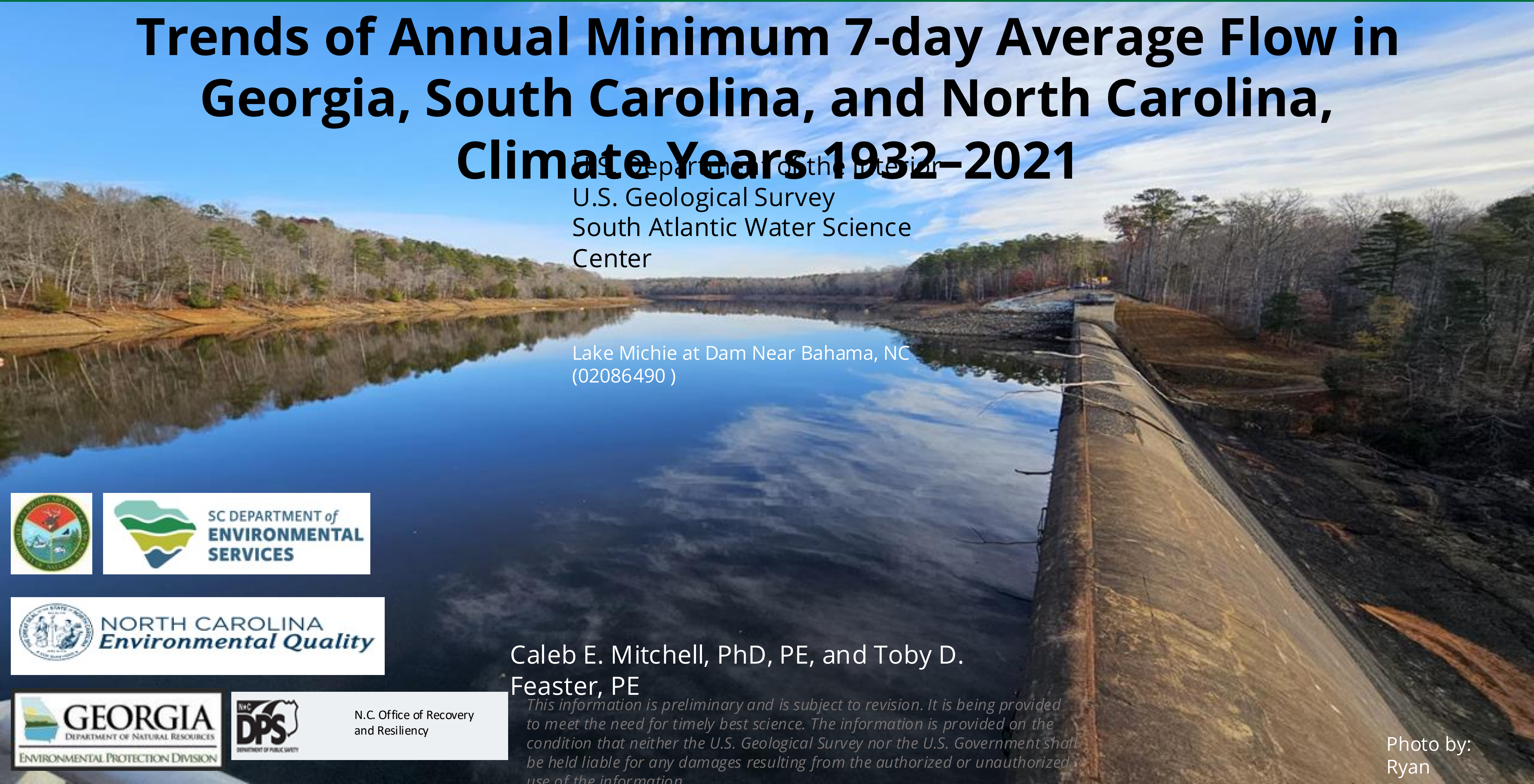
Trends of Annual Minimum 7-day Average Flow in Georgia, South Carolina, and North Carolina, Climate Years 1932–2021

U.S. Department of the Interior
U.S. Geological Survey
South Atlantic Water Science Center



Lake Michie at Dam Near Bahama, NC
(02086490)

SC DEPARTMENT of
ENVIRONMENTAL
SERVICES

NORTH CAROLINA
Environmental Quality

GEORGIA
DEPARTMENT OF NATURAL RESOURCES
ENVIRONMENTAL PROTECTION DIVISION

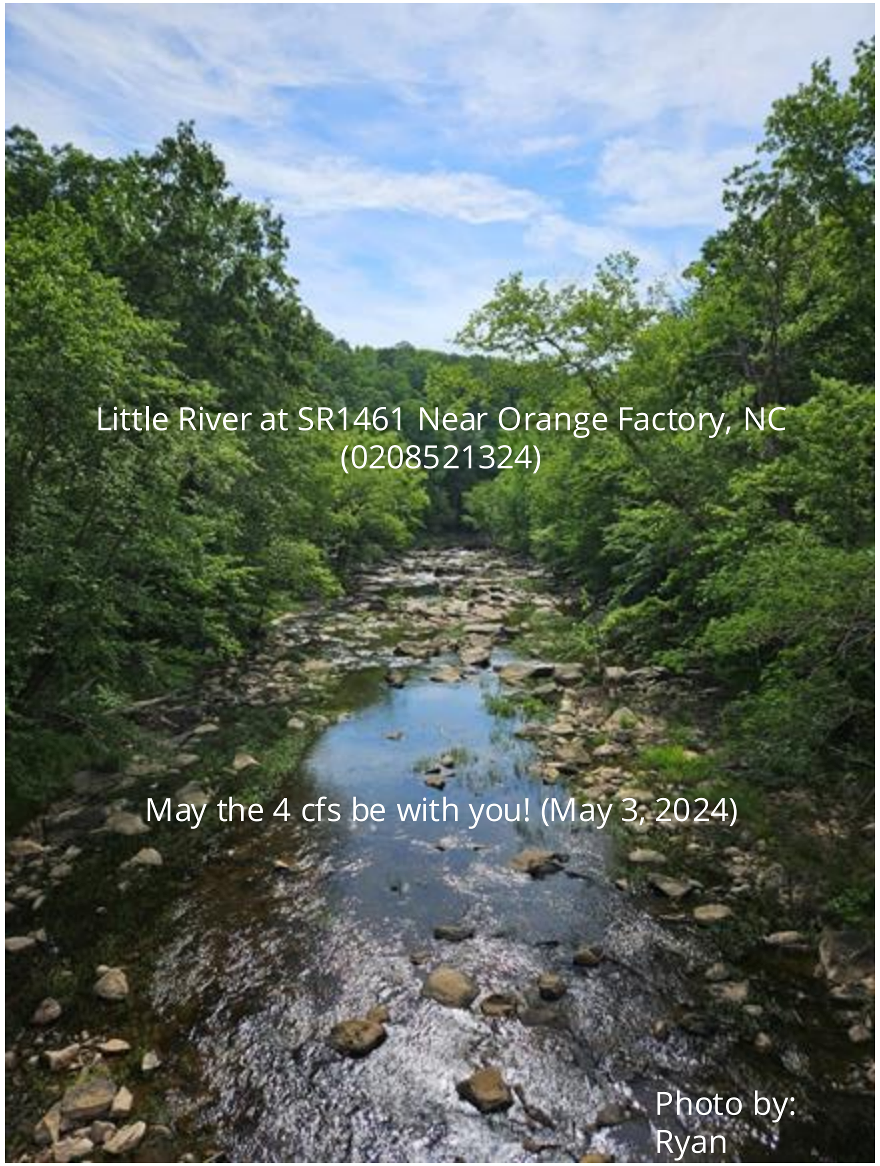
N.C. Office of Recovery
and Resiliency

Caleb E. Mitchell, PhD, PE, and Toby D. Feaster, PE

Photo by:
Ryan

Presentation Outline

- Introduction
    - Low flow and its impacts to aquatic ecosystems
    - Can we assume stationarity?
- Methods
    - Streamgages in Georgia, South Carolina, and North Carolina with >30-yr record
    - Modified Mann-Kendall Theil Sen Slope
- Results and Discussion
    - Temperature, Precipitation, Minimum 7-day Average Streamflow
- Conclusions
    - Balance the needs of aquatic life with the needs of humans

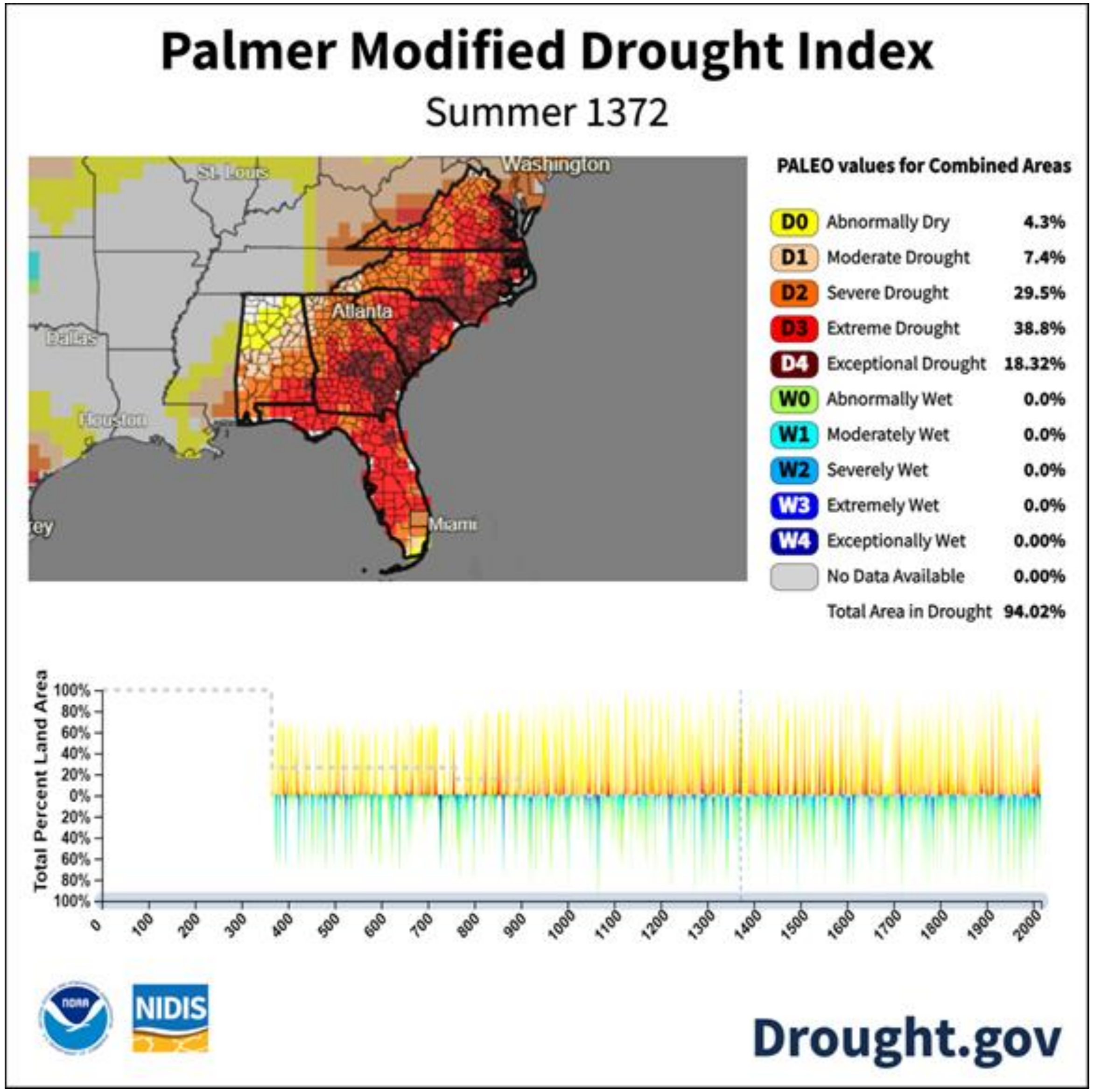


Little River at SR1461 Near Orange Factory, NC (0208521324)

May the 4 cfs be with you! (May 3, 2024)

Photo by: Ryan

Historical Perspective

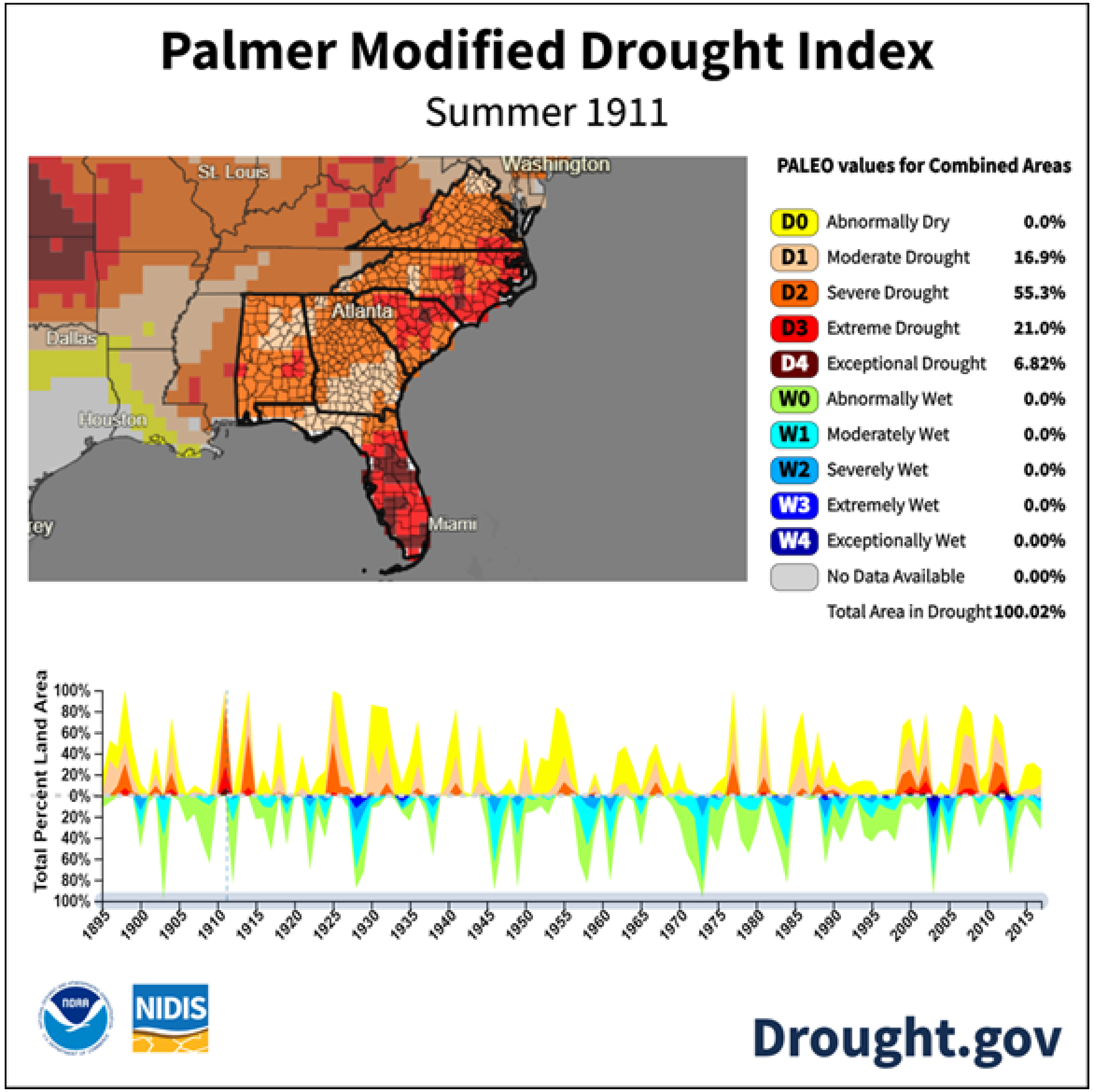


Palmer Modified Drought Index

Summer 1372

PALEO values for Combined Areas

D0	Abnormally Dry	4.3%
D1	Moderate Drought	7.4%
D2	Severe Drought	29.5%
D3	Extreme Drought	38.8%
D4	Exceptional Drought	18.32%
W0	Abnormally Wet	0.0%
W1	Moderately Wet	0.0%
W2	Severely Wet	0.0%
W3	Extremely Wet	0.0%
W4	Exceptionally Wet	0.00%
	No Data Available	0.00%
	Total Area in Drought	94.02%



Palmer Modified Drought Index

Summer 1911

PALEO values for Combined Areas

D0	Abnormally Dry	0.0%
D1	Moderate Drought	16.9%
D2	Severe Drought	55.3%
D3	Extreme Drought	21.0%
D4	Exceptional Drought	6.82%
W0	Abnormally Wet	0.0%
W1	Moderately Wet	0.0%
W2	Severely Wet	0.0%
W3	Extremely Wet	0.0%
W4	Exceptionally Wet	0.00%
	No Data Available	0.00%
	Total Area in Drought	100.02%

What do we mean by “low flow”?

- Low flow is referred to as base flow or “sustained fair-weather flow”
- Composed largely of groundwater flow from surficial aquifers to streams
- Dependent on topographic, geologic, and climatic conditions
- Low flows are a seasonally influenced phenomenon, and in the Southeast, tend to occur most frequently in the late summer or early fall (end growing season)

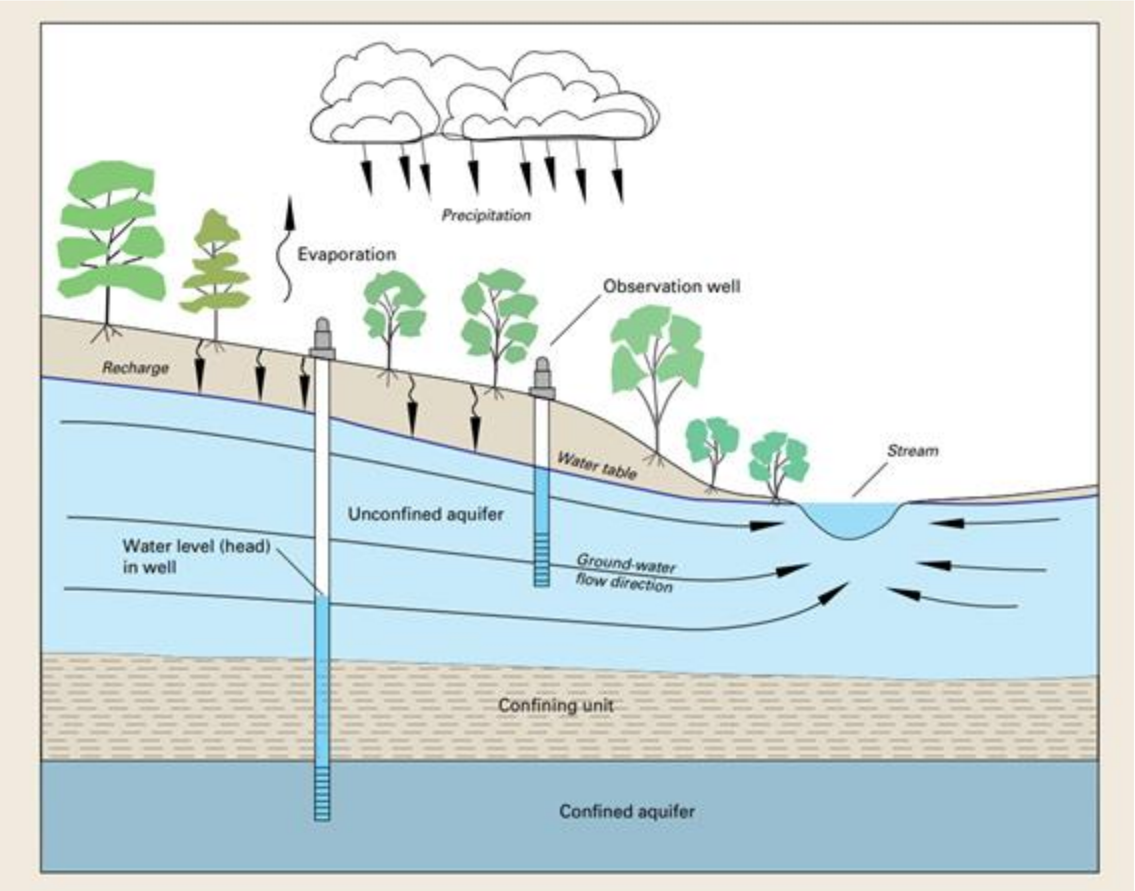


Figure A–2. *Cross-section sketch of a typical ground-water-flow system showing the relation between an unconfined and confined aquifer, a water table, and other hydrologic elements.*

Source: Ground-water-level Monitoring and the Importance of Long-Term Water-Level Data USGS Circular 1217 by Taylor and Alley, 2002 (Figure A-2, page 4)

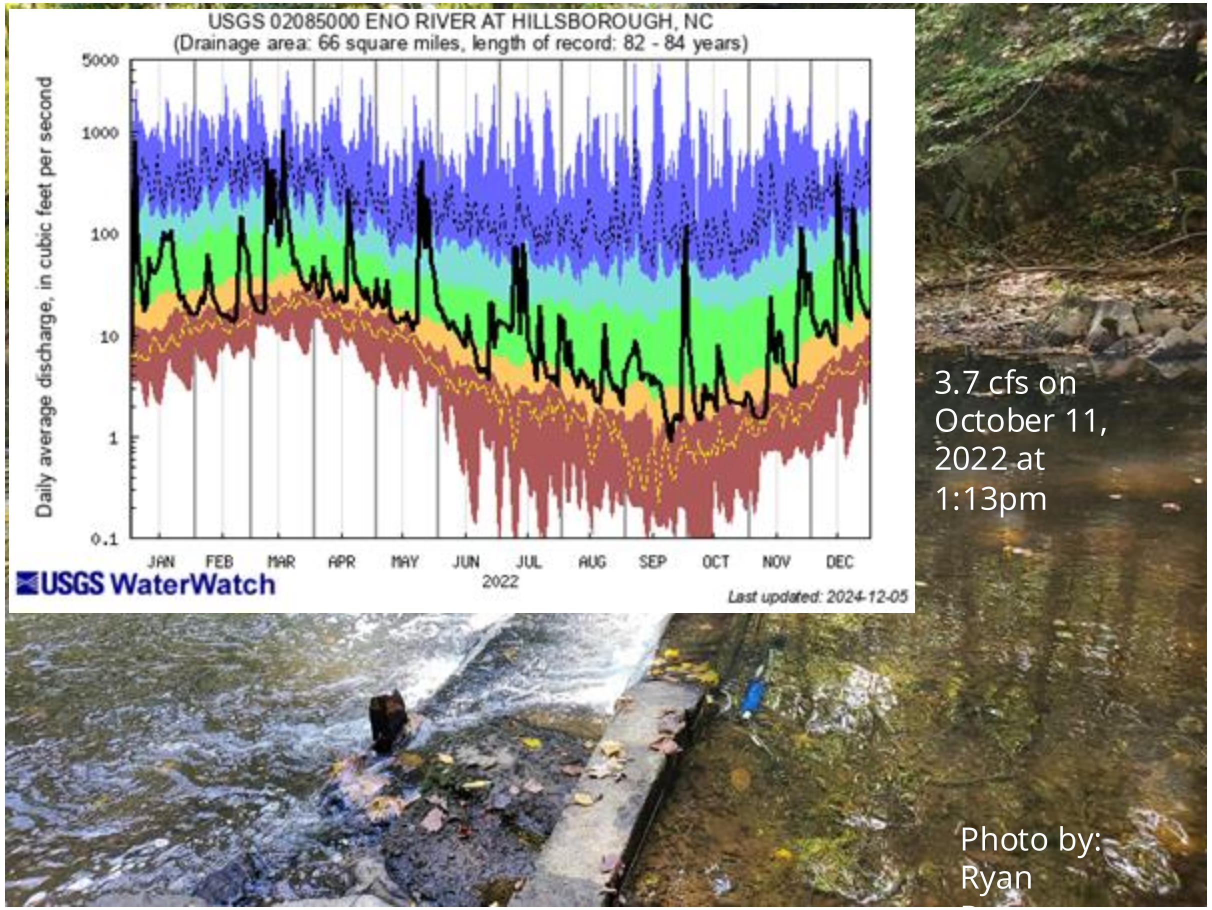
Why do we care about low flows? Because humans need water

Photo by:
Julia

Seljalandsfoss on the Seljalands River
in Iceland

Hoover Dam at Lake Mead on the Colorado River
in Nevada

Fish need water to access habitat and refuge areas



3.7 cfs on October 11, 2022 at 1:13pm

Photo by: Ryan

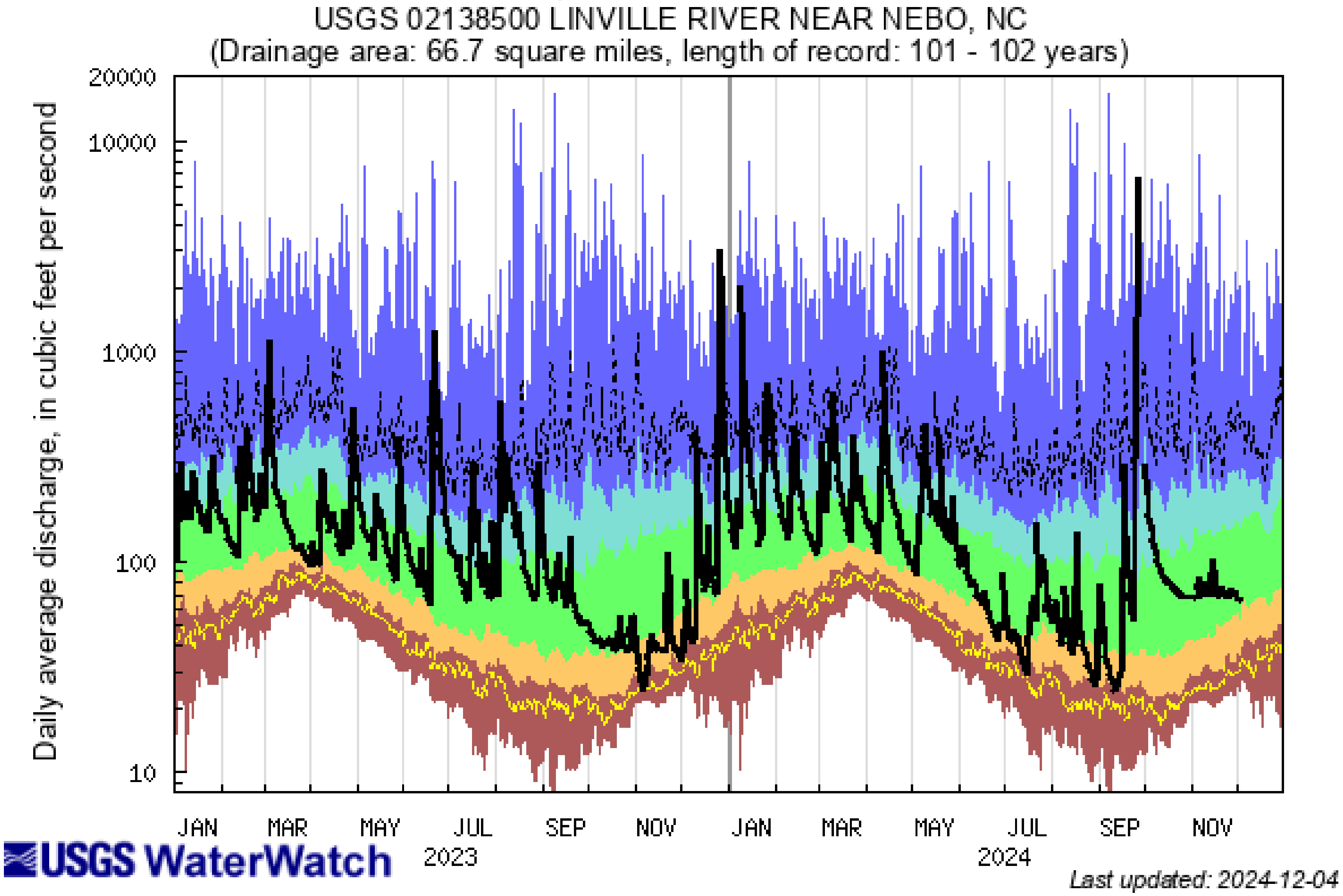
Low-head dams may block fish migration

Unnamed Tributary to Walnut Creek near Farmer's Market in Raleigh, NC

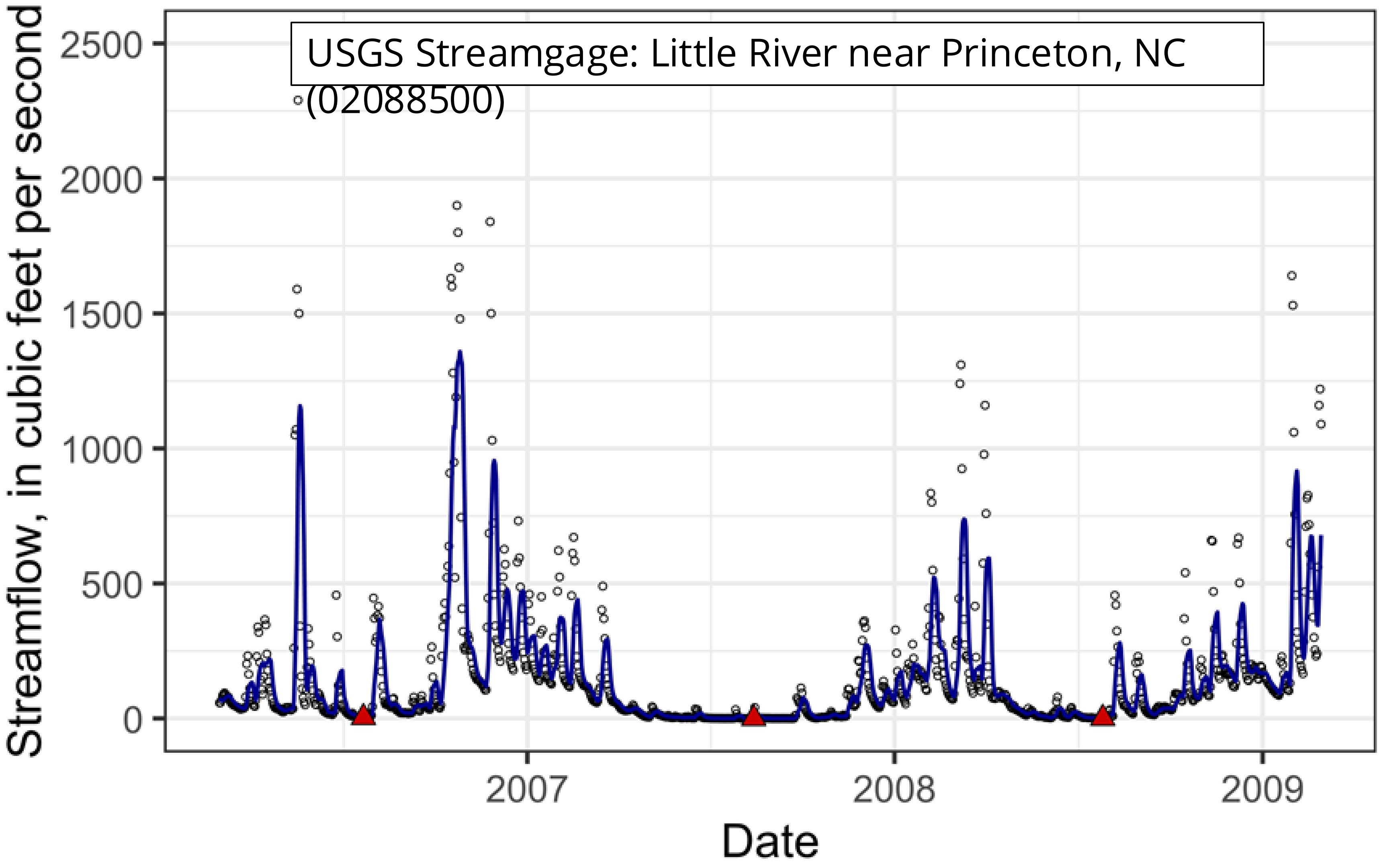
Photo by: Ryan

Incised urban streams may be disconnected from floodplain habitat

Flows vary across seasons



Calculate the lowest 7-day average flows for each



Explanation

○ Daily mean streamflow

— 7-day mean streamflow

▲ Annual minimum 7-day mean streamflow

Do our streamflows change over time?

GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L23402, doi:10.1029/2005GL024476, 2005

Nature's style: Naturally trendy

Timothy A. Cohn and Harry F. Lins
U.S. Geological Survey, Reston, Virginia, USA

Received 29 August 2005; revised 29 September 2005; accepted 12 October 2005; published 8 December 2005.

[1] Hydroclimatological time series often exhibit trends. While trend *magnitude* can be determined with little ambiguity, the corresponding *statistical significance*, sometimes cited to bolster scientific and political argument, is less certain because significance depends critically on the null hypothesis which in turn reflects subjective notions about what one expects to see. We consider statistical trend tests of hydroclimatological data in the presence of long-term persistence (LTP). Monte Carlo experiments employing FARIMA models indicate that trend tests which fail to consider LTP greatly overstate the statistical significance of observed trends when LTP is present. A new test is presented that avoids this problem. From a practical standpoint, however, it may be preferable to acknowledge that the concept of statistical significance is meaningless when discussing poorly understood systems. **Citation:** Cohn, T. A., and H. F. Lins (2005), Nature's style: Naturally trendy, *Geophys. Res. Lett.*, *32*, L23402, doi:10.1029/2005GL024476.

1. Introduction

[2] Hydroclimatological records (henceforth "HC") such as *discharge* and air temperature are increasingly examined for evidence of a *structural shift* or *trend*, defined as an upward or downward tendency in the data over time. There is typically little argument about the magnitude of observed trends whether estimated by eye or statistical methods [*Craigmile et al.*, 2004] (although D. Koutsoyiannis (personal communication, 2005) has expressed doubts about the existence of a rigorous and consistent definition of trend). The *statistical significance*, or *p-value*, associated with an observed trend, however, is more difficult to assess because it depends on subjective assumptions about the underlying stochastic process [*von Storch and Zwiers*, 1999; *Woodward and Gray*, 1993; *Weatherhead et al.*, 1998]. In this paper, we consider the idea introduced by *Hurst* [1951] and discussed by others [*Mandelbrot and Wallis*, 1969a; *Klemeš*, 1974; *Lettenmaier and Burges*, 1978; *Potter*, 1976; *Potter and Walker*, 1981; *Hosking*, 1984; *Bras and Rodriguez-Iturbe*, 1985; *Vogel et al.*, 1998; *Koutsoyiannis*, 2000] that HC records are realizations of physical processes whose behavior exhibits long-term persistence (LTP). Such behavior is sometimes modeled as fractional Gaussian noise (fGn) or fractionally differenced ARIMA (*FARIMA* or *arfima*) processes. The purpose of this paper is not to evaluate claims related to LTP, but rather to explore what LTP, if present, implies about the significance of observed trends.

2. A Family of Trend Models

[3] We assume that an HC record, $\vec{\mathbf{Y}} \equiv (Y_1, \ldots, Y_N)^T$, arises from a stochastic process, and that the process can be partitioned into a deterministic linear trend component and a stochastic component [*Kendall et al.*, 1983; *Craigmile et al.*, 2004] such that

$$Y_t = \mu + \beta \cdot t + \epsilon_t \qquad (1)$$

where t represents time (conveniently discretized into $(1, 2, \ldots, N)$), μ is a location parameter, β is the trend coefficient (the change per unit time), and ϵ_t represents the "error."

[4] The errors are assumed to be multivariate normal with zero mean and covariance matrix $\mathbf{\Sigma}$. The LTP, autoregressive, or moving average structure, if present, is completely characterized by $\mathbf{\Sigma}$. To simplify the analysis, we constrain $\mathbf{\Sigma}$ to be a function of ϕ (a lag-one autoregression (AR(1)) parameter); $\mathbf{d}$ (the fractional differencing parameter, sometimes described by H, the Hurst coefficient, where $H = d + 0.5$); θ (a lag-one moving average (MA(1)) parameter); and σ (a scale parameter). The complete stochastic process corresponding to equation 1 is denoted by $S_{\beta,(\phi,d,\theta)}(t)$, where the parameters μ and σ can be omitted without loss of generality.

[5] Stationarity is an important issue if we wish to determine whether long-term "excursions" observed in the data should be attributed to ordinary process dynamics around a fixed mean versus permanent structural changes to the process. Precise conditions for stationarity of $S_{\beta,(\phi,d,\theta)}(t)$ are given by *Kendall et al.* [1983]; however, necessary conditions include $\beta = 0$ and $d < 0.5$.

[6] All stationary stochastic processes, $S_{0,(\phi,0,\theta)}(t)$, where $d = 0$, exhibit the following property: For observations far apart in time, the correlation between $S(t)$ and $S(t + k)$ is bounded by: $\rho_k \le c^{|k|}$ as $k \to \infty$ where c is a constant and $|c| < 1$ [*Koutsoyiannis*, 2000], which implies short-term persistence in the sense that the covariance structure involves exponential decay.

[7] The stochastic process $S_{0,(0,d,0)}(t)$, $0.5 > d > 0$, exhibits long-term persistence [*Hosking*, 1984]. The correlation between observations is given by [*Hosking*, 1984]: $\rho_k = \Gamma(1-d)\Gamma(k+d)/(\Gamma(d)\Gamma(k+1-d)) \approx \Gamma(1-d)/\Gamma(d)k^{2d-1}$ where $\Gamma(\ )$ denotes the complete gamma function. When $0.5 > d > 0$, the correlation declines "slowly", as a power function in k. More important, as *Mandelbrot and Wallis* [1969b, pp. 230–231] observed, "[a] perceptually striking characteristic of fractional noises is that their sample functions exhibit an astonishing wealth of 'features' of every kind, including trends and cyclic swings of various frequencies." It is easy to imagine that LTP could be mistaken for trend.

3. Implications for Hypothesis Testing

[8] Trend assessment seeks to answer two questions:

[9] 1. What is the approximate magnitude of the trend, β?

JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
Vol. 47, No. 3 AMERICAN WATER RESOURCES ASSOCIATION June 2011

STATIONARITY: WANTED DEAD OR ALIVE?[1]

Harry F. Lins and Timothy A. Cohn[2]

ABSTRACT: Aligning engineering practice with natural process behavior would appear, on its face, to be a prudent and reasonable course of action. However, if we do not understand the long-term characteristics of hydroclimatic processes, how does one find the prudent and reasonable course needed for water management? We consider this question in light of three aspects of existing and unresolved issues affecting hydroclimatic variability and statistical inference: Hurst-Kolmogorov phenomena; the complications long-term persistence introduces with respect to statistical understanding; and the dependence of process understanding on arbitrary sampling choices. These problems are not easily addressed. In such circumstances, humility may be more important than physics; a simple model with well-understood flaws may be preferable to a sophisticated model whose correspondence to reality is uncertain.

(KEY TERMS: stationarity; nonstationarity; long-term persistence; Hurst-Kolmogorov phenomenon; trend testing; hypothesis testing.)

Lins, Harry F. and Timothy A. Cohn, 2011. Stationarity: Wanted Dead or Alive? *Journal of the American Water Resources Association* (JAWRA) 47(3):475-480. DOI: 10.1111/j.1752-1688.2011.00542.x

INTRODUCTION

Earth's climate continually changes, at all temporal scales, at all spatial scales, always has, and always will. As a technical matter, there is no dispute within the water resources planning community that climate is nonstationary. Thus, recent calls for abandonment of the stationarity assumption in water planning and design (Milly *et al.*, 2008) are not new, and the water resources planning community has never been ignorant of the limitations associated with assuming stationarity. However, these renewed calls raise an interesting question: If nonstationarity is an intrinsic characteristic of the climate system and if all existing dams and bridges were designed using statistical tools that did not account for nonstationarity and if failure to account for nonstationarity is a critical weakness, then why have there been "very few failures of the nation's water management infrastructure – i.e., where the infrastructure failed before its design capacity was exceeded" (Stakhiv, 2010)?

In part, the answers reside outside the restricted domain of science and mathematics. Successful water resource management is an adaptive and multidisciplinary activity based on data, physics, statistics, economics, politics, nonquantifiable factors, and, above all, humility. It is by no means an exact science. Yet, there are some components that we can

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[1] Paper No. JAWRA-10-0062-P of the *Journal of the American Water Resources Association* (JAWRA). Received April 27, 2010; accepted December 3, 2010. © 2011 American Water Resources Association. This article is a U.S. Government work and is in the public domain in the USA. **Discussions are open until six months from print publication.**

[2] Respectively, Hydrologists (Lins, Cohn), U.S. Geological Survey, 415 National Center, Reston, Virginia 20192 (E-Mail/Lins: hlins@usgs.gov).

JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
Vol. 47, No. 3 AMERICAN WATER RESOURCES ASSOCIATION June 2011

A PERSPECTIVE ON NONSTATIONARITY AND WATER MANAGEMENT[1]

Robert M. Hirsch[2]

ABSTRACT: This essay offers some perspectives on climate-related nonstationarity and water resources. Hydrologists must not lose sight of the many sources of nonstationarity, recognizing that many of them may be of much greater magnitude than those that may arise from climate change. It is paradoxical that statistical and deterministic approaches give us better insights about changes in mean conditions than about the tails of probability distributions, and yet the tails are very important to water management. Another paradox is that it is difficult to distinguish between long-term hydrologic persistence and trend. Using very long hydrologic records is helpful in mitigating this problem, but does not guarantee success. Empirical approaches, using long-term hydrologic records, should be an important part of the portfolio of research being applied to understand the hydrologic response to climate change. An example presented here shows very mixed results for trends in the size of the annual floods, with some strong clusters of positive trends and a strong cluster of negative trends. The potential for nonstationarity highlights the importance of the continuity of hydrologic records, the need for repeated analysis of the data as the time series grow, and the need for a well-trained cadre of scientists and engineers, ready to interpret the data and use those analyses to help adjust the management of our water resources.

(KEY TERMS: Water Resources Management; climate variability/change; runoff; streamflow; water policy.)

Hirsch, Robert M., 2011. A Perspective on Nonstationarity and Water Management. *Journal of the American Water Resources Association* (JAWRA) 47(3):436-446. DOI: 10.1111/j.1752-1688.2011.00539.x

INTRODUCTION

Much discussion has taken place since several of my colleagues and I published a perspectives article in Science Magazine (Milly *et al.*, 2008) regarding stationarity and water management. Our purpose in writing it was to get scientists and engineers to think more about these issues. We were clear in saying that we really did not have answers, but rather that we had questions and wanted to present some challenges about the need to develop new approaches to analysis, planning, and management. I still believe that we do not have the answers but we are perhaps getting better at posing the questions. In that spirit, this essay elaborates on some of the problems that the climate change issue poses to the water resources community and proposes a few ideas about a way forward.

NONSTATIONARITY IS NOTHING NEW TO WATER PLANNING AND MANAGEMENT

In water resource planning and management, we usually consider nonstationarity in those cases where

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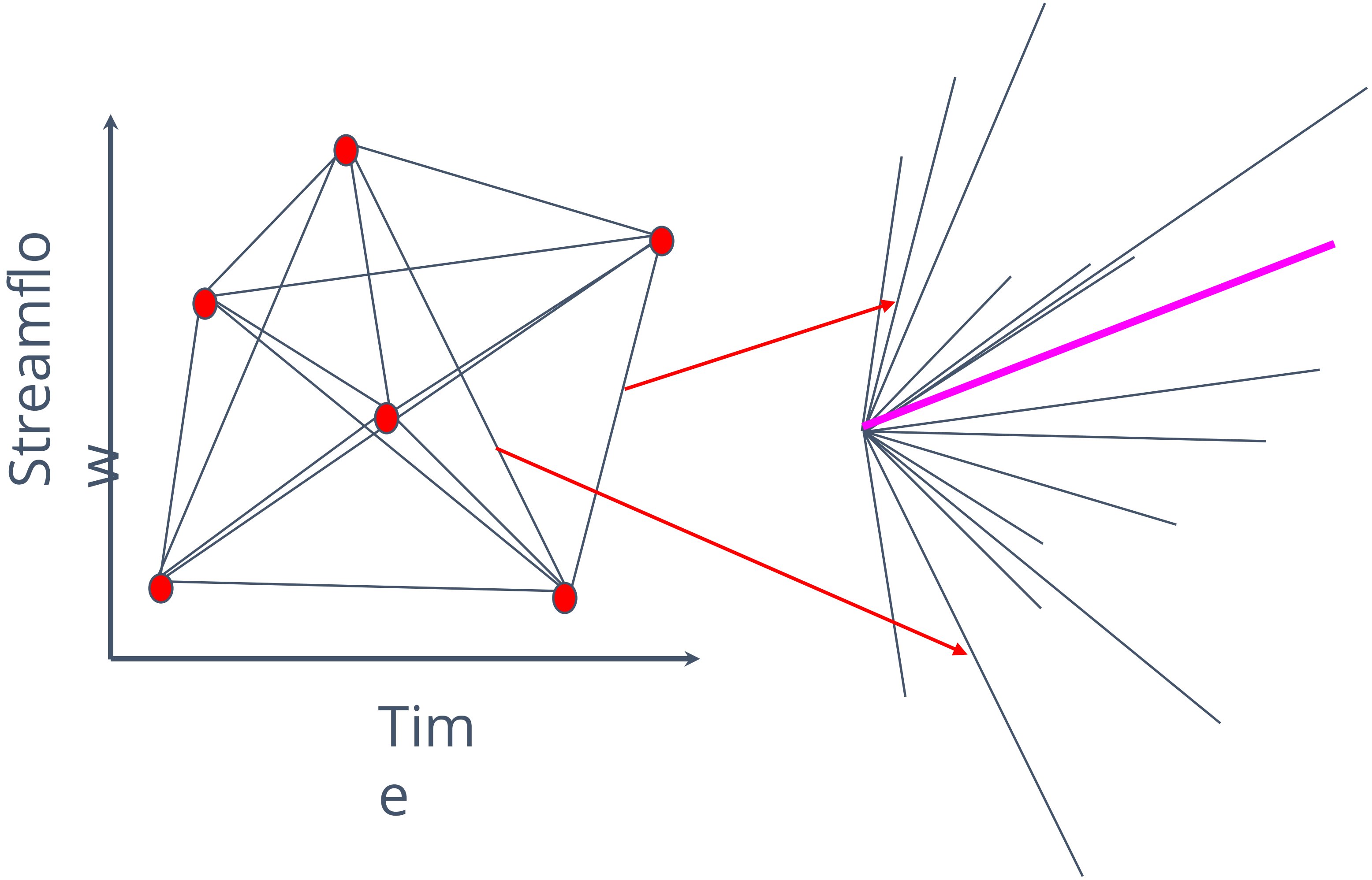
[1] Paper No. JAWRA-10-0053-P of the *Journal of the American Water Resources Association* (JAWRA). Received April 19, 2010; accepted August 26, 2010. © 2011 American Water Resources Association. This article is a U.S. Government work and is in the public domain in the USA. **Discussions are open until six months from print publication.**

[2] Research Hydrologist, U.S. Geological Survey, 432 National Center, Reston, Virginia 20192 (E-Mail/Hirsch: rhirsch@usgs.gov).

Mann-Kendall Theil-Sen Slope: one way to calculate trends



Modified Mann-Kendall Assumptions:

(1) **independence ***,

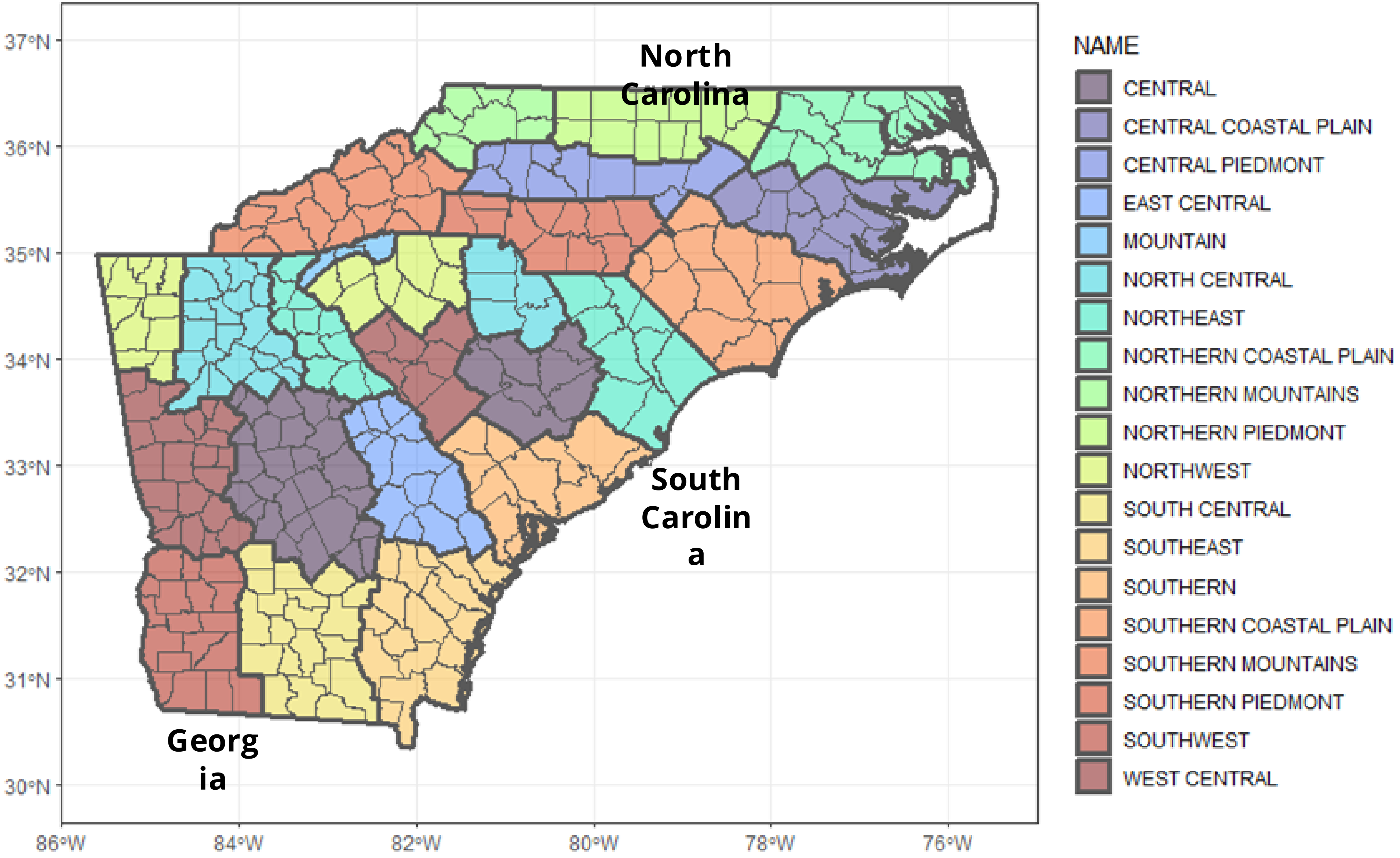
(2) **short-term persistence** †,

(3) **long-term persistence** ‡

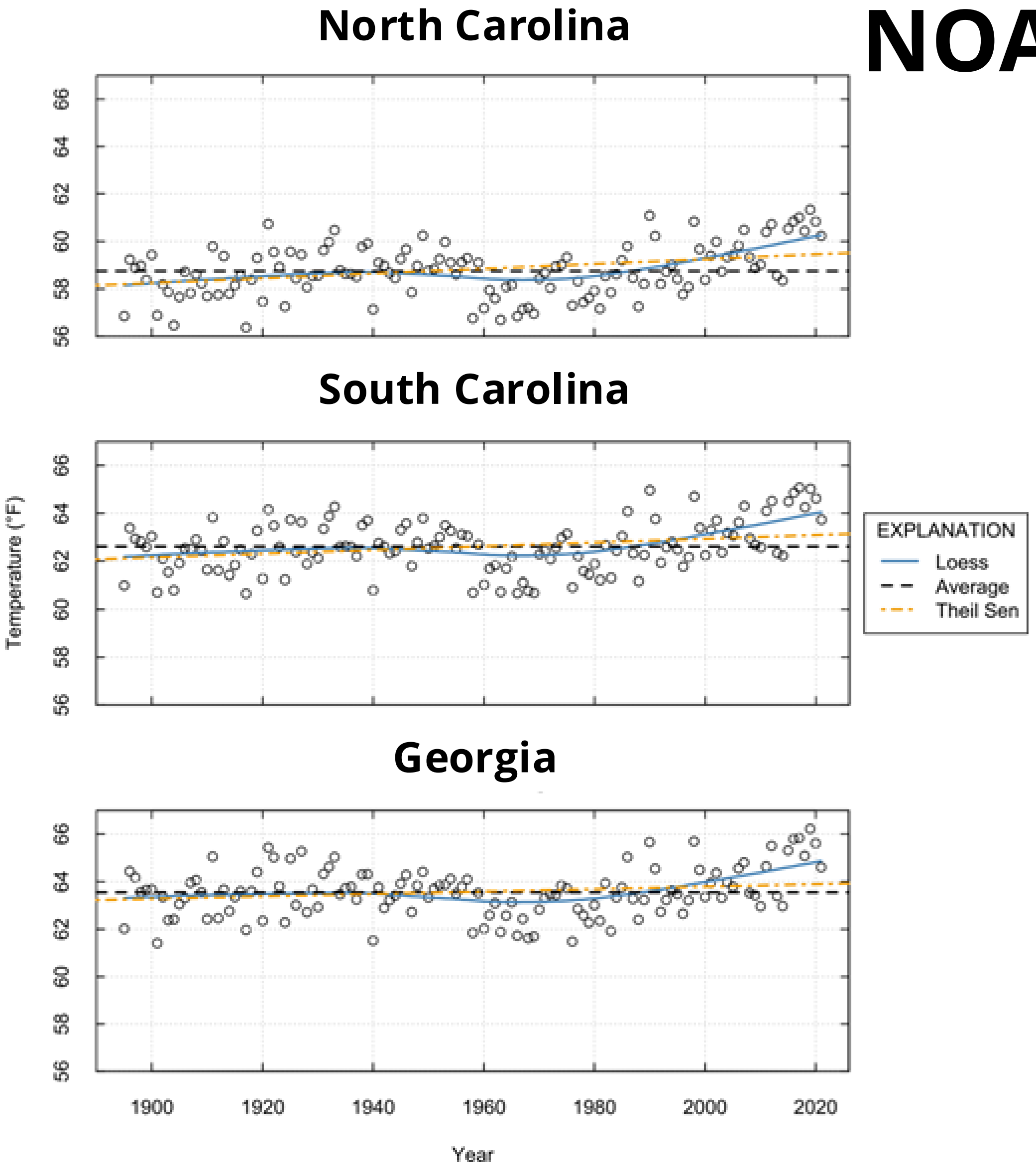
Significant at α = 0.10

USGS data release for R code to modify the trend test is available at: DOI

Study area: South Atlantic (GA, SC, & NC)



Annual average temperature trends by state from NOAA NCEI



North Carolina

Average: 57.8 °F

Theil-Sen Slope: 0.10 °F/decade *†

South Carolina

Average: 62.6 °F

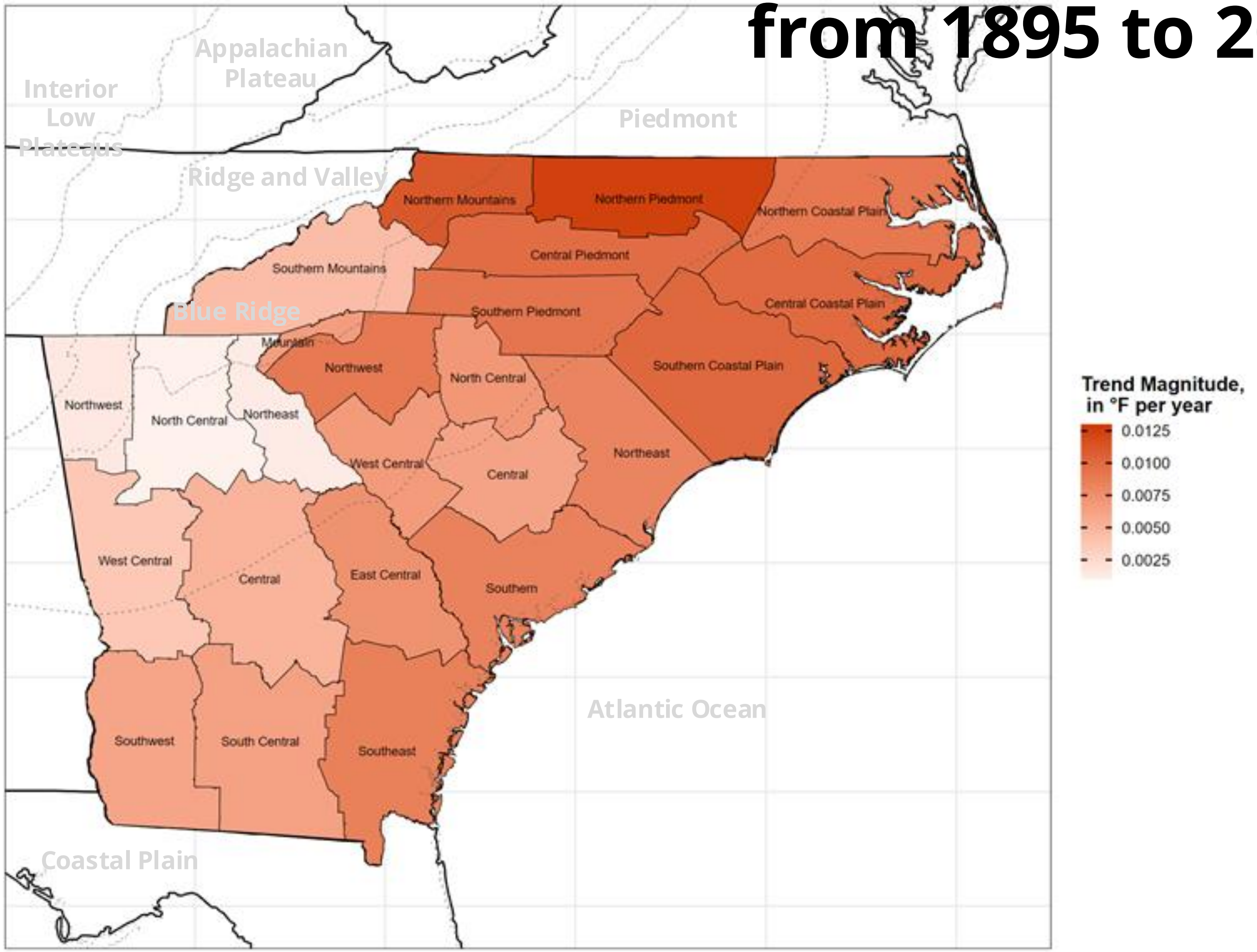
Theil-Sen Slope: 0.07 °F/decade *†

Georgia

Average: 63.6 °F

Theil-Sen Slope: 0.05 °F/decade *

Annual average temperature trends by climate division from 1895 to 2021



Climate divisions with significant trends:

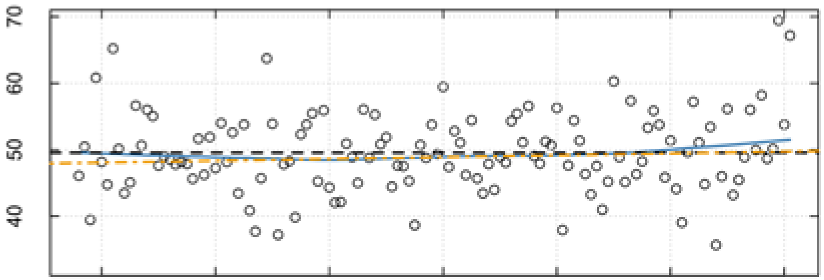
Independence*:
20 of 24 (83%)

Short-term dependence †:
17 of 24 (71%)

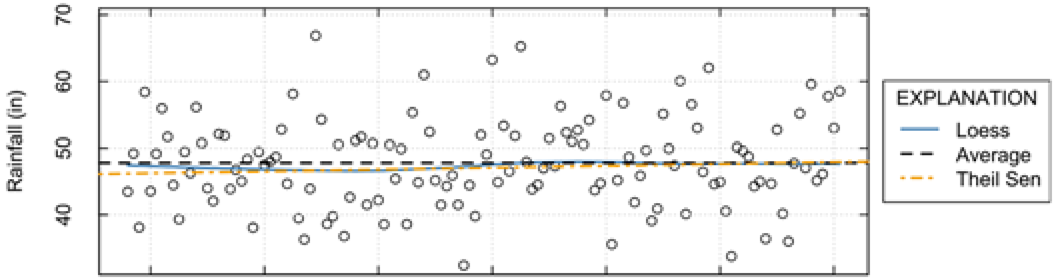
Long-term dependence ‡:
3 of 24 (13%)

Annual average total rainfall trends by state

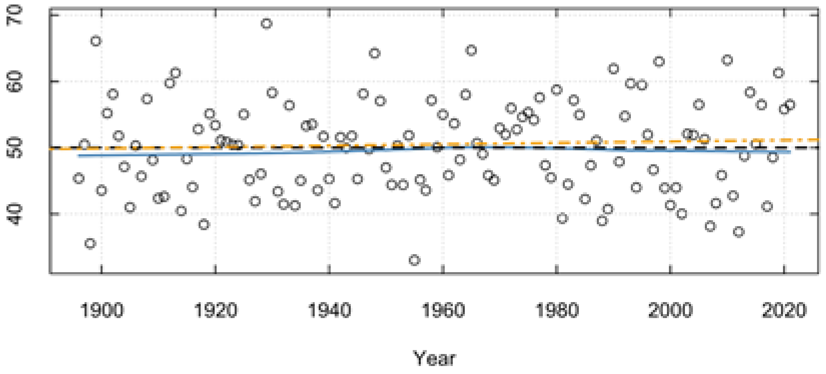
North Carolina



South Carolina



Georgia



North Carolina

Average: 49.6 in

Theil-Sen Slope: 0.14 in/decade

South Carolina

Average: 47.8 in

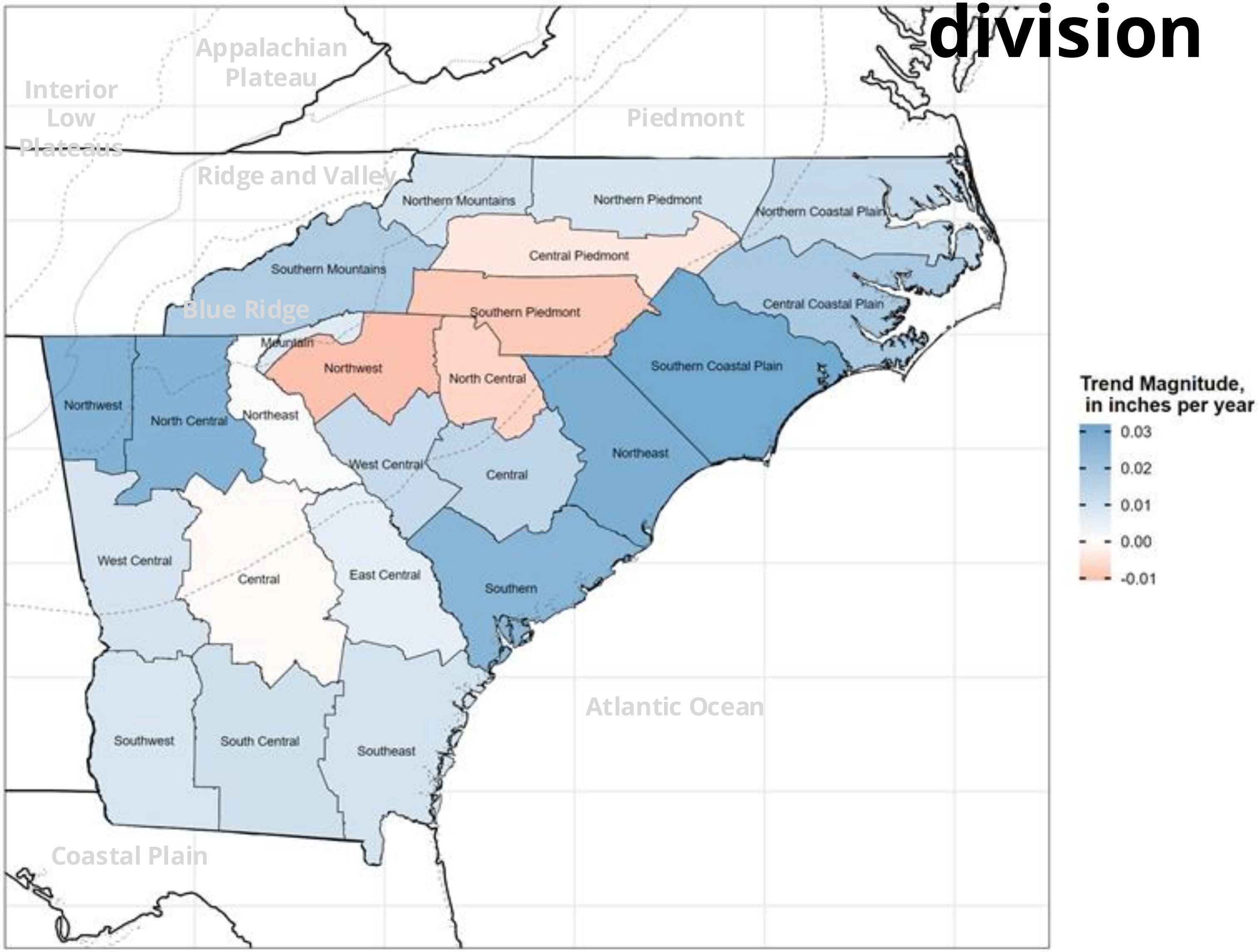
Theil-Sen Slope: 0.14 in/decade

Georgia

Average: 50.0 in

Theil-Sen Slope: 0.10 in/decade

Annual average total rainfall trends by climate division



Climate divisions with significant trends:

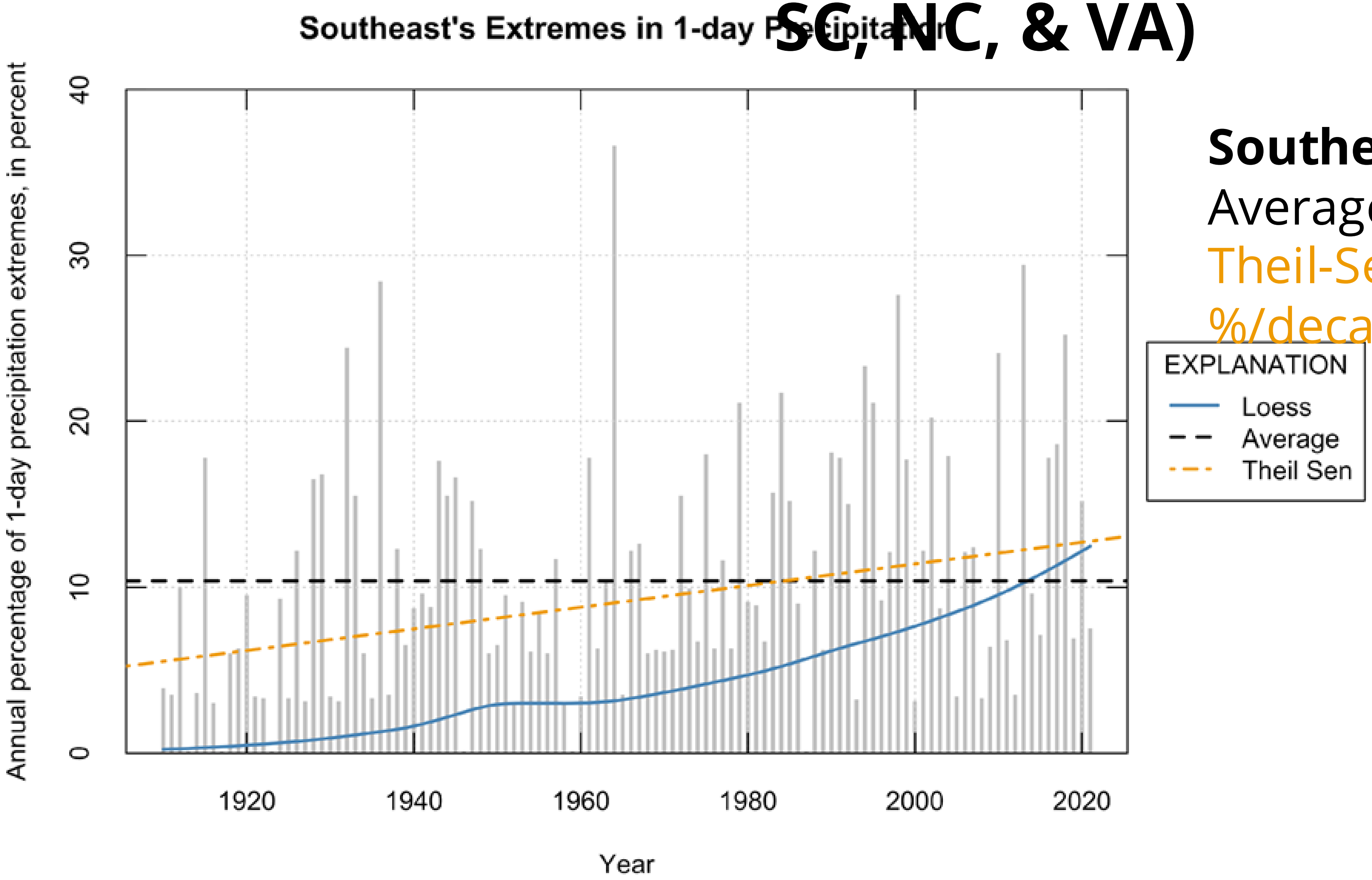
Independence*:
2 of 24 (8%)

Short-term dependence†:
2 of 24 (8%)

Long-term dependence‡:
1 of 24 (4%)

Preliminary Information-Subject to Revision. Not for Citation or

1-day extreme rainfall trends for the Southeast (AL, FL, GA, SC, NC, & VA)



Southeast

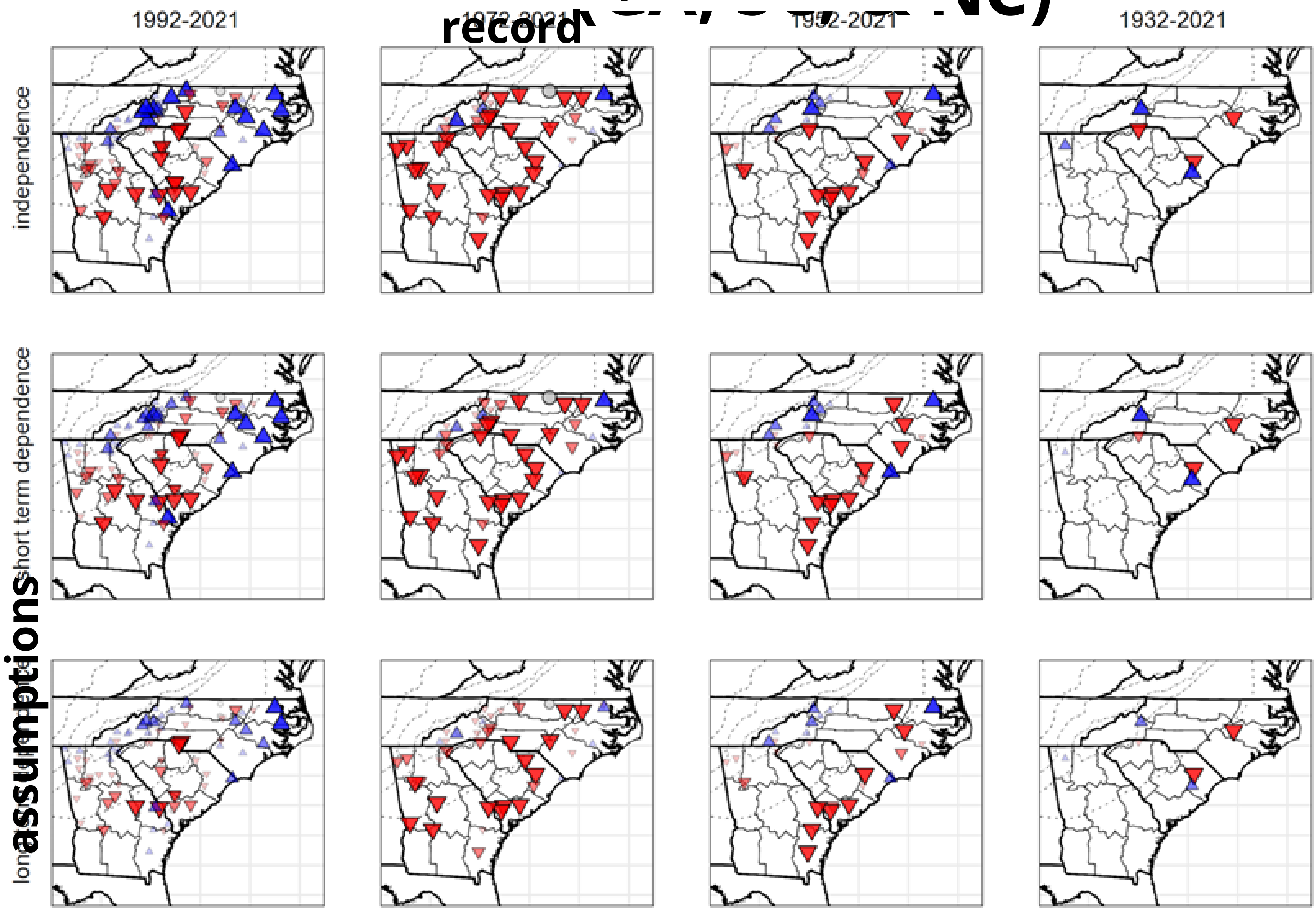
Average: 10.5 %

Theil-Sen Slope: 0.6 %/decade

Minimum 7-day average streamflow for the South Atlantic (GA, SC, NC)

Various periods of record

Different Mann-Kendall test assumptions



Explanation

Likelihood		Probability
Likely	□	> 85%
Somewhat likely	□	70 to 85%
Just as likely as not	□	< 70%
Just as likely as not	□	< 70%
Somewhat likely	□	70 to 85%
Likely	□	> 85%

Minimum 7-day average streamflow for the South Atlantic (GA, SC, & NC)

Percentage of streamgages with likely, somewhat likely, and just as likely as

Data assumption	Likelihood	30-yr	50-yr	70-yr	90-yr
Independence *	Likely ☐	15%	2%	7%	33%
	Somewhat likely ☐	9%	4%	18%	0%
	Just as likely as not ☐	22%	6%	7%	17%
	Just as likely as not ☐	15%	15%	15%	0%
	Somewhat likely ☐	18%	11%	7%	0%
	Likely ☐	17%	56%	44%	50%
Short-term dependence †	Likely ☐	10%	2%	11%	33%
	Somewhat likely ☐	14%	4%	15%	0%
	Just as likely as not ☐	22%	6%	7%	17%
	Just as likely as not ☐	19%	15%	15%	0%
	Somewhat likely ☐	19%	17%	15%	17%
	Likely ☐	12%	50%	37%	33%
Long-term dependence ‡	Likely ☐	3%	0%	4%	0%
	Somewhat likely ☐	12%	4%	15%	33%
	Just as likely as not ☐	32%	9%	15%	17%
	Just as likely as not ☐	32%	30%	26%	17%
	Somewhat likely ☐	13%	22%	11%	0

How many streamgages had significant trends in low flow?

Percentage of streamgages with significant

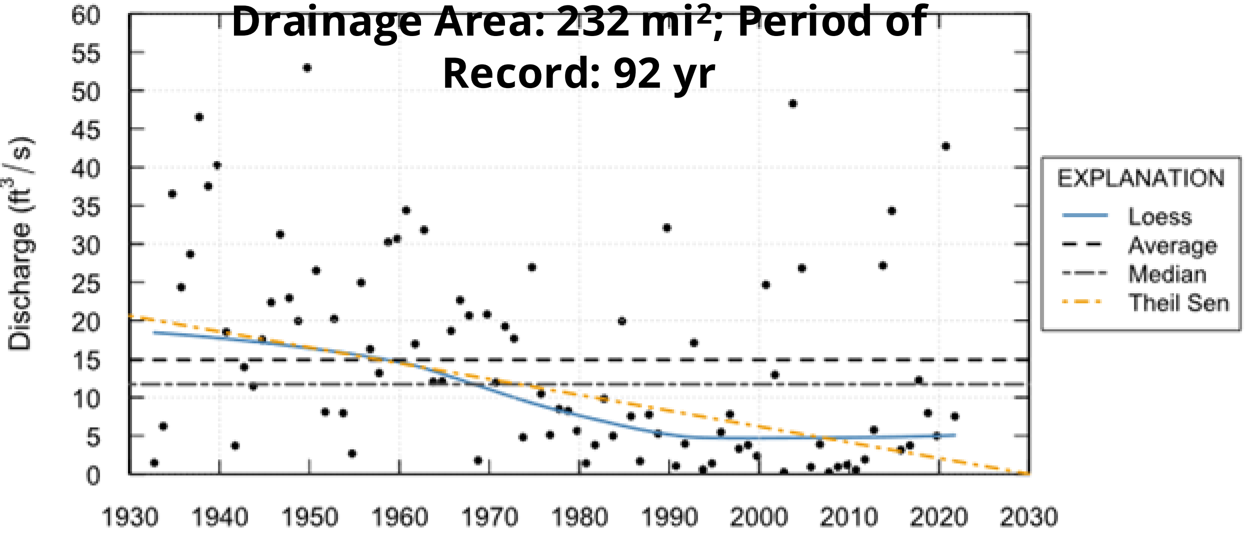
Data assumption		30-yr	50-yr	70-yr	90-yr
			(%)		
Independence *	🟦	3%	0%	7%	0%
	🟥	8%	39%	33%	33%
Short-term dependence †	🟦	4%	0%	4%	0%
	🟥	3%	26%	26%	33%
Long-term dependence ‡	🟦	0%	0%	0%	0%
	🟥	0%	13%	19%	17%

Most streams had no significant trend

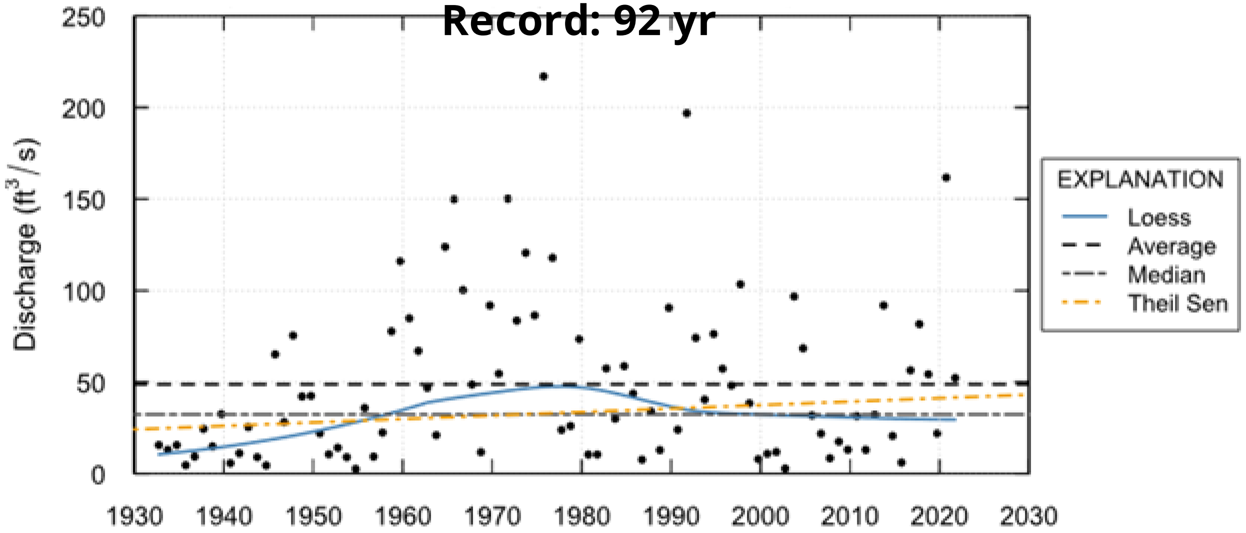
More streams had downward significant trends than upward trends

Largest trends in minimum 7-day average streamflow for longest continuous streamgages

Little River near Princeton, NC (02088500)
Drainage Area: 232 mi²; Period of Record: 92 yr



Black River at Kingstree, SC (02136000)
Drainage Area: 1,252 mi²; Period of Record: 92 yr



Median: 11.7 cfs

Theil-Sen Slope: -2.1 cfs/decade

Relative total change: -158%

Drains watersheds between Raleigh and Wilson, NC

Median: 32.4 cfs

Theil-Sen Slope: 1.9 cfs/decade

Drains watersheds between Columbia and Florence, SC

Conclusions

- People need water
- Aquatic life needs water
- Temperatures have increased (what about ET?)
- Annual rainfall has remained somewhat steady
- Extreme storms have covered larger areas in the Southeast
- Some low flows have decreased in areas of the South Atlantic
- Few streams had persistent trends

- People should manage water for the health of humans and ecosystems

- Most gages had no significant trend, similar to other studies