

# 1 **Nonstationarity of low flows and their timing in the eastern** 2 **United States**

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4 **S. Sadri<sup>1</sup>, J. Kam<sup>1</sup> and J. Sheffield<sup>1</sup>**

5 [1]{Princeton University, Princeton, NJ}

6 Correspondence to: J. Sheffield (justin@princeton.edu)

## 7 8 **Abstract**

9 The analysis of the spatial and temporal patterns of low flows as well as their generation  
10 mechanisms over large geographic regions can provide valuable insights and understanding  
11 for climate change impacts, regional frequency analysis, risk assessment of extreme events,  
12 and decision-making regarding allowable withdrawals. The goal of this paper is to examine  
13 non-stationarity in low flow generation across the eastern U.S. and explore the potential  
14 anthropogenic influences or climate drivers. We use nonparametric tests to identify abrupt  
15 and gradual changes in time series of low flows and their timing for 508 USGS streamflow  
16 gauging sites in the eastern US with more than 50 years of daily data, to systematically  
17 distinguish the effects of human intervention from those of climate variability. A time series  
18 decomposition algorithm was applied to 1-day, 7-day, 30-day, and 90-day annual low flow  
19 time series that combines the Box-Ljung test for detection of autocorrelation, the Pettitt test  
20 for abrupt step changes and the Mann-Kendall test for monotonic trends. Examination of the  
21 USGS notes for each site showed that many of the sites with step changes and around half of  
22 the sites with an increasing trend have been documented as having some kind of regulation.  
23 Sites with decreasing or no trend are less likely to have documented influences on flows.  
24 Overall, a general pattern of increasing low flows in the northeast and decreasing low flows in  
25 the southeast is evident over a common time period (1951-2005), even when discarding sites  
26 with significant autocorrelation, documented regulation or other human impacts. The north-  
27 south pattern of trends is consistent with changes in antecedent precipitation. The main  
28 exception is along the mid-Atlantic coastal aquifer system from eastern Virginia northwards,  
29 where low flows have decreased despite increasing precipitation, and suggests that declining  
30 groundwater levels due to pumping may have contributed to decreased low flows. For most

1 sites, the majority of low flows occur in one season in the late summer to autumn, as driven  
2 by the lower precipitation and higher evaporative demand in this season, but this is  
3 complicated in many regions because of the presence of a secondary low flow season in the  
4 winter for sites in the extreme northeast and in the spring for sites in Florida. Trends in low  
5 flow timing are generally undetectable, although abrupt step changes appear to be associated  
6 with regulation.

7

## 8 **1 Introduction**

9 Low flows - the minimum flow in a river during the dry periods of the year--- are an  
10 important part of the streamflow regime that have direct impacts on water supply, water  
11 quality, and ecosystem health (Bradford and Heinonen, 2008). Knowledge of low flow  
12 characteristics and generation mechanisms over large geographic regions is important for  
13 regional frequency analysis, risk assessment of extreme events, decision-making regarding  
14 allowable basin withdrawals and water quality, and understanding climate change impacts  
15 (Tallaksen and van Lanen, 2004). For example, in every state of the U.S., estimates of low  
16 flow statistics are needed for issuing and/or renewing of National Pollution Discharge  
17 Elimination System permits, as required by provisions in the Clean Water Act of 1977 (U.S.  
18 Senate, 2002). Furthermore, low flow periods are critical to aquatic habitats due to potentially  
19 low dissolved oxygen concentrations and/or high pollutant concentration (U.S. Senate, 2002).  
20 However, the study of low flow statistics and patterns have received little attention in  
21 comparison to droughts and floods (Kroll et al., 2004). Poff et al. (1997) emphasize the need  
22 of paying particular attention to low flows because they present critical stresses and  
23 opportunities for a wide array of riverine projects.

24 Low flows are generally controlled by subsurface flows sourced from groundwater that  
25 maintain flows during the dry periods of the year, such that low flow volumes are related to  
26 the physiological and geological make up of the area. In some regions, where precipitation is  
27 significant in the warm season, surface flows also play a role in maintaining low flows.  
28 However, our understanding of these low flow generating mechanisms is limited (Smakhtin,  
29 2001), and is further compounded by the sensitivity of low flows to changes in climate, land  
30 use and human impacts on stream flow (Rolls et al., 2012). For example, large-scale  
31 teleconnections may play an important role in driving inter-annual to multi-decadal changes  
32 in streamflow (e.g. Mauget, 2003) and low flows (e.g. Giuntoli et al., 2013). Regulation

1 generally introduces non-stationarity into low flow time series that impedes the development  
2 of regional or at-site frequency analysis models. In most instances, such models show a high  
3 standard error between modeled and observed quantiles (Kroll et al., 2004).

4 In the eastern United States, (defined as the area covering the 20 ecoregions of the eastern US  
5 (USGS, 2012)), both direct anthropogenic and climate influences may have impacted low  
6 flows, including land use change impacts via changes in sub-surface flow and groundwater  
7 recharge, direct impacts on flows via reservoirs and other streamflow management, and  
8 changes in precipitation and evaporation that have altered recharge. In particular:

9 1. In the U.S., more than 85% of the surface runoff is artificially controlled and nearly 1  
10 million km of rivers are affected by dams (Poff et al., 1997). Surface water covers 4.5% of the  
11 eastern U.S., and the majority of streams have been flagged by the U.S. Geological Survey  
12 (USGS) as regulated. The USGS estimates that the spatial extent of surface water increased  
13 by 1.3% during 1973-2000, with most of this increase in the southern coastal plain and  
14 southern Florida coastal plain (USGS, 2012) and associated with reservoir developments  
15 required to meet the needs of the expanding population. Figure 1a shows the location of major  
16 dams in the eastern U.S. (defined as those 50 feet or more in height, or with a normal storage  
17 capacity of 5,000 acre feet (~6,200,000 m<sup>3</sup>) or more, or with a maximum storage capacity of  
18 25,000 acre feet (~30,800,000 m<sup>3</sup>) or more (USACE, 2012)). Generally dams and reservoirs  
19 are considered the largest man-made regulations on streamflow, but other sources include  
20 farm ponds, surface water extraction, inter-basin transfers, and wastewater treatment plant  
21 discharge (e.g. Walker and Thoms, 1993; Acreman et al., 2000; Brandes et al., 2005; Thomas,  
22 2006; Deitch et al., 2009; Kustu et al. 2010).

23 2. The eastern U.S. has gone through significant land use change over the past several  
24 decades. For example, between 1973 and 2000, 8.2% of the 23,620,000 km<sup>2</sup> of the northeast  
25 ecoregion and 8.9% of the 30,000,000 km<sup>2</sup> of the southeast ecoregion experienced changes  
26 associated with active timber harvesting and replanting, which may have impacted low flows  
27 and related environmental and ecosystem well-being (USGS, 2012). Furthermore, in the  
28 expanding urbanized areas of the region with high levels of impervious ground, infiltration  
29 has decreased, which may have led to a decrease groundwater recharge and low flow volumes  
30 (USGS, 2013). On the other hand, urbanization can lead to increase in low flows because of  
31 leakages from water supply and wastewater pipes, direct wastewater discharge, reduced

1 evapotranspiration, and water imports that can offset groundwater pumping (e.g. Brandes et  
2 al., 2005).

3 3. The region is one of the wettest parts of the U.S. receiving 700-1600 mm of precipitation  
4 per year. However, due to population growth and associated increased use of surface and  
5 groundwater resources, the future is expected to bring water stress for this area (Averyt et al.,  
6 2013). Some of these changes are already being observed. For example, USGS (2013) reports  
7 on 3-10 km<sup>3</sup> of depletion of unconsolidated and semi-consolidated sand and gravel aquifers  
8 of the east coast between 1900 and 2008. Overuse of surface water in turn does not allow  
9 recharge of groundwater leading to groundwater depletion. In parts of the eastern U.S.,  
10 groundwater resources have become limited and hence municipal and industrial water users  
11 are increasingly relying on surface waters (e.g. Daniel and Dahlen, 2002). Changes in both  
12 surface water and groundwater use have impacts on low flows.

13 4. Precipitation has likely changed over the past several decades (Karl and Knight, 1998;  
14 Small et al., 2006). Evaporation may have changed due to increasing atmospheric demand  
15 from higher temperatures (e.g. Walter et al., 2004), although direct measurements of  
16 evaporation are limited in spatial and temporal coverage. Each of these changes may impact  
17 on low flows and in some cases may combine to exacerbate or counteract changes in low  
18 flows. Warmer temperatures may have also impacted winter-time low flows, via changes in  
19 snow (Burakowski et al., 2008) and river ice (Hodgkins et al., 2005).

20 Past evaluations of changes in low flows over the eastern U.S. have mainly been within  
21 studies on the entire U.S. and often with respect to mean and high flows. Douglas et al. (2000)  
22 estimated trends in both flood and 7-day low flows for three major geographic regions in the  
23 U.S. (East, Midwest, and West) over two time periods: 1959-1988 and 1939-1988, and found  
24 evidence of upward trends in low flows across the Midwest, but not in the eastern U.S. Other  
25 studies have attempted to explain the general patterns of low flow trends. For example, Small  
26 et al. (2006) analyzed trends in annual 7-day low flow, average, and high flows along with  
27 seasonal precipitation over individual basins in the U.S. for 1948-1997. The number of sites  
28 shown to have statistically significant trends in low flows and fall precipitation in the eastern  
29 U.S. was small and restricted to the south of Maine, western Pennsylvania, coastal areas of  
30 South Carolina, and western Florida. In the northeast and west of Pennsylvania, precipitation  
31 showed an increasing trend during the fall but not during the spring and the increase in fall  
32 precipitation appeared to result in an increase in low flows in the northeast areas. The only

1 statistically significant decrease in the low flows was found in the south Atlantic-Gulf region,  
2 west of Florida, consistent with the findings from Lins and Slack (1999). However, no  
3 specific reason for this decreasing trend was given. McCabe and Wolock (2002) examined  
4 historic changes in streamflow, using the annual minimum, median, and maximum daily  
5 streamflow at 400 sites across the U.S. during 1941-1999. They found an increase in annual  
6 minimum and median daily streamflow around 1970 that primarily occurred in the eastern  
7 U.S. as a step change, rather than a gradual trend. Andreadis et al. (2006) used model  
8 simulations to examine trends in soil moisture, runoff, and drought characteristics over the  
9 U.S. for the period 1915-2003. They found increasing runoff over parts of the northeast,  
10 which was most evident during winter months, with decreases in hydrological and agricultural  
11 drought, and drying trends in the summer in the southeast, with increases in drought. These  
12 changes were attributed to changes in precipitation, and they speculated that increasing  
13 drought in the southeast was associated with higher atmospheric demand due to warming.  
14 Although these studies are generally consistent for the eastern U.S. they tend to focus on the  
15 spatial pattern of trends in 7-day low flows only, and were limited to earlier periods available  
16 at the time of the study. Furthermore, these studies focused on sites that were deemed to have  
17 minimal anthropogenic influence, and so did not explore the role of anthropogenic influences,  
18 such as land cover change or water withdrawals (Brown et al., 2013).

19 The goal of this paper is to examine non-stationarity in low flow generation across the eastern  
20 U.S. by attempting to identify time series that are potentially free of the effects of human  
21 intervention and examine these in terms of the impact of climate variability. A way to  
22 determine whether a river has been subject to anthropogenic influences, at least in terms of  
23 regulation, is to examine the site notes for the gauging station. However, site notes might not  
24 be available, complete, or accurate, and examining the notes for multiple sites can be  
25 unwieldy. Furthermore, whether a site is determined to be regulated or not is often based on  
26 high flows and not on low flows. Here, we develop an approach that makes the simplification  
27 that the impact of human activities can be detected in the streamflow data in a systematic  
28 way. This is generally more efficient and can complement site notes or compensate for errors  
29 in them. Low flow time series (and flows in general) can show two general types of non-  
30 stationarity: gradually increasing or decreasing trends, and abrupt changes (Villarini et al.,  
31 2009) in the mean and/or variability. As McCabe and Wolock (2002) observe, the distinction  
32 between a gradual trend and a step change is important, particularly for climate-change  
33 impact studies, since climate change usually manifests as a trend and not a step change. We

1 therefore make the simplification that step changes (abrupt and visually obvious) in the time  
2 series are indicative of an anthropogenic effect, and that gradual trends reflect a climate  
3 effect, which may be due to anthropogenic climate change or long-term persistence (Cohn and  
4 Lins, 2005). As it is possible that step changes may be driven by natural variability (e.g.  
5 McCabe and Wolock, 2008) this simplification is based on identifying abrupt and visually  
6 obvious step changes.

7 Our overall approach is to use nonparametric statistical tests to identify abrupt and gradual  
8 changes in the value and timing of n-day low flows, and identify stationary segments of the  
9 time series. Furthermore we analyze the co-variability of low flows with antecedent  
10 precipitation to understand the influence of changes in precipitation and atmospheric demand  
11 (as quantified by potential evapotranspiration) on changes in low flows. The paper is  
12 organized as follows: Section 2 describes the streamflow data and the methodology, including  
13 the use of three straightforward and already-established statistical methods, for identifying  
14 non-stationarity in annual low flow time series. The results on the systematic identification  
15 and characterization of abrupt changes in low flow volumes and timing are presented in  
16 Section 3. The results on the variability and trends in are given in Section 4. Finally, we  
17 discuss the results, the potential drivers of changes and their implications, and present  
18 conclusions in Section 5.

19

## 20 **2 Data and methods**

### 21 **2.1 Study area**

22 Our study area covers the eastern U.S. from Maine in the northeast to Florida in the southeast  
23 and westwards to the Appalachian Mountains and the Mississippi River in the south, and is  
24 based on the 20 ecoregions of the eastern U.S. (USGS, 2012). According to the USGS (2012),  
25 52.4% of the eastern ecoregion in 2000 was forest. However, both forests and agriculture  
26 have been in decline since 1973 and instead, urbanization has increased and continues to  
27 increase. Most land cover change has occurred in the southeast and is associated with forest  
28 harvesting, agricultural abandonment, and development (USGS, 2012). Changes in the  
29 northeast have been mostly associated with timber harvesting. Changes in the north Central  
30 Appalachian region have been more heterogeneous and include examples of non-mechanical  
31 transitional change. Unlike the northeastern Coastal Plain, the southern Florida Coastal Plain

1 has not experienced loss of agricultural land, but the largest decrease in surface water and  
2 significant loss of wetlands (-2.4%). Changes in surface water in the southern Coastal Plain  
3 have primarily been due to urbanization (USGS, 2012).

4 The eastern U.S. is one of the wettest parts of the country (Small et al., 2006), with average  
5 precipitation of about 1100 mm per year, with maxima along the coastal plain and the  
6 mountains of the Appalachians. Part of the precipitation in the northeast falls as snow in the  
7 wintertime (Hayhoe et al., 2007). The eastern seaboard is susceptible to tropical storms and  
8 hurricanes during the Atlantic hurricane season, normally running from June to end of  
9 November, which enhance precipitation across southern and eastern parts, and play a role in  
10 alleviating drought (Kam et al., 2013). The El Niño-southern Oscillation (ENSO) alters  
11 precipitation patterns across the southeast (Colby, 2008). Coastal extra-tropical cyclones bring  
12 the bulk of the wintertime precipitation to that region, forming along the natural temperature  
13 gradient of the Gulf stream before moving up the coastline (Gurka et al., 1995). Seasonally,  
14 there are slight changes in the precipitation distribution through the year. For example,  
15 Burlington, Vermont has a summer maximum and a winter minimum while Portland, Maine  
16 has a fall and winter maximum, with a summer minimum in precipitation. The water supply  
17 in the northeast is mainly derived from surface waters, which are heavily regulated to meet  
18 the water supply demand of urbanized areas such as New York City, although there has been  
19 an increase in groundwater sources in recent years. In contrast, the southeast, including  
20 Florida, lies on active aquifers (USGS, 2009). Projections of future climate indicate an  
21 increase in precipitation over the eastern U.S. (Hayhoe et al., 2007; EPA, 2008) with  
22 consequences for changes in low flows across the region.

## 23 **2.2 Streamflow data**

24 Initially, 4878 sites with daily streamflow records were retrieved from the USGS National  
25 Water Information System (NWIS) (USGS, 2014) for the eastern U.S. as defined by  
26 Hydrological Unit Codes (HUC) of 01, 02, or 03. Previous studies on low flows (e.g. Kroll et  
27 al., 2002, 2004; Douglas et al., 2000) have used the USGS Hydro-Climatic Data Network  
28 (HCDN; now updated to HCDN-2009; Lins, 2012), in part because anthropogenic influences  
29 at these sites are deemed to be negligible, but as such, is limited to 204 sites across the  
30 domain. Of the original 4878 sites, 2811 were active in the 2000's or later. Among these, 1092  
31 sites had at least 30 years worth of daily data, 740 sites had 50 years or more, and 324 sites  
32 had 75 years or more. We used sites with at least 50 years of data as a balance between having

1 enough of data at each site to identify long-term changes and the need to have many sites to  
2 characterize the spatial pattern of changes. We included only sites that did not have any  
3 missing years of daily data. This reduced the number of sites to 508 (Figure 1b). Only 64 of  
4 these sites are in the HCDN-2009 database and have data for the common time period (1951-  
5 2005) that is used for analyzing trends across the domain (see section 4). The drainage area of  
6 the candidate sites ranges from very small (5-100km<sup>2</sup>) to large (38,000-67,000km<sup>2</sup>), with the  
7 majority of areas between 200-500 km<sup>2</sup> and these are spread fairly uniformly across the study  
8 area. The majority of the 508 sites are clustered on the eastern flank of the Appalachians and  
9 the northeast from eastern Virginia to New Hampshire. There is also a cluster of smaller  
10 catchments in central Florida. The mean, median, minimum and maximum record lengths are  
11 74, 72, 50, and 120, respectively.

12 Based on the USGS site notes (available on the NWIS website), we identified sites that are  
13 flagged as: regulated, partially regulated, flow below the rating curve limit, dam failure,  
14 affected by urbanization, change of base discharge, and change of gauge datum. It should be  
15 noted that the USGS flags are developed for instantaneous peak flows and while it is  
16 uncertain whether these are directly applicable to low flows, it is likely that low flows are  
17 more sensitive to regulation. Some of the flags are unrelated to anthropogenic influences and  
18 are unlikely to have impacted the continuity of flow magnitudes, such as “change of base  
19 discharge”, which is a level above which peak flows are recorded, or “change of gauge  
20 datum”, which is the arbitrary zero gauge height for the rating curve. Figure 1c shows the  
21 location, flag type, and the number of the sites under each flag. Almost half of the sites have  
22 no flag and these are located throughout the domain. A few sites have more than one type of  
23 flag and we show the flag associated with a higher likelihood of the flows being affected (e.g.  
24 regulated). The majority of regulated or partially regulated sites are concentrated in the  
25 northeast, but this is also where the majority of all sites are located. The sites in the mid-  
26 Atlantic states are generally more affected by urbanization or have experienced a change of  
27 gauge datum. Overall, 198 sites out of 508 sites are flagged as affected in terms of  
28 anthropogenic influences. In the results section, we show how the results of our statistical  
29 methods compare with the USGS site flags that are related to regulation or some other human  
30 influence.



## 1 **2.3 Low Flow Indices**

2 We analyze four variants of low flows based on different time scales, to understand how non-  
3 stationarity is dependent on the time scale as the data become smoother, with implications for  
4 the detection of non-stationarity. The 1-day minimum low flow, Q1, is the annual minimum  
5 daily streamflow. The other three variants, Q7, Q30, Q90, are obtained by applying the same  
6 analysis to 7-day, 30-day, and 90-day moving average versions of the time series. Together,  
7 we refer to the four low flow variables as the n-day minimum flows. Q7 (dry weather flow) is  
8 the most widely used low flow statistic in the U.S. (Kroll et al., 2004; Smakhtin, 2001), but  
9 the others are important for different applications, such as Q1 for ecological assessments and  
10 Q90 for reservoir operations. We also calculate the day of the year of low flows and use this  
11 to identify the primary (and in some regions the secondary) low flow season, as well as any  
12 long-term changes in timing. The primary season is defined as the 4-month period that  
13 contains the majority of the low flow occurrences, and the secondary season as the 4-month  
14 period that contains the majority of the remaining low flows. If the onset time of the low flow  
15 season for a site occurs 70% to 100% in a specific month, that site is assumed to have only  
16 one low flow season. The sites that have low flow events occurring 40-70% of the time in one  
17 month and 20-40% of the time in a different month are characterized as having two low flows  
18 seasons. We focus the presentation of the results on Q7 and Q30 flows.

## 19 **2.4 Identification of Stationary Time Series**

20 A sequence of realizations of random variables,  $Y$ , is stationary if the distribution of the  
21 sequence is independent of the choice of starting point (Kendall et al., 1983; Ruppert, 2011).  
22 Determining stationarity of a time series is not straightforward (Lins and Cohen, 2011) and in  
23 practice, it is common to look at restricted measures of stationarity. A time series is defined as  
24 weakly stationary if it satisfies three criteria:

$$25 \quad E(Y_i) = \mu, \quad (\forall i) \quad (1a)$$

$$26 \quad Var(Y_i) = \sigma^2, \quad (\forall i) \quad (1b)$$

$$27 \quad Corr(Y_i, Y_j) = \rho(|i - j|), \quad (\forall i, \forall j) \quad (1c)$$

28 where  $\mu$  is the sample mean,  $\sigma$  is the standard deviation and  $\rho$  is the correlation, with  $i$   
29 representing one realization of a time series. This means that for a weakly stationary variable,  
30 the mean and variance do not change with time and the correlation between two values

1 depends only on the lag (the time between values). Visual inspection of the time series and  
2 the changes therein can provide an indication in the attempt to assess stationarity, in that a  
3 change in the underlying process leads to changes in values that are obvious (Lins and Cohen,  
4 2011; Koutsoyiannis, 2011; Serinaldi and Kilsby, 2015).

5 We apply three tests to identify weak stationarity: (1) the Mann-Kendall test (Mann, 1945;  
6 Kendall, 1975), which tests for increasing or decreasing trends; (2) the Pettitt test (Pettitt,  
7 1979), which tests for abrupt changes or change points; and (3) the Ljung-Box test (Ljung and  
8 Box, 1978), which tests for autocorrelation. An identified change in the mean by either of the  
9 first two tests would rule out stationarity, except in the case of autocorrelated data, for which  
10 the Pettitt and Mann-Kendall tests will characterize too many sequences of the time series as  
11 having a step or trend and therefore increase the rejection rate of the null hypothesis of no  
12 change (Douglas et al., 2000; Serinaldi and Kilsby, 2015). Therefore, analysis of  
13 autocorrelation is carried out before conducting the Mann-Kendall and Pettitt tests. Even  
14 when a site is identified as non-stationary, further analysis is required to understand the  
15 overall regime of the data at such a site. For example, the time series may have two separate  
16 stationary regimes with one change point in between or an overall trend. We then assume that  
17 the change year corresponds to human intervention, which is generally borne out by  
18 investigating the site notes.

## 19 **2.5 Decomposition Algorithm**

20 The three statistical tests (Ljung-Box, Pettitt and Mann-Kendall) were combined into a  
21 recursive algorithm to identify non-stationarity in the low flow time series and decompose the  
22 series into potentially stationary sub-series. In the first step of the algorithm, a Ljung-Box test  
23 with 20 lags was applied to the entire time series of each site, and sites with significant overall  
24 autocorrelation (5% significance level) were identified. The Ljung-Box test identifies sites  
25 that are non-stationary and is able to identify sites with abrupt changes because the series of  
26 values before the change appear to be autocorrelated relative to the values after the change,  
27 and vice-versa. This was confirmed by visual inspection of the time series. For the sites with  
28 significant overall autocorrelation, we then applied the Pettitt test (5% significance level) to  
29 confirm the existence of any step change and identify its timing. The series were pre-whitened  
30 to remove lag-1 autocorrelation using the trend-free pre-whitening method of Yue et al.  
31 (2002) and implemented by Kumar et al. (2009). It is necessary to identify sites with potential  
32 step changes using the Ljung-Box test first because the Pettitt test will identify step changes

1 in time series with gradual trends. Similarly the MK test will identify gradual trends in series  
2 with step changes. If a significant change is found by the Pettitt test, the series is split into two  
3 parts either side of the step change. Each part is assumed to be a new series at the same  
4 location, and if it has a record length of 30 years or more, the decomposition algorithm is  
5 applied again. If the length is less than 30 years, the site is removed from further  
6 consideration. If a statistically significant step change is not identified, we note that the series  
7 is autocorrelated overall. We then applied the Mann-Kendall (MK) test (5% significance  
8 level) on the remaining sites to identify statistically significant trends in the data. Again, the  
9 series were pre-whitened to remove lag-1 autocorrelation. The series and sub-series are  
10 assigned categories as follows:

11 Category 1: Non-autocorrelated site with no trend (MK=0);

12 Category 2: Non-autocorrelated site with a statistically significant decreasing trend (MK=-1);

13 Category 3: Non-autocorrelated site with a statistically significant increasing trend (MK=1);

14 Category 4: Autocorrelated site with statistically significant step change, time series split and  
15 the sub-series re-categorized recursively;

16 Category 5: Autocorrelated site with no step change.

17

### 18 **3 Stationarity results**

#### 19 **3.1 Categorization of sites**

20 Figure 2 shows the spatial distribution and the number of sites in each category after the first  
21 recursive level of the decomposition algorithm. The results for Q7 and Q30 low flow metrics  
22 are presented for the available length of record at each site, which ranges between 1891 and  
23 2011. No site has a record length less than 50 years and no site has any gap in the n-day low  
24 flow series. As we move from Q7 to Q30, a larger number of sites appear stationary (category  
25 1) and the number of sites identified using the Pettitt test as having an abrupt shift in the time  
26 series (category 4) decreases. The algorithm re-applies the Pettitt test to category 4 sites to  
27 identify useable sub-series. For example, the Q7 time series of 112 sites are split into two  
28 parts, which are subjected to further categorization.

1 Figure 3 summarizes the time periods that were identified as useable at each step of the  
2 recursive algorithm for all sites for Q7. The vertical axis shows the site number from 1 to 508  
3 ordered from the lowest to highest latitude. Therefore, site 1 is the most southerly and site 508  
4 is the most northerly. The left panel of Figure 3 shows the record length of sites, which, in the  
5 first step of categorization, had no significant autocorrelation. These sites are colored  
6 according to whether they contain a step change, have a significant trend or have no trend.  
7 The middle panel shows the sites identified in step 1 with a step change, with each series split  
8 into two parts. The two parts of the series are again colored according to whether they contain  
9 a step change or have a trend. The right panel shows the parts of the time series that were  
10 recovered in the third step of the decomposition algorithm. As long as the record length is  
11 greater than or equal to 30 years the algorithm is applied recursively on the remaining parts of  
12 the time series. The number of sites shown in the right panel is small but their data are still  
13 useful for subsequent analysis.

## 1    **3.2    Comparison with USGS flags**

2    Table 1 shows the breakdown of the number of sites in each category and the relation to  
3    USGS flags for Q7 and Q30, and indicates that in every category, anthropogenic influences  
4    are documented by the USGS. For Q7, the majority of sites in categories 4 (57%; step change)  
5    are flagged by the USGS as somehow affected. This suggests that the algorithm has some  
6    skill in identifying managed or altered flow series. However, there are also many sites in  
7    category 1 (36%; no trend), 2 (16%; decreasing trend) and 3 (42%; increasing trend) that are  
8    also flagged (see Figure 4) suggesting that anthropogenic impacts for these sites are minimal  
9    and/or are overwhelmed by any climate or land use induced changes. The fact that the  
10    majority of stationary sites (category 1) are not flagged is encouraging. Figure 4 shows all the  
11    sites from each of the 5 categories that have no anthropogenic flag for Q7: 310 out of 508  
12    sites are not flagged but only 153 of these 310 sites show absolute stationarity behavior  
13    (category 1) and the rest exhibit some form of non-stationary.

14    From Table 1 we observe that:

15    1.    If a site is flagged and its low flow series has a trend, the flags are mostly for  
16    regulation of partial regulation; sites with increasing trends are more likely to be flagged as  
17    regulated.

18    2.    If a site is flagged and it exhibits a step change, the flag is mostly associated with  
19    regulation, or possibly urbanization;

20    3.    If a site is in category 5 (not considered further due to significant autocorrelation), it  
21    may be flagged as regulated;

22    4.    If a site shows no trend but is still flagged, the flag relates to regulation. This suggests  
23    that the impact of the flagged change was either minimal or good management practices have  
24    been put in place. The majority of these sites are located in the upper Mid-Atlantic in the  
25    states of New York, New Jersey, and Virginia.

26    We also applied the algorithm to the HCDN-2009 sites within the domain, to confirm that the  
27    algorithm can identify sites that have been independently determined as unaffected by human

1 influences. We found that 82% and 86% of these sites were placed in category 1 (stationary)  
2 for Q7 and Q30, respectively, with most of the remaining sites in category 3 (increasing trend;  
3 9% and 8%) or category 6 (autocorrelated; 5% and 4%).

### 4 **3.3 Variability in year of abrupt change**

5 For sites that were identified by the Pettitt test as having an abrupt change, Figure 5a,b shows  
6 the variability of the year of change for Q7 and Q30. Most of the changes occurred between  
7 1962 and 1986, and as discussed above, most of these are flagged as having regulation. The  
8 spatial distribution of changes indicates that stream regulation began in the northeast before  
9 spreading to the southeast. The Pettitt test tends to identify significant changes away from the  
10 either ends of the time series, and so may not identify changes in the earlier or later part of the  
11 record. However, earlier or later step changes are identified in the second recursion of the  
12 decomposition algorithm.

13 We further examined the consistency of the change year among the Qn series, with the  
14 expectation that abrupt changes would be identified for the same year across all or most Qn  
15 time series. Figure 5c shows the spatial distribution and the number of sites with a consistent  
16 year of change between Q7 and Q30. Out of 111 sites whose Q7 time series were identified as  
17 having a step change by the Pettitt test, more than half (61) showed the same change year for  
18 as the Q30 series. Although we have identified the change year for all Qn, the results for Q7  
19 may be the most appropriate for identifying a change since the data are close to the original  
20 values, but are less affected by measurement errors than Q1 (WMO, 2008).

21

## 22 **4 Variability and Trends in Low Flows and Timing**

### 23 **4.1 Trends in low flows**

24 We identified a time period (1951-2005) common to all sites for which they have useable  
25 data, and calculated statistics of Qn, including the trend, and the consistency of trends among  
26 Qn values. The MK trends for Qn for the sites that were categorized as 1, 2, or 3 by the  
27 decomposition algorithm and are shown in Figure 6a for Q7 and Q30. Sites with lower trend  
28 magnitudes tend to become non-significant (MK=0) as we move from Q1 to Q90 (not  
29 shown). Overall, the northeastern sites show increasing trends in low flows and the southeast  
30 sites show decreasing trends.

1 A summary of the consistency of trends between Q7 and Q30 low flows is shown in Figure  
2 6c. 336 sites (88% of the sites) have the same trend, such that the Q7 and Q30 series are all  
3 increasing, decreasing, or not changing. 162 sites (32%) agree on the sign of trend for three  
4 out of four of the Qn trends, and 87 sites (17%) agree for 2 out of 4 of the Qn trends. Overall,  
5 the consistency in trends among the Qn series is generally uniformly distributed across the  
6 domain.

7 Figure 7 (top left) shows the spatial pattern of the MK trend test values for Q7 for all sites  
8 (without testing for step changes or autocorrelation), and when we only consider sites without  
9 step changes (top right). In both cases, the pattern of increasing trend in low flows in the  
10 northeast and a decreasing trend in the southeast is apparent. However, ignoring the effect of  
11 autocorrelation may give rise to misleading results by showing a denser pattern of significant  
12 trends. The bottom left panel shows the results removing sites with step changes and pre-  
13 whitening the data for the remaining sites. The bottom right panel show the trends when sites  
14 that have USGS flags are also excluded, e.g. for sites without documented anthropogenic  
15 impacts. The drivers of trends at these sites are therefore likely related to climate  
16 variability/change and/or land use change, rather than management of, or influence on, flows.

17

## 18 **4.2 Variability in low flow timing**

19 Figure 8 summarizes the distribution of the onset of the low flow season for Q7, for the  
20 primary season (top panels) and the second season (bottom panels). The left panels show the  
21 onset month of the season and the right panels show the probability of the onset season in that  
22 month. If the onset time of the low flow season for a site occurs 70% to 100% in a specific  
23 month, that site is assumed to have only one low flow season. For Q7, 353 sites out of 395  
24 (almost 90%) sites have a single low flow season, and the onset of the season changes from  
25 north to south. Most of the sites north of North Carolina have low flow seasons starting in  
26 July, which is generally driven by the slight decline in precipitation during the autumn as well  
27 as the increased evaporation during the summer (Small et al., 2006). In Florida the season  
28 starts in April-May. For coastal sites, the season starts earlier (mostly in June), and for sites in  
29 the southwestern part of the domain, the season starts mostly in September-October.

30 The sites with two low flows seasons are mostly in Florida, and along the coastline of  
31 Georgia, South and North Carolina, New York, New Jersey, and Maine and their second

1 season occurs mostly in fall. For New York, New Jersey, and some sites along the west  
2 coastline of Florida, the second low flow season mostly starts in November and December.  
3 Sites near the Gulf of Mexico and some sites in North Carolina have second low flow seasons  
4 starting in April. The second low flow season for the far northeast sites begins in December or  
5 January and can be related to freezing conditions that may store water as snow and river ice.

### 6 **4.3 Changes in low flow timing**

7 To determine whether low flow timing has changed over time, we examined sites with one  
8 low flow season as defined as 70% of low flow occurrences in the same season, again for the  
9 common time period of 1951-2005. Analysis of changes in timing irrespective of the season  
10 (not shown) did not show evidence of shifts in timing from one season to another. For Q7, for  
11 example, 47 sites out of the total 508 were removed because their low flow season occurs less  
12 than 70% of the time in one season. Out of the remaining 467 sites, 20 sites showed a  
13 decreasing (earlier) trend in timing and were mostly in Pennsylvania and the Carolinas  
14 (Figure 9) and 14 showed an increasing (later) trend with most of these in the northeast. The  
15 MK test for Q30 timings showed mainly decreasing (earlier) trends (26 sites), with most  
16 overlap with the Q7 results in Pennsylvania. These sites have low flow seasons starting in  
17 July, and half of them are regulated or partially regulated. Only a few sites were identified by  
18 the Pettitt test (5% significance) to have a significant step change in either direction.

19 The tendency for low flows (Q7 and Q30) to occur earlier in the season in recent years may  
20 be because of a shift of low precipitation from the late to mid summer, but given the small  
21 number of sites with significant trends and their low spatial coherence, this is speculative.  
22 Although the sites in Pennsylvania did not show a trend in low flow volumes, the overall  
23 trend for the northeast is an increasing trend in low flow volumes suggesting that early  
24 summer low precipitation might also be increasing. More investigation is required to confirm  
25 whether low precipitation is happening earlier in summer, for example during May and June,  
26 and whether the amount is increasing.

27



## 1 **5 Discussion and conclusions**

### 2 **5.1 Potential drivers of trends in low flows**

3 We found spatially coherent patterns of increases in low flows in the northeast and decreases  
4 in the southeast, which was robust to the presence of USGS flags and autocorrelation in the  
5 time series, despite the smaller number of sites. The pattern of increasing low flows in the  
6 northeast is consistent with regional scale studies (e.g. Hodgkins and Dudley, 2011) and are  
7 consistent with the increases in 7-day low flows and fall precipitation shown in Small et al.  
8 (2006) that focused on a smaller set of sites across the eastern U.S. from the HCDN. Several  
9 other studies (e.g. Douglas et al., 2000; McCabe and Wolock, 2002; Hayhoe et al., 2007;  
10 Andreadis and Lettenmaier, 2006) have identified an overall increasing trend in precipitation  
11 over the past 50 years, and a decreasing pattern in soil moisture drought over the much of the  
12 U.S. including the northeast (Andreadis and Lettenmaier, 2006). Therefore, an increase in low  
13 flow volumes in the northeast is consistent with the overall shift to wetter conditions. The  
14 generally decreasing trends in the southeast are also consistent with the results from Small et  
15 al. (2006) and Lins and Slack (1999), which is despite an overall increase in precipitation in  
16 the region.

17 To understand the potential drivers of these trends more comprehensively, Figure 10 shows  
18 the Q7 trend magnitude and the antecedent precipitation for the previous 180 days. This  
19 period was chosen as it provides the highest correlation with low flow volumes (Kam et al,  
20 2015), although the results with 150 and 90 days are similar. The precipitation data are taken  
21 from the long-term precipitation dataset of Livneh et al. (2013) and are averaged over the  
22 basin corresponding to each site. The similarity between the trends in low flows and  
23 antecedent precipitation is striking with a clear increasing trend in the north and decrease in  
24 the south, although many of the trends are not statistically significant.

25 The main disparity is in coastal plains of eastern Virginia, Maryland and northwards to  
26 Maine, where Q7 low flows have decreased but antecedent precipitation is increasing (both  
27 often statistically significant). The reason for this is unclear, but groundwater is likely playing  
28 a role across the coastal plain aquifer of the mid-Atlantic states and up into New England  
29 (Dudley and Hodgkins, 2013) either via changes in recharge or indirectly through  
30 anthropogenic impacts. Groundwater pumping has reduced levels in the north Atlantic  
31 Coastal Plain aquifer system by tens of meters (e.g. Konikow, 2013, USGS, 2006) and has

1 likely reduced discharge to streams in the northeast (e.g. Pucci and Pope, 1995; Brutsaert,  
2 2010; Barlow and Leake, 2012). Similarly, overuse of groundwater resources in the southeast  
3 (Konikow, 2013) may be contributing to decreases in low flows across the region (e.g. Bosch  
4 et al., 2003; Opsahl et al., 2007; Brutsaert, 2010).

5 Increases in evaporation (Walter et al., 2004; Nolan et al., 2007; Huntington and Billmire,  
6 2014) may have also led to declines in groundwater recharge and streamflow (Hodgkins and  
7 Dudley, 2011), and potentially cancelled out the overall increases in precipitation across much  
8 of the U.S. (Andreadis and Lettenmaier, 2006). Figure 10 also shows an estimate of the trend  
9 in late summer/early fall potential evaporation based on the NLDAS2 dataset of Xia et al.  
10 (2012). Potential evaporation has increased over the eastern U.S. with statistically significant  
11 trends over much of the mid-Atlantic states and the southeast. This suggests that increasing  
12 atmospheric demand in the southeast may have exacerbated declines in low flows, and this  
13 may have offset increasing precipitation somewhat in the northeast. Changes in land use may  
14 also explain trends in both regions, whereby land abandonment in the northeast and forest  
15 harvesting and urban development in the southeast may have contributed to the respective  
16 trends in each region (Cho et al., 2009; Payne et al., 2005; USGS, 2012), although attribution  
17 is difficult.

18 The analysis of trends in timing of low flows showed one cluster of sites with a trend to  
19 earlier timing. These sites are mostly in central and west Pennsylvania, and central southern  
20 New York. The reasons for the changes are unclear, but may be related to regulation and  
21 possibly a shift in the low precipitation season to earlier in the summer. The timing of low  
22 flows in the other parts of the domain has not changed based on a 5% significance level.

## 23 **5.2 Conclusions**

24 This study has examined the presence of non-stationarity in low flows across the eastern U.S.  
25 in terms of volumes and timing. We focused on the full period of available data at each site to  
26 identify abrupt shifts that may be associated with management, in particular dam construction,  
27 and gradual trends that may be an impact of climate change, land use change or  
28 surface/ground water withdrawals. A decomposition algorithm was used to identify useable  
29 sub-series of the data that could then be further analyzed for trends. Comparison with USGS  
30 site flags indicates that the majority of sites with identified step changes and increasing trends  
31 are noted to be regulated in some way, and some are documented as having undergone

1 urbanization. For sites with decreasing and increasing trends, about one sixth and one half,  
2 respectively, have USGS flags and these are almost all for regulation. Furthermore, about one  
3 third of sites with no trend are also flagged as being regulated or partially regulated. Our  
4 approach is therefore generally capable of identifying sites with documented regulation, and  
5 confirmed by the evaluation of the HCDN-2009 sites, but regulation does not always manifest  
6 in a detectable change in the low flow time series. This may be because the documented  
7 regulation or other change did not have an impact or that the signal is small compared to the  
8 variability in the time series. This is particularly the case for higher low flow metrics such as  
9 Q90, for which the regulation is generally less detectable. For sites with documented  
10 regulation but no detectable signal, the fact that the USGS flags relate to high flows rather  
11 than low flows may help explain this, or that the sites are well managed in terms of low flows.  
12 For example, flows are often artificially elevated above the natural levels of low flow to  
13 create "anti-droughts" to manage the restoration of river systems (Bunn et al., 2006).

14 Several outstanding questions remain, most importantly what are the low flow generating  
15 mechanisms across the eastern U.S. and what are the drivers of long-term changes in the  
16 volumes and timing. Potential mechanisms include, but are not limited to: changes in  
17 antecedent precipitation and teleconnections with large-scale climate (e.g. the North Atlantic  
18 Oscillation; Kam et al., 2015), land use change, surface and groundwater abstraction, and  
19 streamflow regulation. The results of this study suggest that low flow variability in the eastern  
20 U.S. is driven by a mixture of climatic and anthropogenic effects, with suggestions that  
21 changes in climate have played a role in both the northeast and southeast. However, definitive  
22 attribution will require detailed analysis of these competing factors and possibly carefully  
23 crafted modeling studies. In parallel with calls for more rigorous efforts at attributing  
24 changes in flood time series (Merz et al., 2012), increased effort is also needed for  
25 understanding and attributing changes in low flows. Several new approaches have been put  
26 forward recently that show promise for detecting and attributing changes in hydrological time  
27 series, including extremes, based on multiple working hypotheses (Harrigan et al., 2014) and  
28 complex statistical modeling (Prosdocimi et al., 2015).

29 The results of this study can help in understanding changes in low flows across the eastern  
30 U.S., and the impact of anthropogenic and natural changes. It can therefore provide  
31 information for water management, and restoration of stream flows and aquatic habitats.  
32 Although we do not claim to make a definitive judgment on whether low flows at a particular

1 site are influenced by human activities or are completely free of influences because of the  
2 complexities of low flow generation, our approach shows promise for systematically  
3 identifying sites for further investigation, especially where supporting information (such as  
4 site notes) are available to support the statistical results. Our approach may be especially  
5 useful for exploring large-scale, climate-driven changes in the low flow regime where pooling  
6 of results across sites increases confidence in the robustness of any identified changes. The  
7 methods are readily transferable to other parts of the U.S. and globally, given long enough  
8 time series of daily streamflow data, although further work is required to understand their  
9 universal application.

10

### 11 **Author Contribution**

12 S. S. and J. S. conceived the study. S. S. performed the analysis with help from J. K. S. S.  
13 prepared the manuscript with contributions from the other authors.

14

### 15 **Acknowledgements**

16 This work was supported by the USGS (G11AP20215) and NOAA (NA14OAR4310130 and  
17 NA14OAR4310218)

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- 3
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1 Table 1. Comparison of the number of streamflow gauging sites in each category of the  
 2 decomposition algorithm and their USGS flags for Q7. DamFail: dam failure; RegPar:  
 3 partially regulated; Reg: regulated; Urban: affected by urbanization.

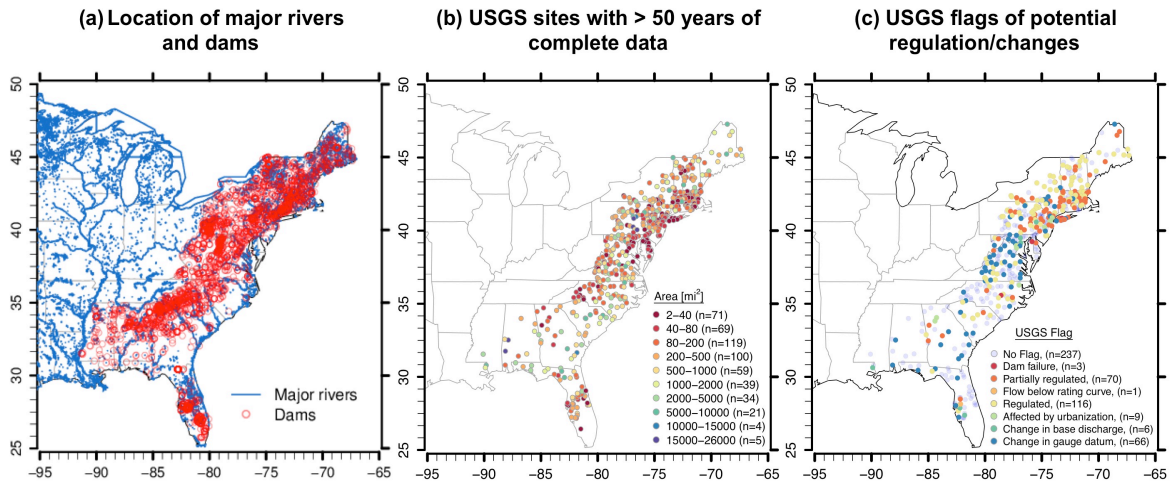
Category	$Q_7$	$Q_{30}$	Flag	$Q_7$	$Q_{30}$	Flag type	$Q_7$	$Q_{30}$
No Trend	240	260	Flagged	87	91	DamFail	1	2
						RegPar	33	37
						Reg	51	48
						Urban	2	4
Not flagged				153	169			
Decreasing Trend	62	61	Flagged	10	6	DamFail	0	0
						RegPar	3	1
						Reg	5	5
						Urban	2	0
Not Flagged				52	55			
Increasing Trend	55	70	Flagged	23	37	DamFail	0	0
						RegPar	8	13
						Reg	15	24
						Urban	0	0
Not Flagged				32	33			
Step Change	111	89	Flagged	64	53	DamFail	1	0
						RegPar	21	16
						Reg	38	32
						Urban	4	5
Not Flagged				48	36			
Autocorrelated	38	27	Flagged	13	10	DamFail	1	1
						RegPar	4	2

Reg	7	7
Urban	1	0

Not Flagged 25 17

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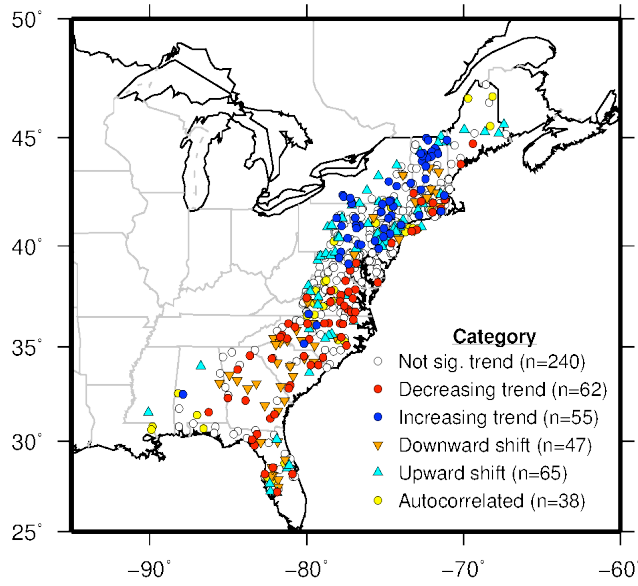


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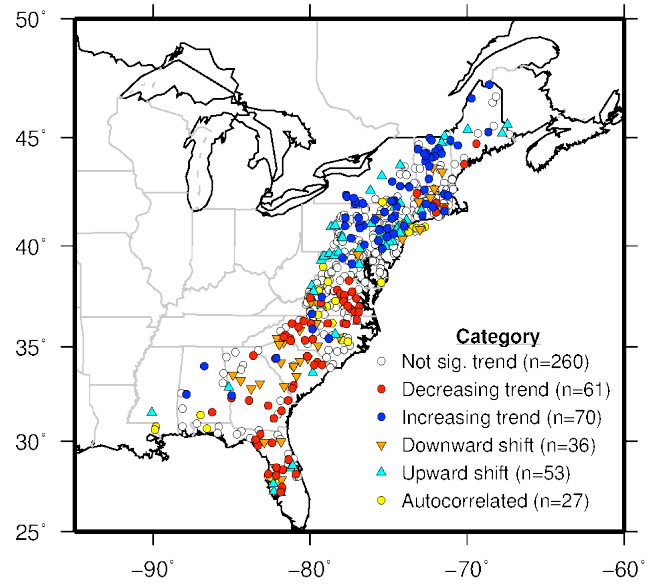
4 Figure 1. (a) Location of 2,352 major dams in the eastern U.S. (b) Location of the 508  
 5 streamflow sites with 50 years or more of complete daily data. (c) Flagged sites according to  
 6 the USGS.

7

(a) Q<sub>7</sub> Low Flow Categories

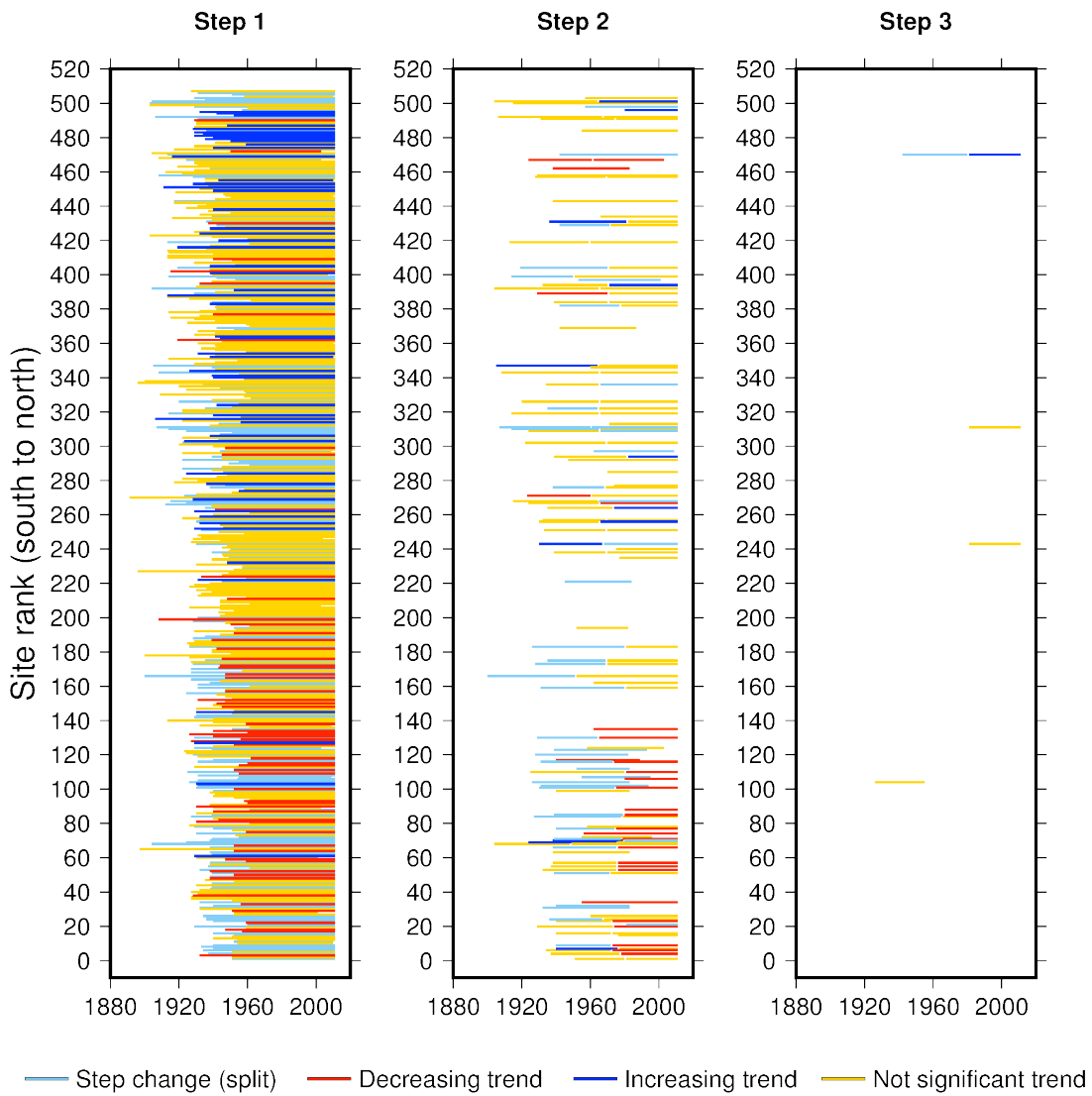


(b) Q<sub>30</sub> Low Flow Categories



1

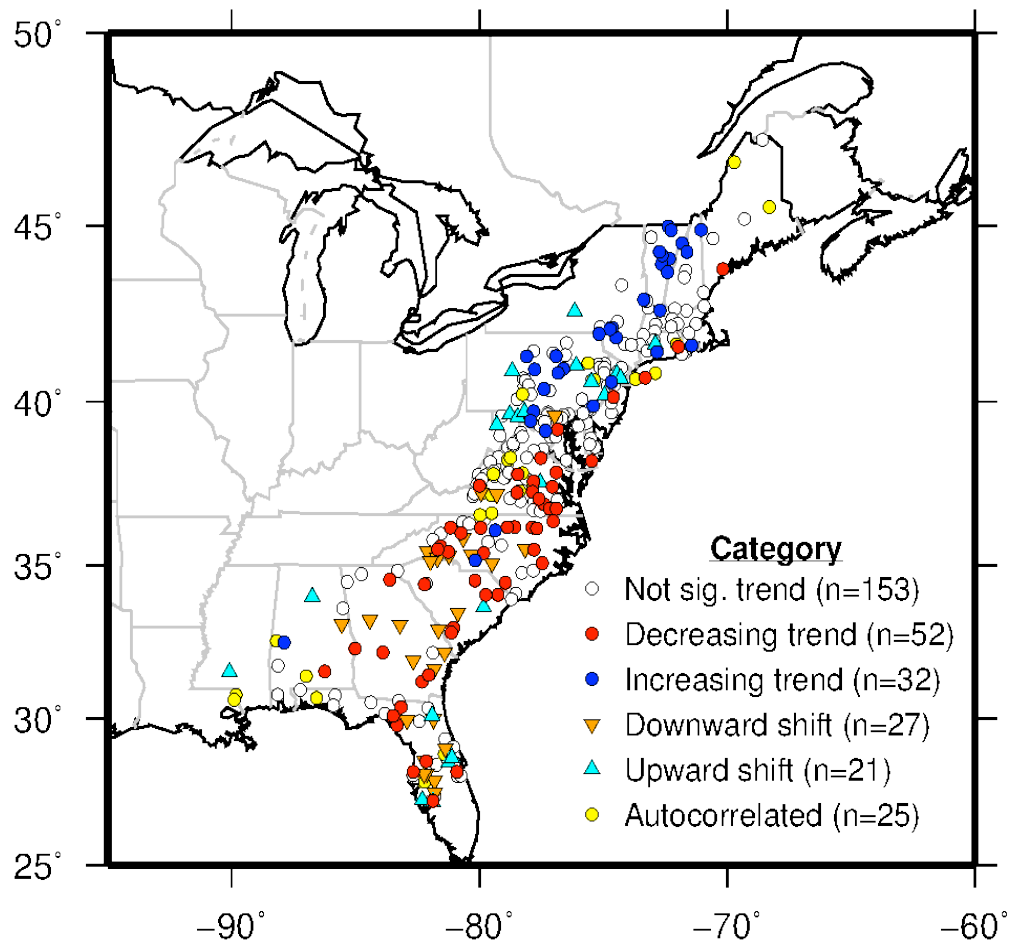
2 Figure 2. Categorization of non-stationarity of sites for Q<sub>7</sub> and Q<sub>30</sub>.



1  
 2 Figure 3. Range of years for each site that contain a step change, show a trend, or are  
 3 stationary, for each step of the decomposition algorithm.

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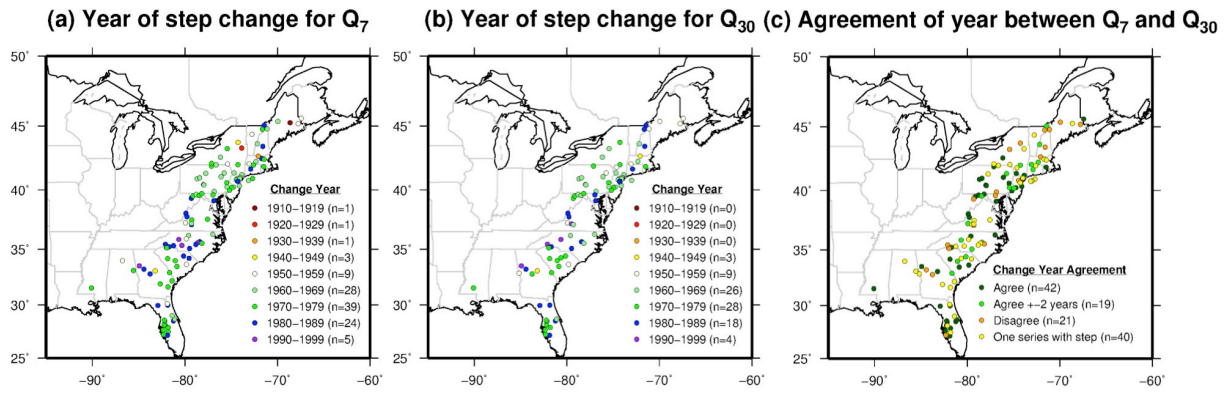
## Q<sub>7</sub> Low Flow Categories, no USGS flags



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2 Figure 4. Categorization of non-stationarity of sites for Q<sub>7</sub> with no USGS flags from the first  
3 step of the decomposition algorithm.  
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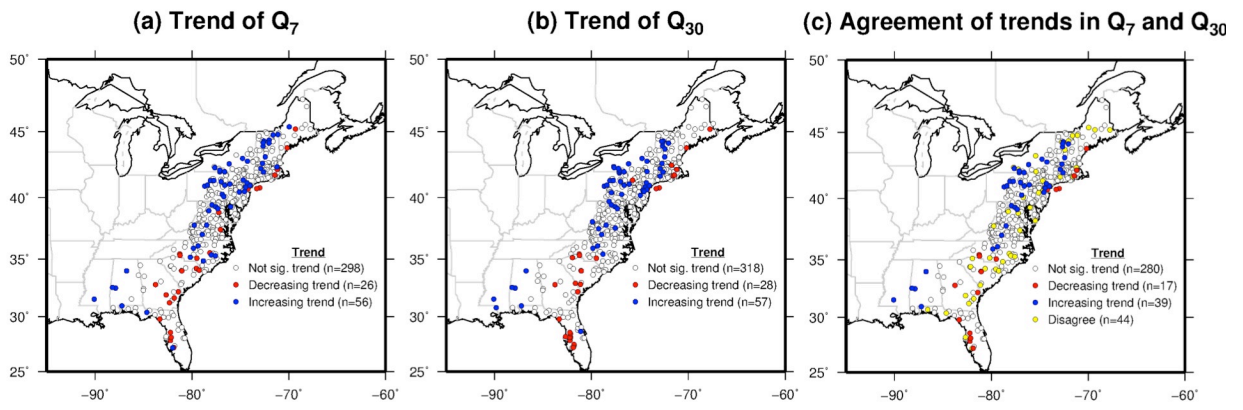


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3 Figure 5. Year of step change for (a)  $Q_7$  and (b)  $Q_{30}$ . (c) Agreement in year of step change  
4 between  $Q_7$  and  $Q_{30}$  time series.

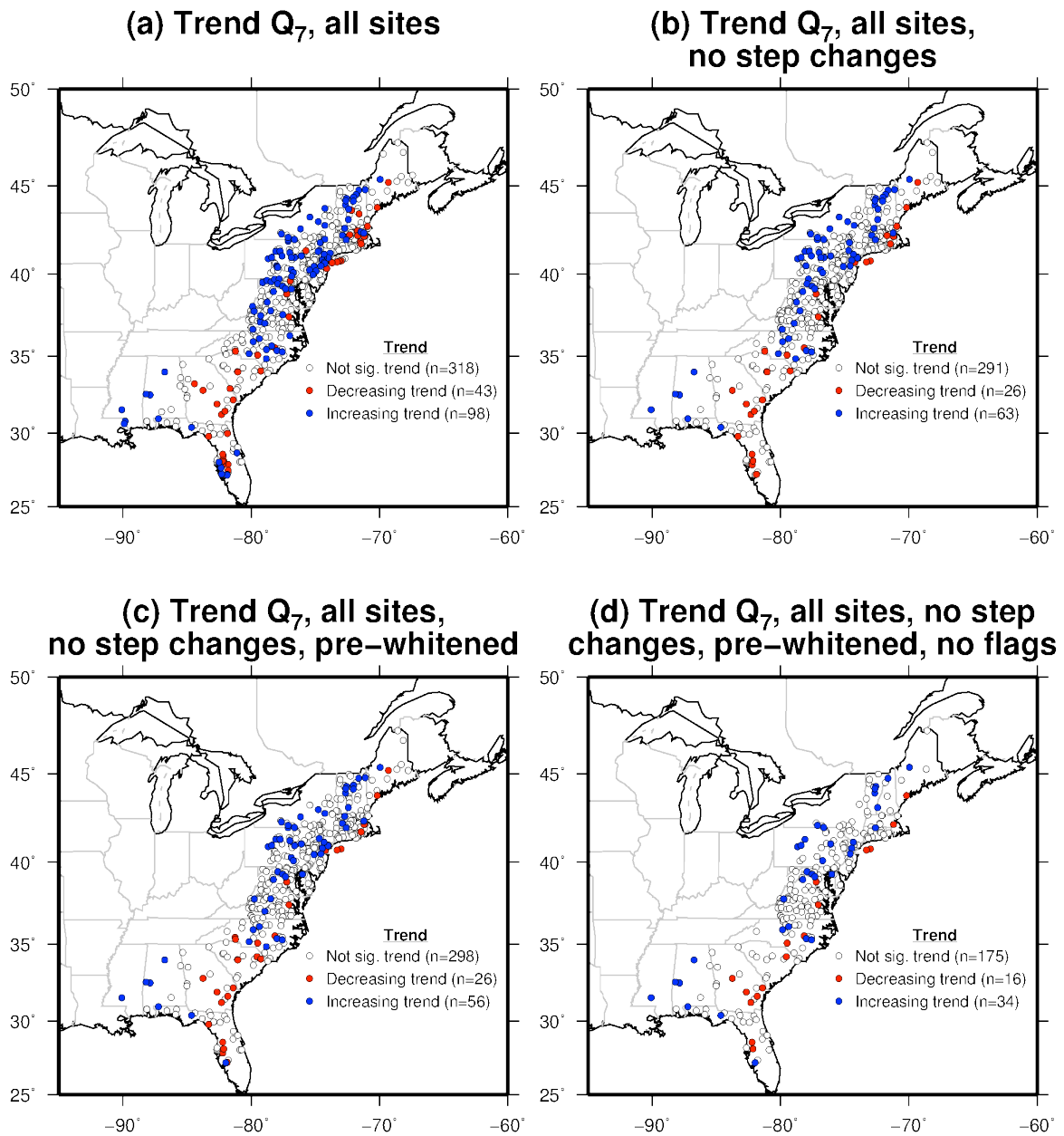
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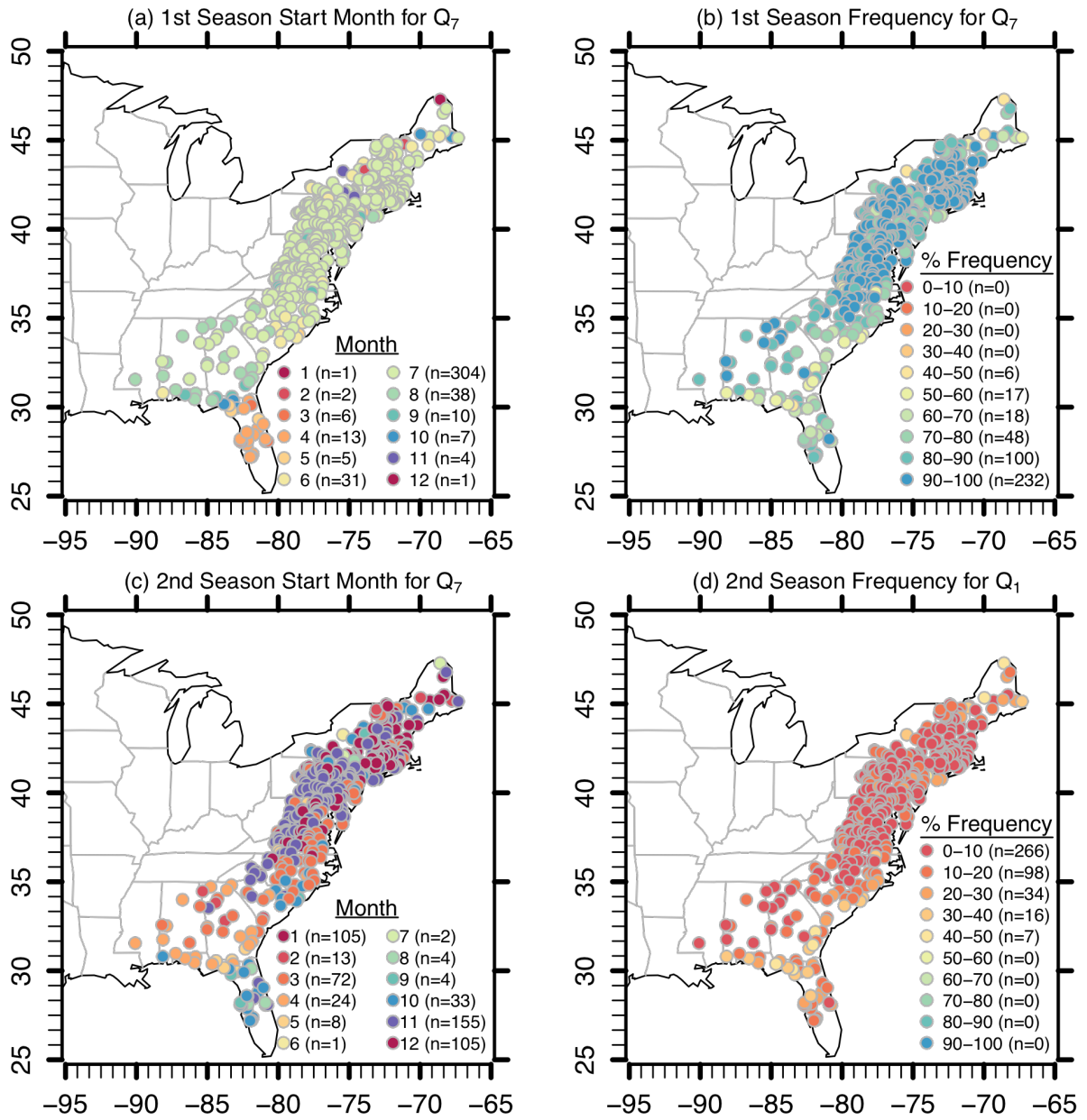
3 Figure 6. Trends in (a)  $Q_7$  and (b)  $Q_{30}$  for 1951-2005 and (c) their agreement.



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Figure 7. Trends in  $Q_7$  for 1951-2005 for (a) all sites, (b) excluding sites with step changes or overall autocorrelation, (c) as (b) but with pre-whitened data, and (d) as (b) but without USGS flags.

1



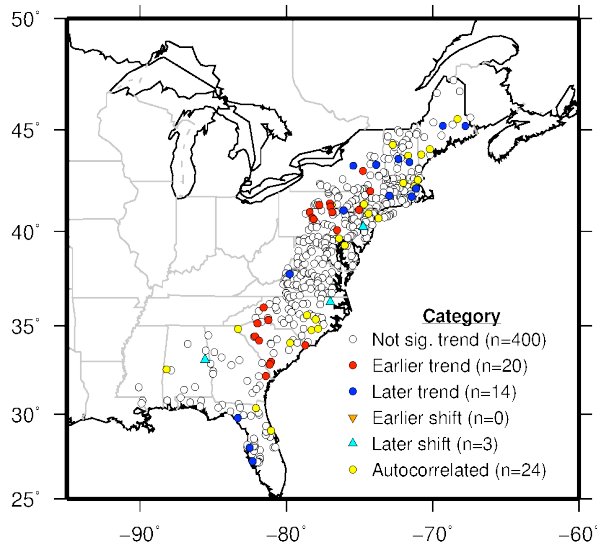
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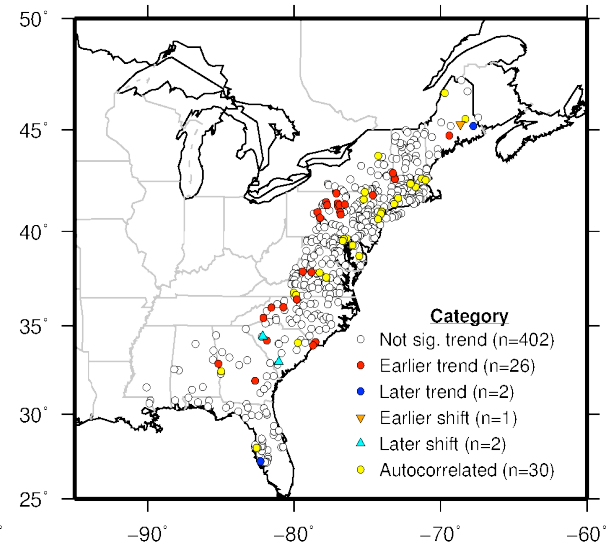
Figure 8. Primary and secondary seasons of occurrence of Q<sub>7</sub> low flows and their frequencies.

4

(a) Q<sub>7</sub> Timing Categories

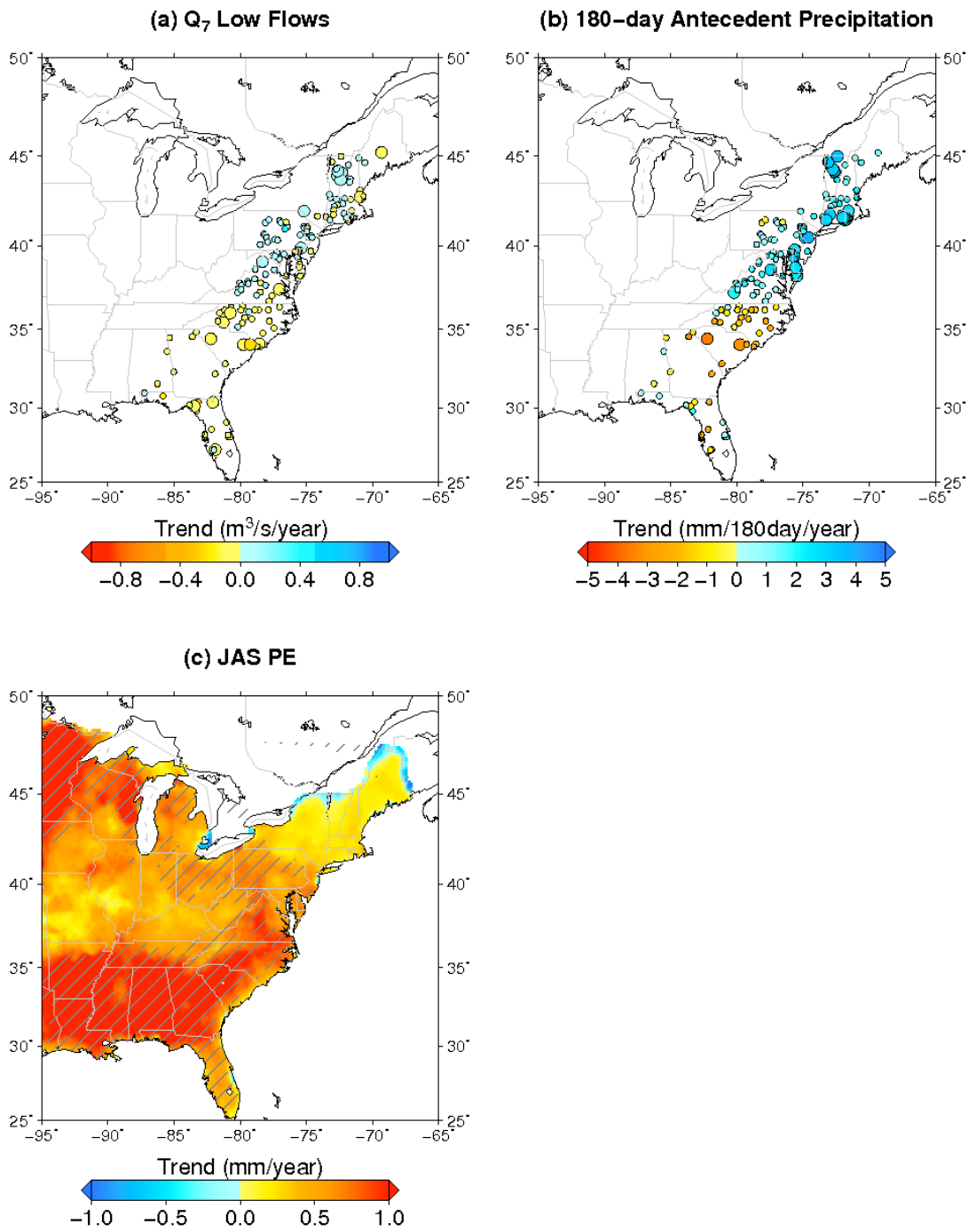


(b) Q<sub>30</sub> Timing Categories



1

2 Figure 9. Categorization of non-stationarity of sites for timing of (a) Q<sub>7</sub> and (b) Q<sub>30</sub>.



1  
 2 Figure 10. (a) Trend in Q<sub>7</sub> low flows for 1951-2005 for the warm season. (b) Corresponding  
 3 trend in 180-day antecedent precipitation. For (a) and (b), trends that are statistically  
 4 significant at the 0.05 level are shown in large symbols. (c) Trend in July-August-September  
 5 (JAS) potential evaporation for 1979-2012. Statistically significant trends are shown by  
 6 hatching.