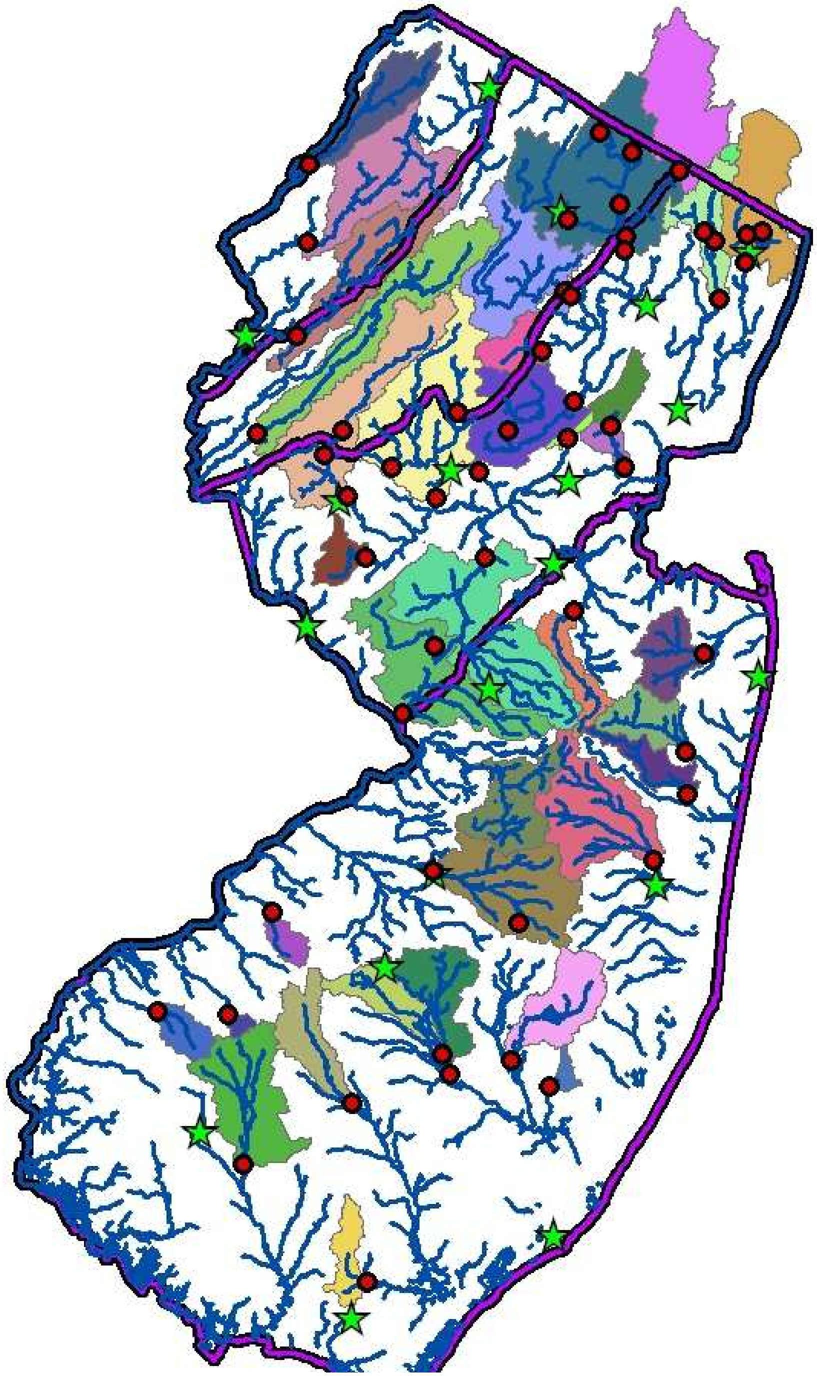


Stream Gage -- Regulated

Stream Gage -- Unregulated

Precipitation stations

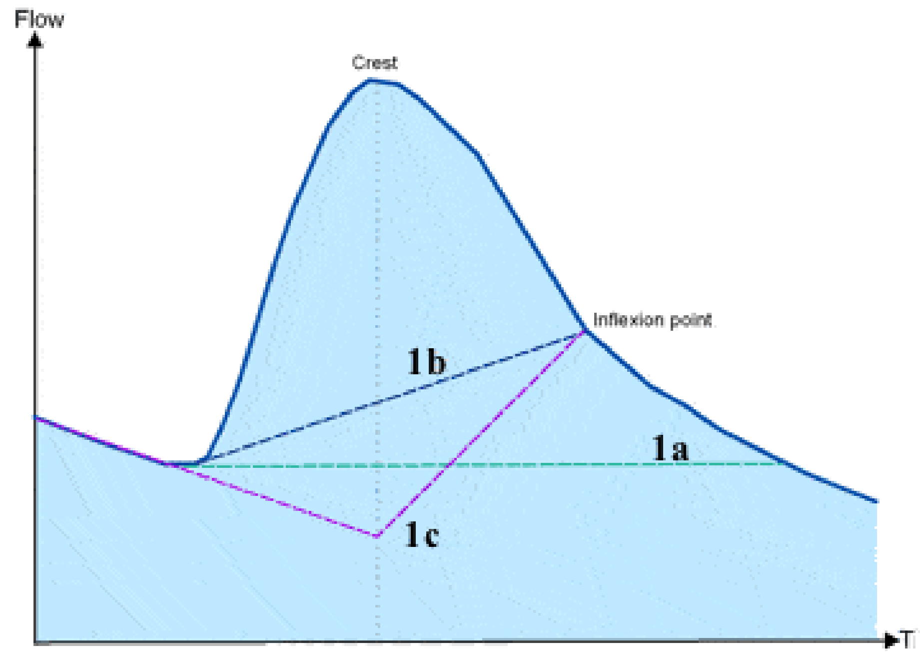
Watersheds of long-term stream gages



- Stream gages
- Precipitation stations

Need to separate measured daily flow into "stormflow" and "baseflow"

- **No definitive answer**
- **Conventional method: "hydrograph interpretation"**
- **Several automated implementations (HYSEP, PART)**



Another type of method:
digital filters, based on signal processing theory

$$b_t = \frac{(1-\beta)\times\alpha\times b_{t-1} + (1-\alpha)\times\beta\times Q_t}{1-\alpha\times\beta}$$

where,
α=filter parameter 1
β= filter parameter 2
b_t =filtered baseflow at the t time step
b_{t-1} =filtered baseflow at the t-1 time step.
Q_t = total streamflow at the t time step

- **"WHAT" is a web implementation of the Eckhardt digital filter**
- **compute daily baseflow; aggregate to annual**

Investigate Different Baseflow Metrics

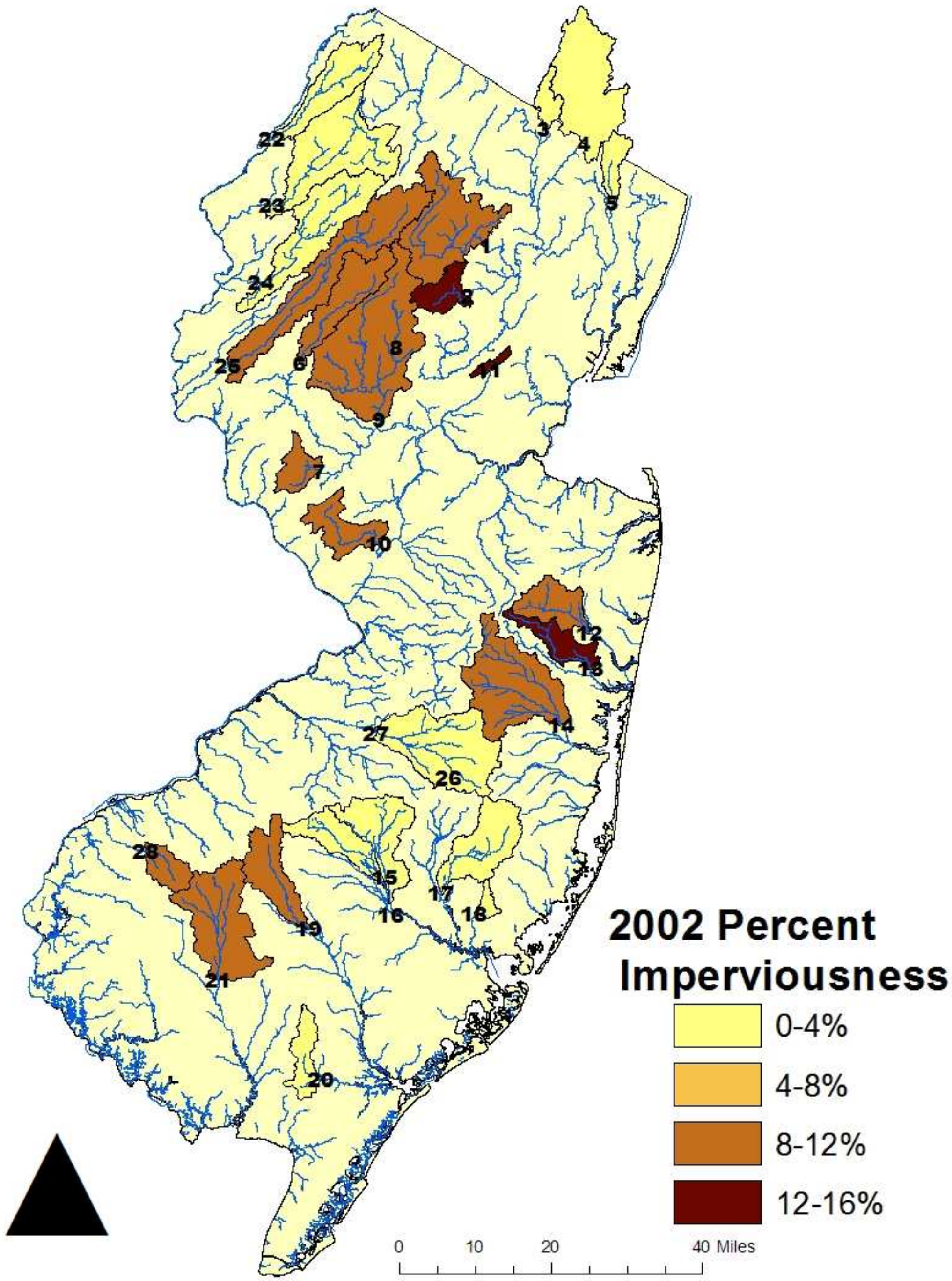
- **Annual baseflow (m^3/yr) divided by watershed area (BF, cm/yr)**
- **BF divided by precipitation (BF/P), percent of precipitation converted to baseflow (P available from NJ state climatologist)**
- **BF divided by total flow (BF/TF, aka baseflow index)**

Generate imperviousness timeseries for each unregulated, gaged, watersheds

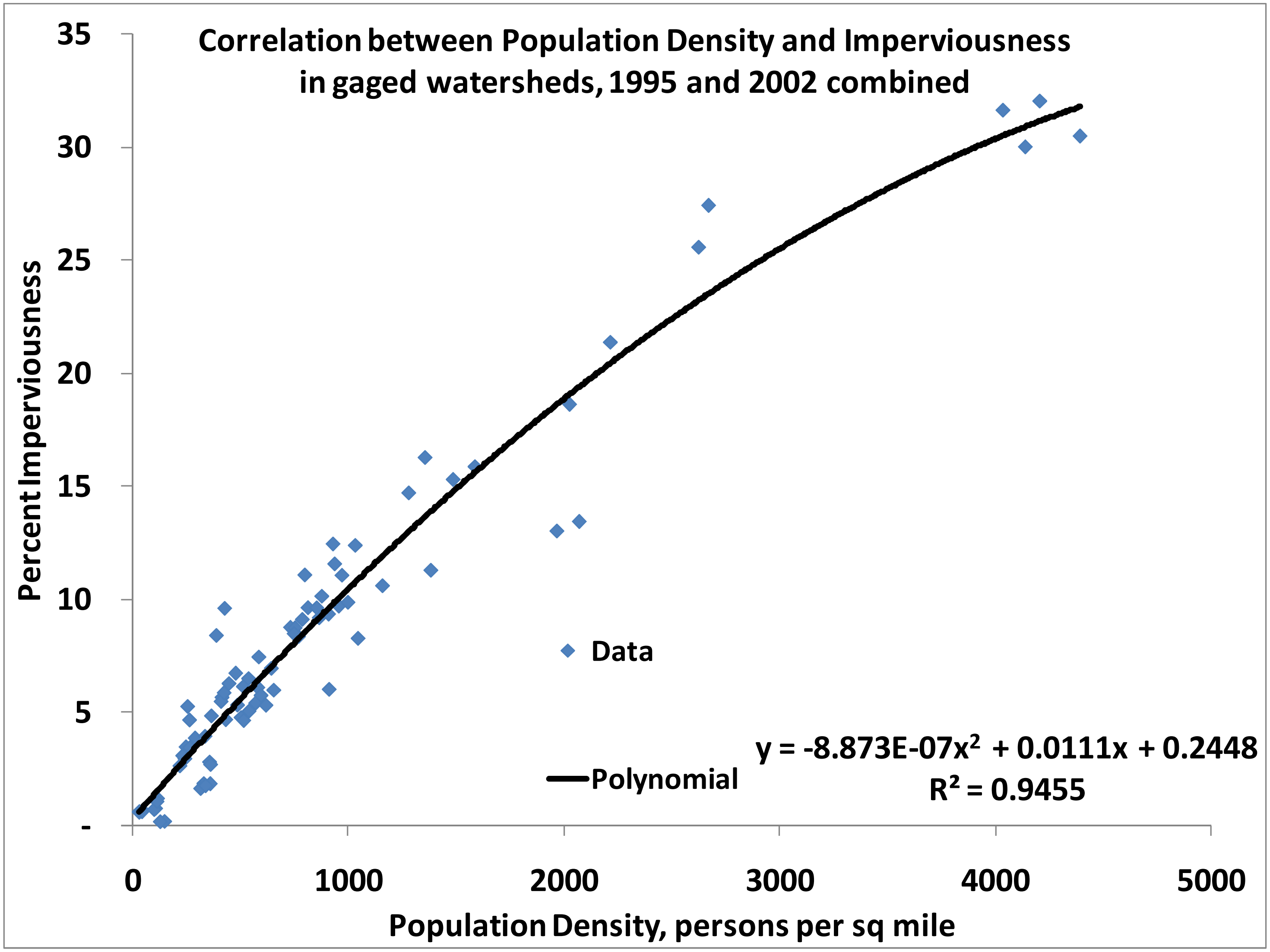
- Imperviousness for 2002 already computed by NJDEP. “Clip” for each watershed.
- Population density from US Census, 2000
- Correlate current (2002) imperviousness and population density
- Develop historical population density timeseries for each watershed using historical census data back to 1940
- Develop historical imperviousness timeseries by correlation with historical population

Percent Imperviousness of <u>unregulated</u> gaged watersheds, 2002

Source: NJDEP



Regression of Imperviousness of unregulated gaged watersheds vs. Population Density, 1995 and 2002



Imperviousness Ranges

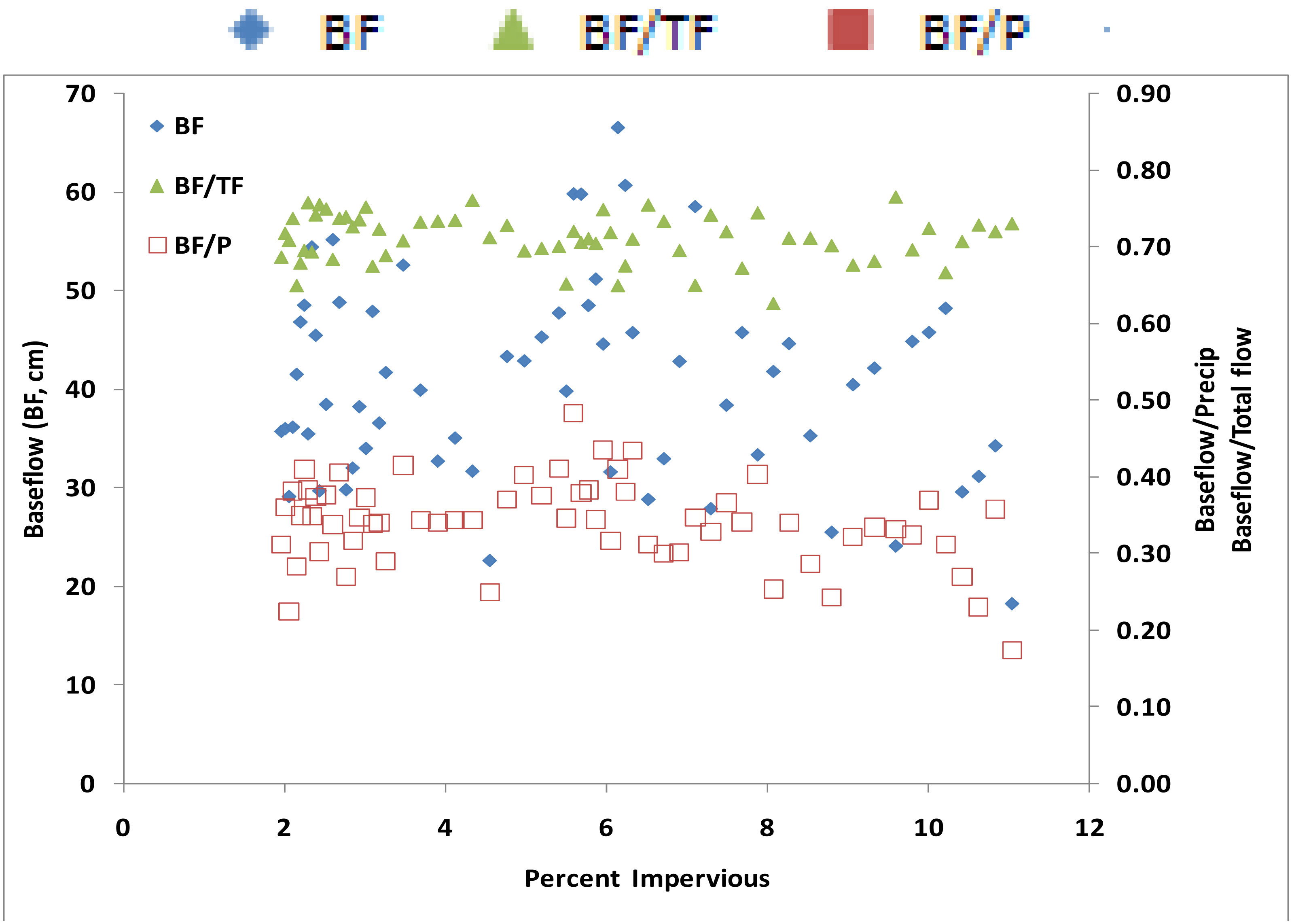
Station name	Start year	Min Imperv	Max Imperv	Difference
Flat Brook near Flatbrookville NJ	1940	0.4	0.7	0.3
Tuckahoe R at Head Of R NJ	1971	0.7	1.3	0.6
Batsto R at Batsto NJ	1940	0.4	1.5	1.1
Oswego R at Harrisville NJ	1940	0.1	1.5	1.4
Pequest R at Pequest NJ	1940	0.8	2.9	2.1
Stony Brook at Princeton NJ	1954	3.2	5.4	2.2
Mullica R near Batsto NJ	1958	1.2	3.6	2.3
Paulins Kill at Blairstown NJ	1940	1.1	3.4	2.3
North Branch Rancocas Cr at Pemberton NJ	1940	0.6	4.2	3.6
North Branch Raritan R near Far Hills NJ	1940	1.6	5.7	4.1
Maurice R at Norma NJ	1940	1.8	6.1	4.3
Neshanic R at Reaville NJ	1940	1.0	5.6	4.6
Musconetcong R near Bloomsbury NJ	1940	1.4	6.5	5.2
Toms R near Toms R NJ	1940	0.7	6.1	5.4
North Branch Raritan R near Raritan NJ	1940	1.3	6.7	5.4
South Branch Raritan R near High Bridge N	1940	1.1	7.4	6.4
Rockaway R Above Reservoir at Boonton NJ	1940	3.0	9.7	6.7
Great Egg Harbor R at Folsom NJ	1940	1.8	9.6	7.8
Whippany R at Morristown NJ	1940	7.0	15.9	8.9
Manasquan R at Squankum NJ	1940	2.0	11.0	9.1

Significant (p<=.10) correlations between imperviousness and baseflow metrics for unregulated basins with increases in imperviousness of >5 percentage points. N = negative correlation (agrees with theory); P = positive correlation (contradicts theory)

Station name	BF	BF/TF	BF/P	Start year	Min Imperv	Max Imperv	Difference
Musconetcong R near Bloomsbury NJ		N	P	1940	1.4	6.5	5.2
Toms R near Toms R NJ			N	1940	0.7	6.1	5.4
North Branch Raritan R near Raritan NJ				1940	1.3	6.7	5.4
South Branch Raritan R near High Bridge N				1940	1.1	7.4	6.4
Rockaway R Above Reservoir at Boonton NJ				1940	3.0	9.7	6.7
Great Egg Harbor R at Folsom NJ			N	1940	1.8	9.6	7.8
Whippany R at Morristown NJ	P		P	1940	7.0	15.9	8.9
Manasquan R at Squankum NJ			N	1940	2.0	11.0	9.1
Number Negative (agreeing with theory)	0	1	3				
Number Positive (contradicting theory)	1	0	2				
N = 8							

Correlation between baseflow and imperviousness using historical, concurrent baseflow and imperviousness

MANASQUAN RIVER AT SQUANKUM NJ, 1940-2005



CONCLUSIONS

•Only eight unregulated drainage areas with a sizeable (>5 percentage points) range of impervious values;none had over 10 points--limits ability to interpret results.
•Cases of negative correlation (agreeing with theory) were not common for any metric (0 for BF; 1 for BF/TF; 3 for BF/P)
•Number of cases of positive correlation were approximately equal to cases of negative correlation for all metrics

MAJOR CAVEATS

- Only a few of the examined watersheds showed significant ranges in percent imperviousness (all < 10%); how much range is needed?
- Impervious-pop. density relationship actually varies over time because household size has been decreasing – I underestimated imperviousness in 1940. Correcting this is not likely to change result.
- Correlation assumes each year is independent – is this correct for baseflow?
- Uncertain what constitutes an "unregulated" gage

Implication: One should not automatically assume urbanization leads to decreasing baseflow.

Evidently other factors can come into play

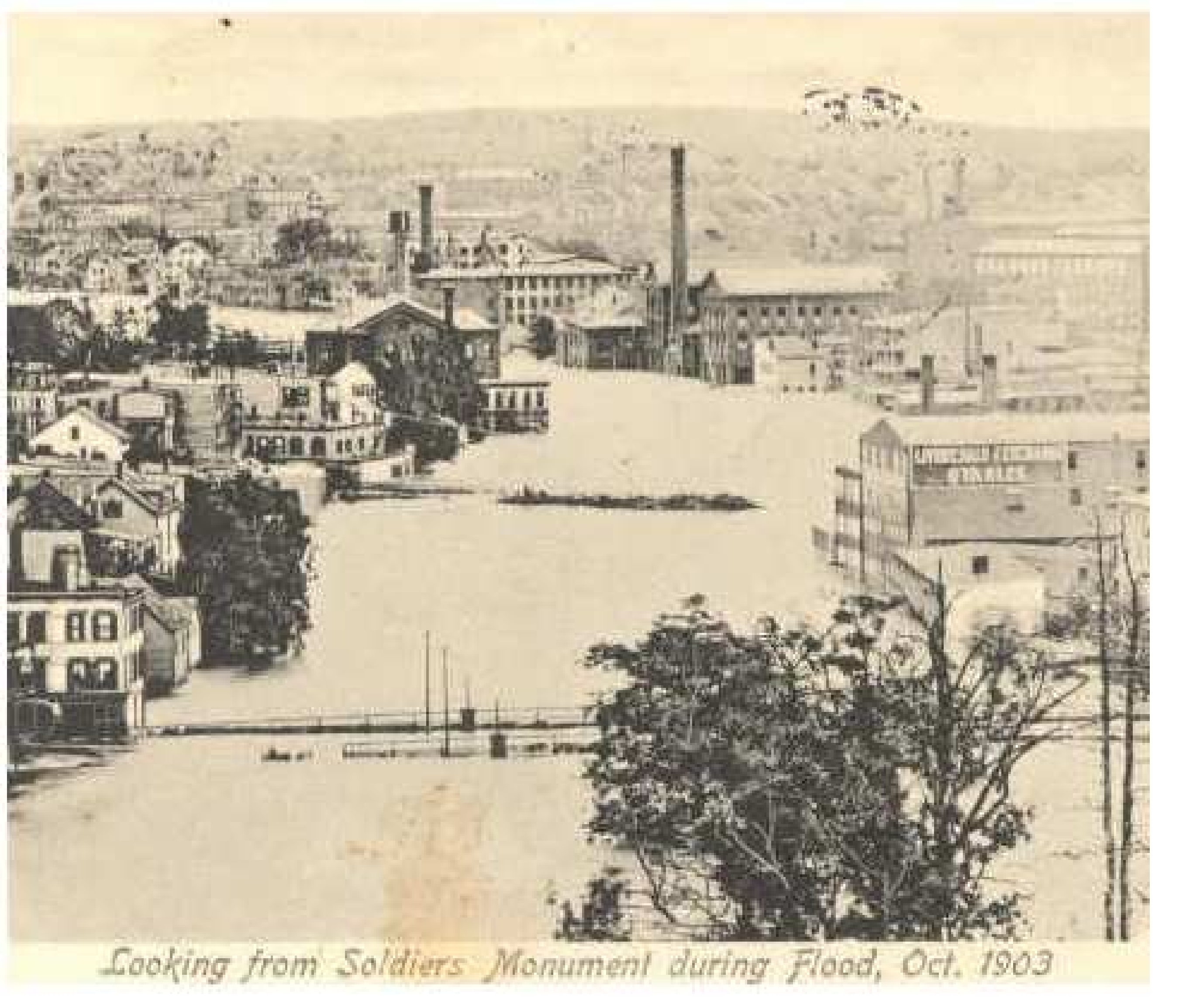
The low range of imperviousness values and the small number of watersheds tempers this conclusion.

Future work:

- account for changing household size

-use gages whose records end before 2005.

Flooding has been a recurring and severe problem for a looong time



On the Passaic River, NJ "Flood of Record": Oct, 1903

2nd largest flood: April, 1902

There is a perception of increased flooding

- **"We used to hear about a 100-year floodplain. Well, there's clearly no 100-year floodplain anymore." Pennsylvania Governor Ed Rendell, 7/9/2006**
- **"It seems chronic flooding is becoming more and more common in New Jersey." Michele Byers, New Jersey Conservation Foundation, Sept. 8, 2006**
- **"We are already experiencing 50 to100-year interval droughts and floods in 5 to 10-year cycles." Bill Wolfe, NJ Chapter of Public Employees for Environmental Responsibility, Feb 2008.**

Worsening Flooding ….

- Typically blamed on “over development”
- Now, climate change is also a suspect

So, it's a "no brainer" that development is making flooding worse, right?

NOT SO FAST!

- **During very large/long rain storms, pervious surfaces become saturated, and their hydrologic behavior <u>approaches</u> that of impervious surfaces**
- **Engineering controls are supposed to mitigate effects of development**

Goal: Empirically test the perception that flooding getting worse.

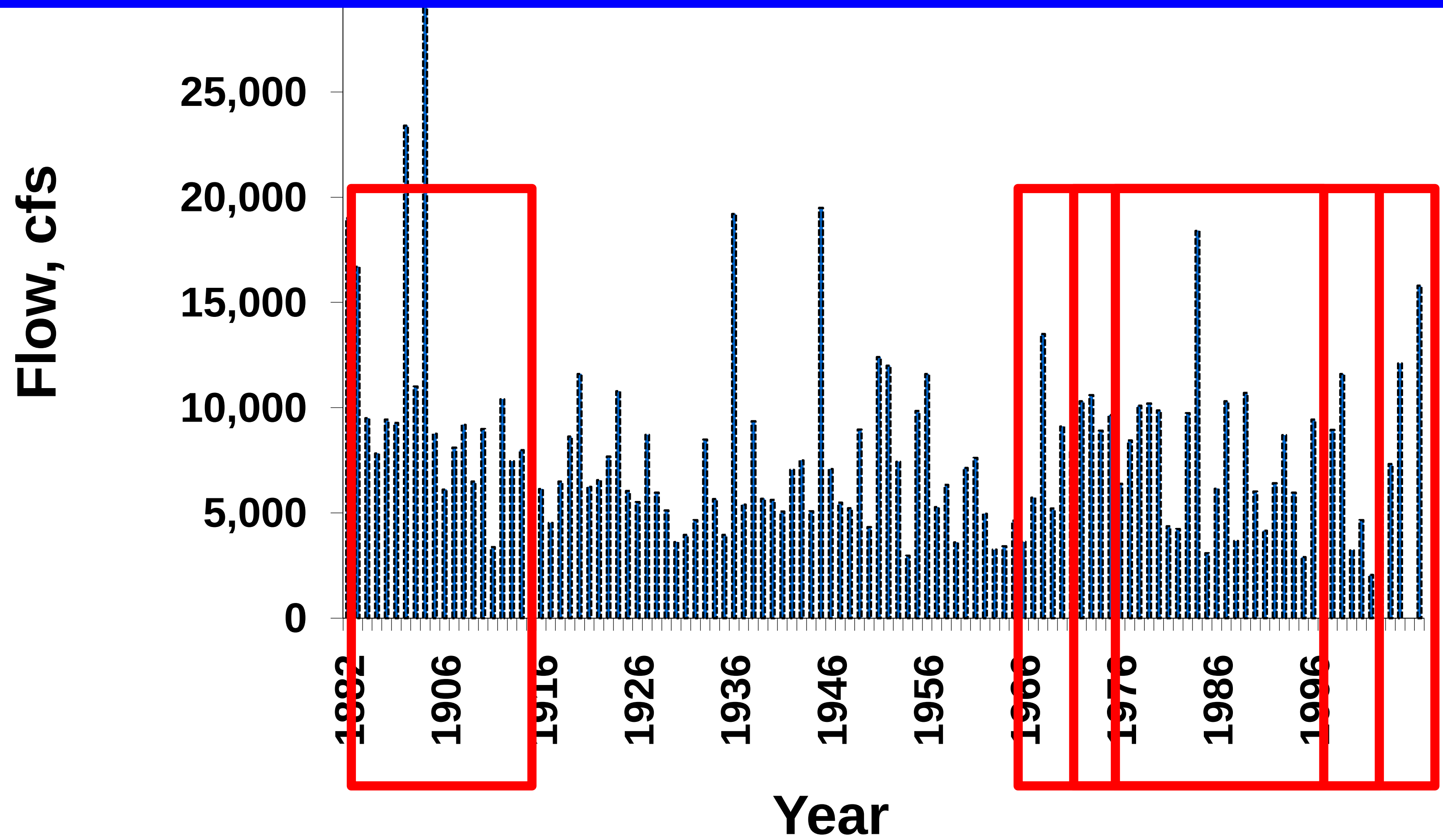
METHODS

- Collect measured peak annual flow timeseries at USGS stream gages with long records
- Compute flows associated with certain “return periods” in moving blocks of 30-years each
- Determine if there is a trend in flood flows using statistical tests
- “WORSE” = increasing trend in flow rate for given return period

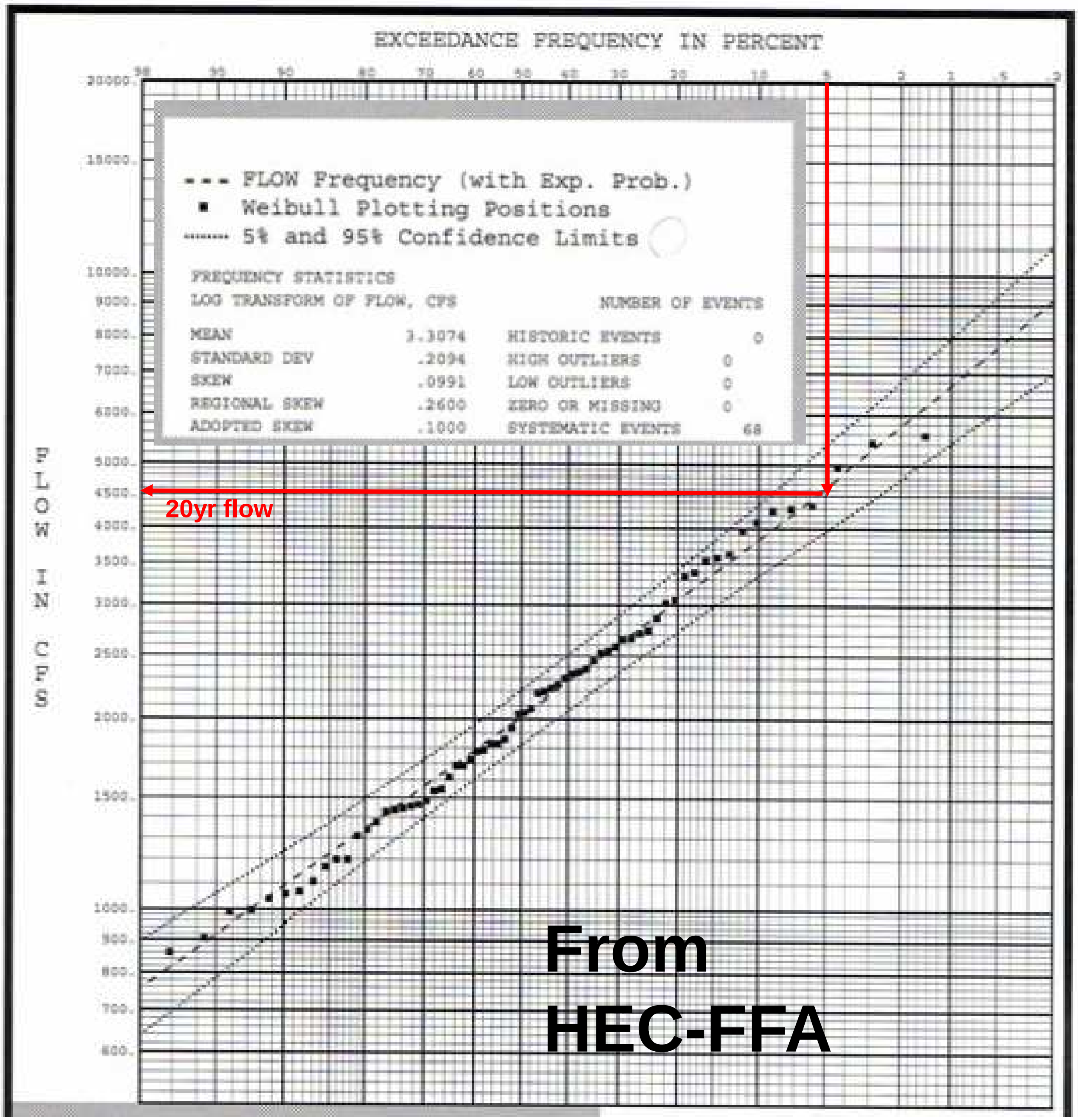
Compute flow values associated with various flood frequencies of moving 30-year blocks

- Flood frequency determination software developed by US Army Corps of Engineers Hydraulic Engineering Center

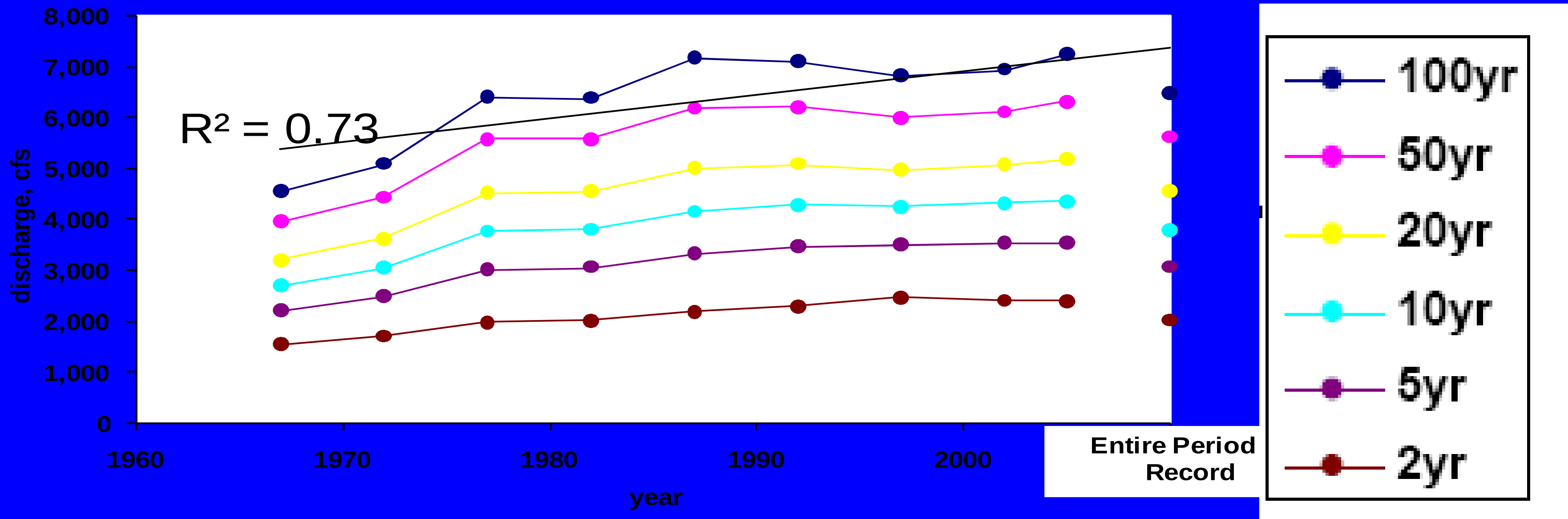
Compute flow values associated with various flood frequencies of moving 30-year blocks



Experience has shown a “log Pearson type III” distribution is the best representation of flood flow frequency distribution



Rockaway River Above Reservoir at Boonton, NJ



	100yr	50yr	20yr	10yr	5yr	2yr
slope	1.0%	1.0%	1.0%	1.1%	1.1%	1.2%
R squared	0.73	0.76	0.79	0.83	0.86	0.92
n	9	9	9	9	9	9
deg freedom	7	7	7	7	7	7
p value	0.0032	0.0023	0.0012	0.0007	0.0003	0.0000
95%-certain trend?	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**

Overall Results: Percent of Gages (n=53) with statistically significant trends

Return Period	2	5	10	20	50	100
Percent of gages with significant …						
Increasing Trend	72%	60%	57%	57%	43%	38%
Decreasing Trend	11%	13%	8%	9%	11%	11%
Ratio, increaing to decreasing	6.3	4.6	7.5	6.0	3.8	3.3

Percent of Gages with <2% imperviousness in 2002 (n=11) with statistically significant trends

	Return period					
	2 year	5 YR	10 year	20 year	50 year	100 year
Percent of gages with …	Percent of gages in category					
No trend	18%	36%	73%	64%	73%	73%
Increasing trend	45%	27%	18%	18%	9%	9%
Decreasing trend	36%	36%	9%	18%	18%	18%
Ratio, increasing to decreasing	1.3	0.8	2.0	1.0	0.5	0.5

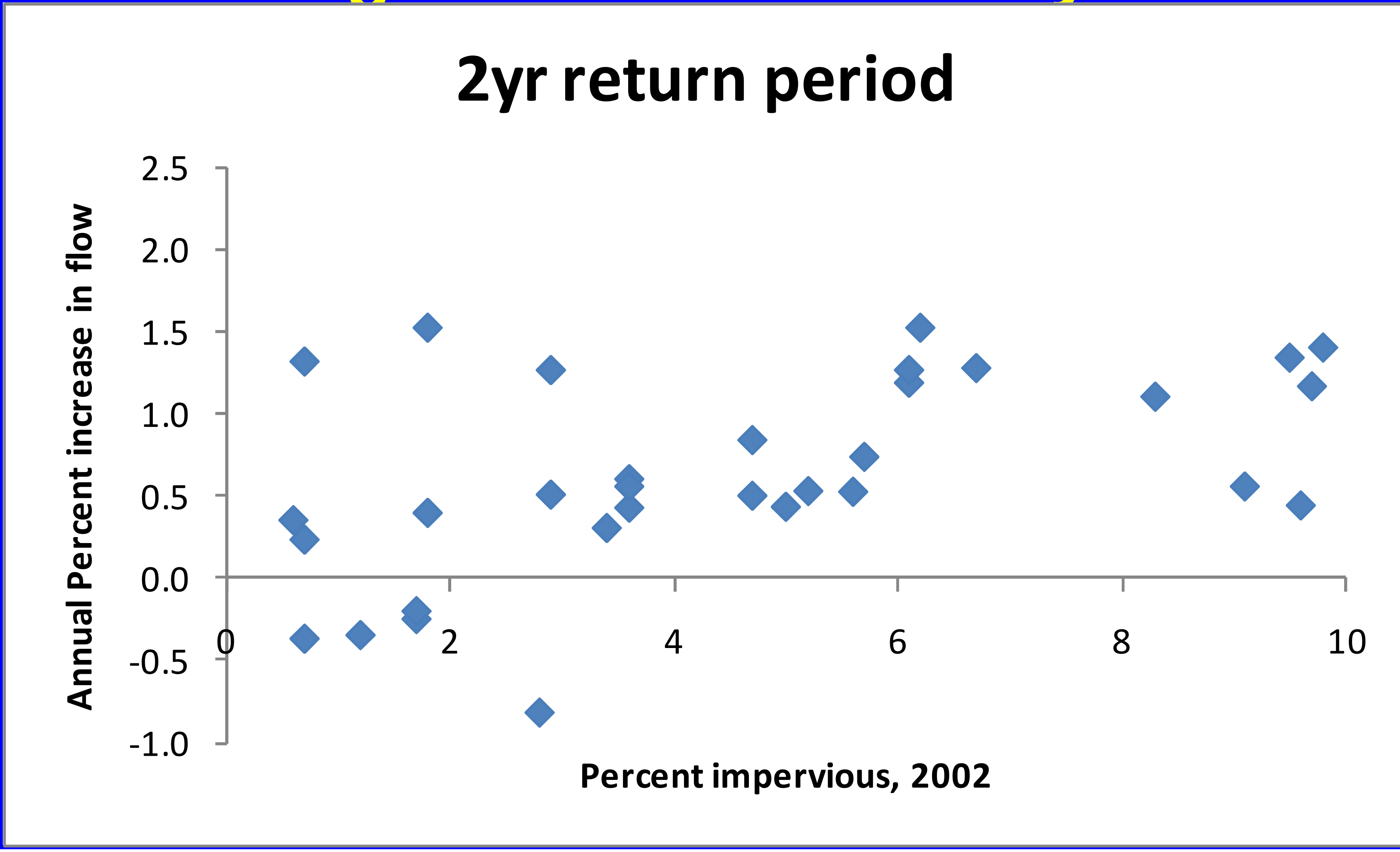
Conclusions

1. **Between 38% and 72% of the 53 gages showed significant increasing linear trends, for the 100 year flow to 2-year flow respectively.**
2. **Increasing trends outnumbered decreasing trends for all return periods (3-7 times more)**
3. **CAVEAT -- inherent rarity of large-return-period flows makes trend detection more difficult. Also, presence of just one or two very large events in a 30-year block has a large effect on Q-100yr and Q-50yr.**
4. **Increasing trends were less common/dominant in watershed that experienced no urbanization**
5. ***By this analysis method, flood flows do appear to be increasing in much of New Jersey, and the increase appears to be correlated with urbanization***

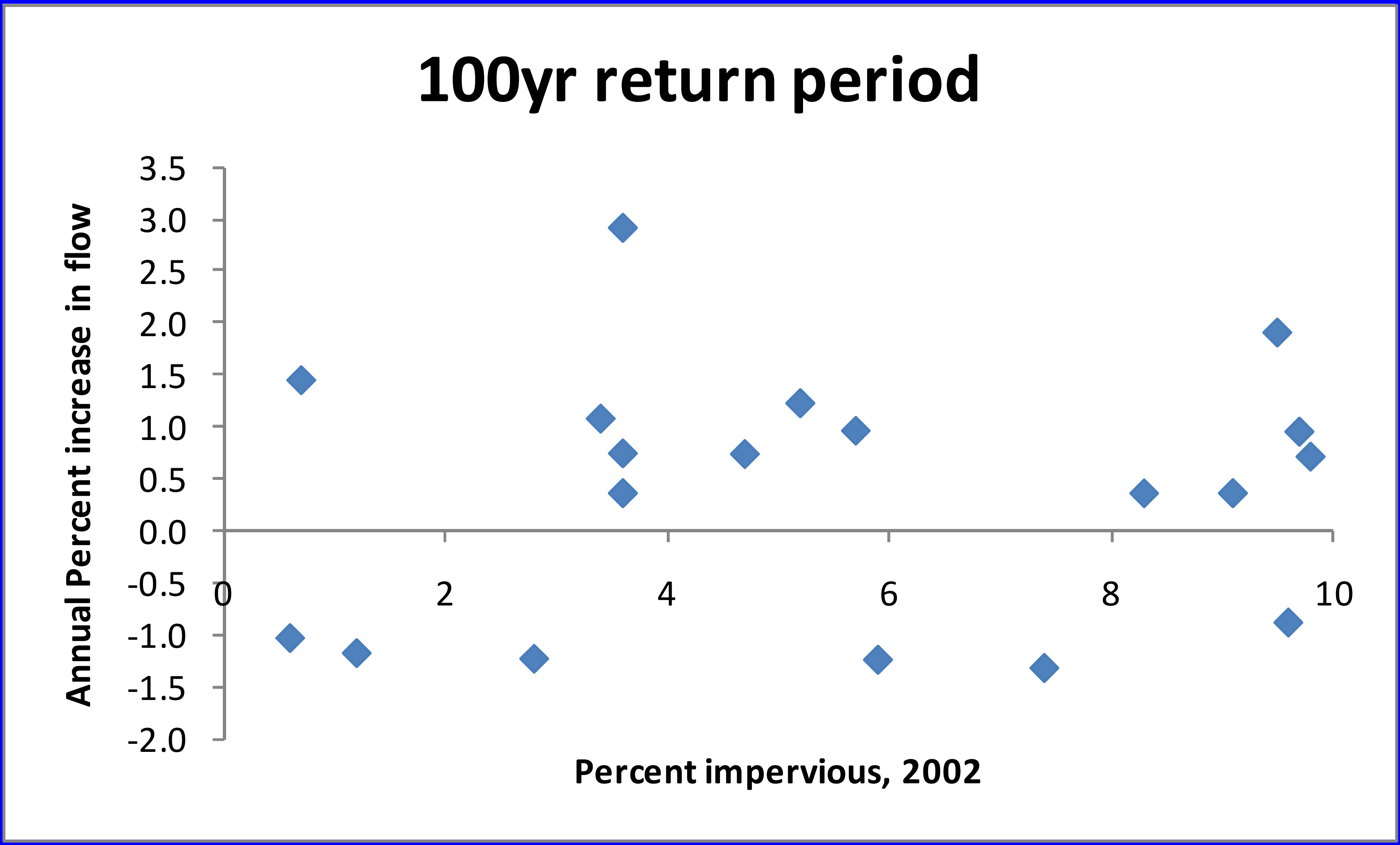
Thank you

Questions, Comments, Suggestions?

Rate of flow increase vs. imperviousness in 2002, significant trends only



Rate of flow increase vs. imperviousness in 2002, significant trends only



Percentage of gages with decreasing and increasing trend

(p=.05; 95% confidence level;)

METRIC	Unregulated gages n=31		Regulated gages n=22	
	Inc	Dec	Inc	Dec
BF	13%	6%	18%	36%
BF/P	16%	23%	18%	14%
BF/TF	13%	13%	14%	18%
AMDF	16%	13%	27%	18%

FOR UNREGULATED GAGES

- **Good news: Absolute baseflow (BF, cm): increasers outnumber decreasers 2 to 1**
- **Normalizing by P → 4-fold increase in decreasers**
- **For BF/TF Increasers ~= Decreasers**

Percentage of gages with decreasing and increasing trend

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BF	13%	6%	18%	36%
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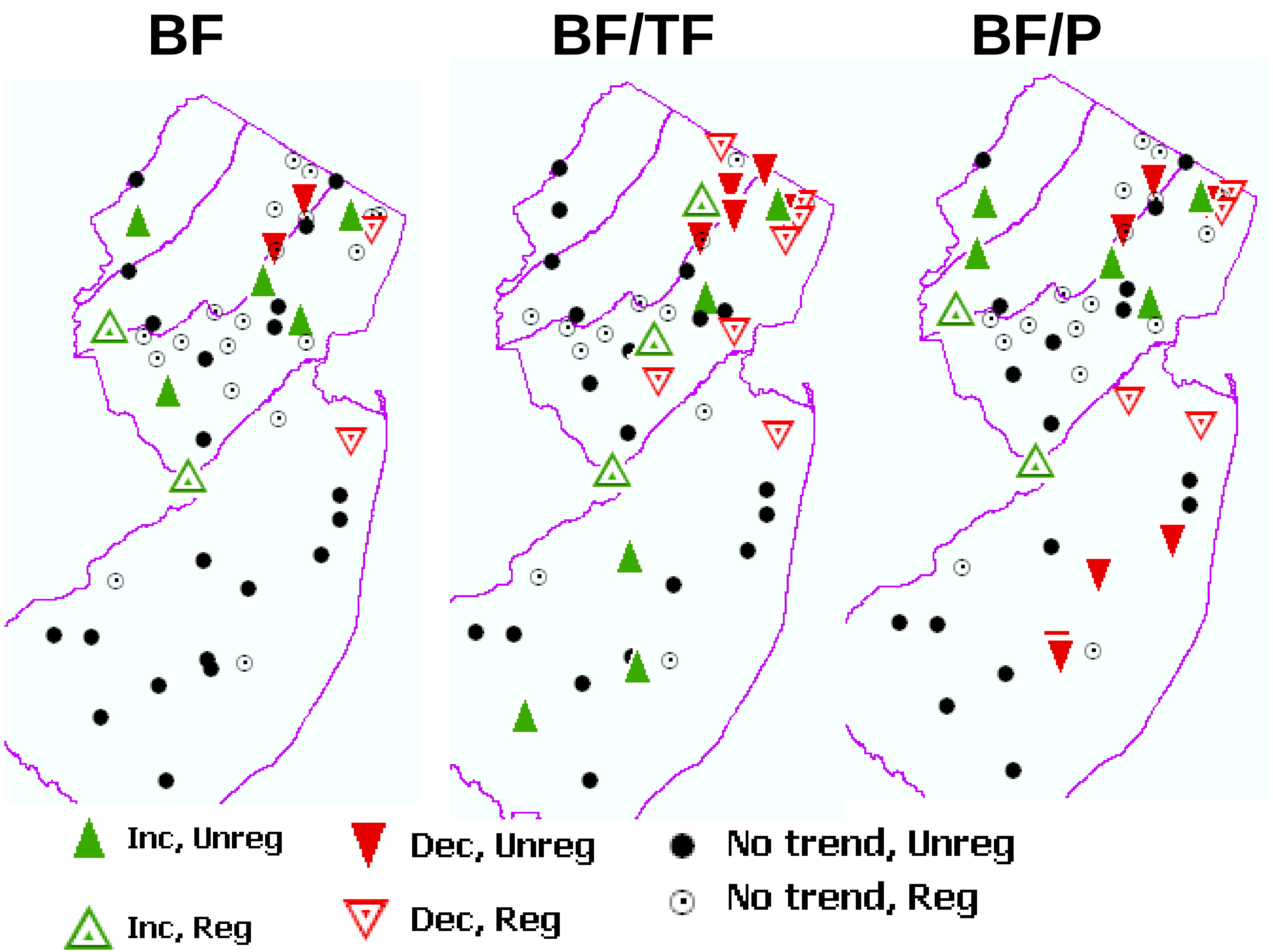
AMDF	16%	13%	27%	18%

FOR <u>REGULATED</u> GAGES

- **Absolute baseflow, decreasers < increasers**
- **BF/TF and BF/P: decreasers > increasers**

  Why? Increasing withdrawals?



BF
BF/TF
BF/P
Inc, Unreg
Inc, Reg
Dec, Unreg
Dec, Reg
No trend, Unreg
No trend, Reg

Percentage of gages with decreasing and increasing trend

(p=.05; 95% confidence level;)

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	Inc	Dec	Inc	Dec
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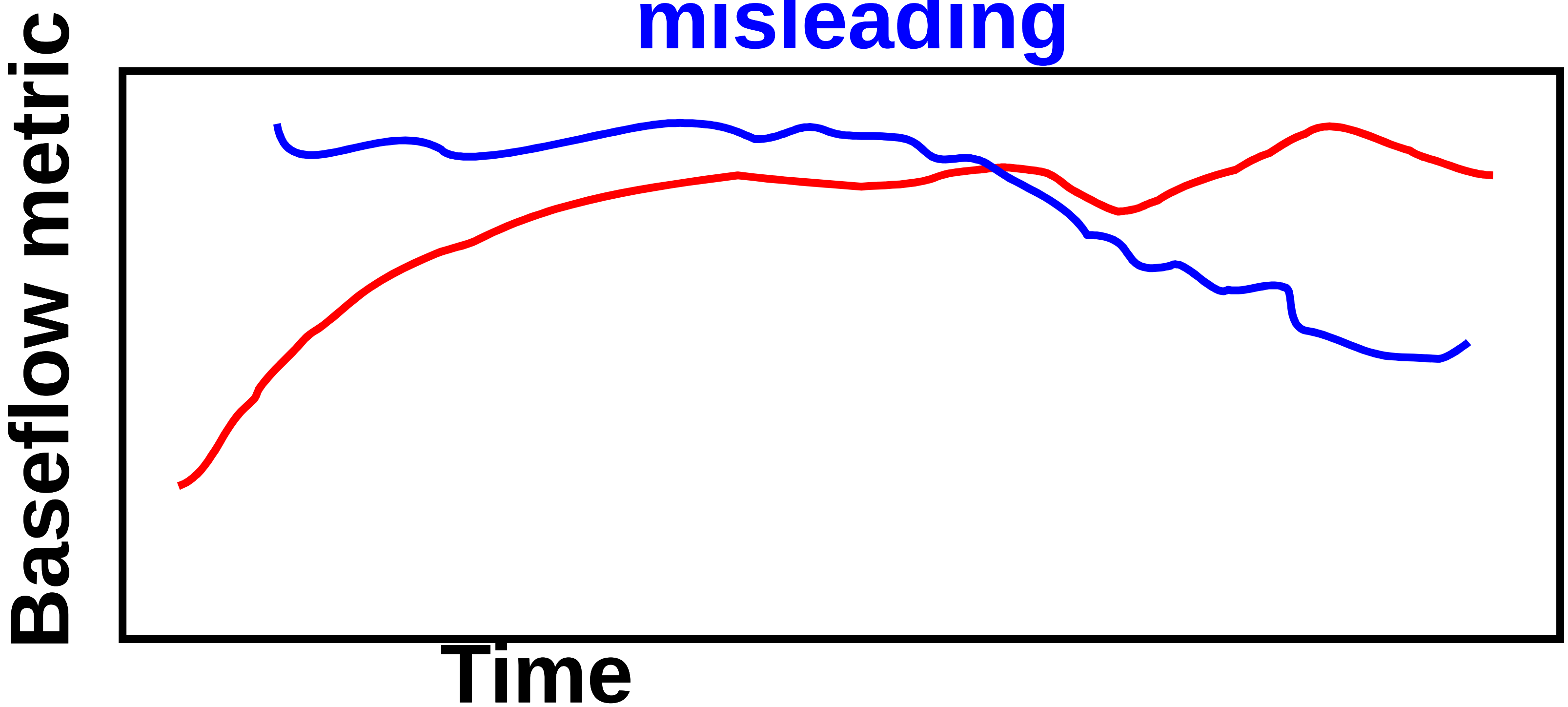
Note sizeable differences in results among metrics – each metric is measuring something different

Investigate for Trends in each Metric Using the Mann-Kendall Test

- **Commonly used for trend detection in hydrology**
- **Each value is compared to all successive values**
- **The direction of change (increase, decrease or no change) is determined for each pair of values (magnitude of change is not considered)**
- **If (number of increases) >> (number of decreases), then statistically “significant” increasing trend**
- **If (number of increases) << (number of decreases), then statistically “significant” decreasing trend**

If you examine only the whole record, the trend detection results might be misleading



So, we investigated successive blocks of years, adding 10-year increments, moving backwards in time from 2005

Percentage of gages with decreasing and increasing trend

(p=.10, ie., 90% certainty of level)

Start Year	Number of years	Number of gages	BF		BF/TF		BF/P	
			Inc	Dec	Inc	Dec	Inc	Dec
1996	10	24	0%	4%	13%	0%	0%	0%
1986	20	28	0%	4%	4%	4%	4%	7%
1976	30	26	0%	0%	0%	0%	0%	12%
1966	40	24	0%	4%	8%	0%	0%	25%
1956	50	23	0%	4%	9%	13%	13%	39%
1946	60	19	0%	0%	11%	21%	16%	42%

CONCLUSIONS

- **Few trends in baseflow proper**
- **Trends in BF/TF balanced between increasing and decreasing**
- **In last 20 years, no many trends in BF/P, but trends decreasing trends are more common over longer time periods**