Changing Seasonality of Annual Maximum Floods over the Conterminous US: Potential Drivers and Regional Synthesis

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Abstract

Understanding the flood generating mechanisms that influence flood seasonality in a region provides information on setting up relevant contingency measures. While former studies had estimated flood seasonality at regional/continental scale, limited/no studies had investigated the climate/basin drivers that influence the changes in flood seasonality. Considering this, the current study performed two analysis i) estimated the changes in the seasonality of annual maximum floods (AMF) between pre- and post-1970 across Hydroclimate Data Network basins over the coterminous United States, and ii) identified the predictors that influence the change in the seasonality from a set of climate and geomorphic variables. Significant changes in the AMF seasonality were noted for approximately half of the basins in the eastern US while low to no change was found in a majority of the basins in the central/western US. We found that a decrease (increase) in the seasonality index, indicating floods arriving more uniformly (more concentrated in time), is typically associated with an increase in the precipitation (temperature) in basins where a strong change in flood seasonality occurs. Elevation has a more dominant role as compared to the drainage area in changing the flood seasonality as the former affects the form of precipitation in basins in higher elevations. This is particularly true for western US where floods arrive more distributed over the year (i.e., decrease in flood seasonality index), which potentially indicates increased warming resulting in early snowmelt.

1. Introduction

Among the natural disasters, floods are the most damaging disasters resulting in significant loss of human life and property (Ohl et al., 2000; WHO, 2002; Jonkman, 2005). Several studies have predicted that the frequency of floods is likely to increase in the near future under global climate change (Yin et al., 2018), while a few studies found no strong evidence of an association between increased temperature and increased flooding (Wasko et al., 2019). Nevertheless, regions that are severely affected by recurring floods require information on the flood potential in the following seasons, thereby providing a basis for setting up contingency measures (Sankarasubramanian and Lall, 2003). Hence, it is of great importance to understand flood generating mechanisms of annual maximum floods (AMF) for ensuring reliable flood prediction and effective mitigation. In this context, one particular statistical attribute of importance is the seasonality of AMFs in a given basin/region (e.g., Villarini, 2015; Li et al., 2016). Analysis of flood seasonality and their temporal changes will provide us critical information on the changing flood risk at the national scale (McCabe and Clark, 2005; Nakamura et al., 2013).

Recently, Villarini (2015) and Ye et al., (2017) summarized the flood seasonality and their changes over the coterminous US (CONUS). Villarini (2015) showed a strong seasonality in flooding exists across the CONUS, with floods occurring during October to March across the western and eastern US and is concentrated in the post-winter (April to May) season in the snow-dominated basins. Villarini (2015) analyzed flood seasonality over 7506 USGS stations, consisting of natural and controlled basins, and found that the changes in flood seasonality is significant, as expected, in controlled basins. In a similar study for Great Britain, Black and Werritty (1997) found that the majority of floods (around 78%) in the country occur during the

October to March period. In southern Canada, Cunderlik and Ouardaa (2009) reported early occurrence of spring floods due to snowmelt from warming temperature (Peterson et al., 2012). However, the study did not find a strong signal related to the timing of the fall floods. Ye et al., (2017) analyzed the changes in AMF seasonality over 250 natural basins from the MOPEX dataset over the CONUS and found that changes in annual maximum rainfall and antecedent storage conditions impact the shift in seasonality. Apart from annual maximum floods, studies have also investigated the streamflow seasonality over the US (Regonda et al., 2004; Petersen et al., 2012). Regonda et al. (2004) found evidence of early spring temperature spells and early occurrence of peak snowmelt which shifts the spring flow timing. Based on the review of existing literature, we understand that i) significant spatial variability in flood seasonality exists in natural basins across the CONUS, ii) the consensus on the large-scale drivers of changes in flood seasonality is still not clear as studies considered only limited basins (e.g., Ye et al., 2017) . The current study augments the findings of Villarni (2015) and Ye et al., (2017) by considering more natural basins (975 stations) from the USGS Hydroclimate Data Network (HCDN) and by associating the drivers of changes in flood seasonality with hydroclimatic variables and basin characteristics. We also synthesize the changes in seasonality and the associated drivers on a regional basis over the CONUS.

Previous studies investigated the dominant drivers of the seasonality of floods from both moisture transport and teleconnection perspective as well as in understanding the role of hydroclimatology of the basin. Flood magnitudes and their dominant season of occurrence have been attributed to oceanic conditions (e.g., El-Nino Southern Oscillation and Pacific Decadal Oscillation conditions), basin-level climatic conditions (e.g., precipitation) and land surface states (e.g., snowpack) (Pizarro and Lall, 2002; Steinschneider and Lall, 2016; Ye et al., 2017).

Basin characteristics (such as drainage area and elevation) also contribute to the shift in seasonality due to changes in the hydroclimatic patterns. Several studies have shown that it is the scale (i.e., the drainage area) which predominantly explain the spatial variability in the seasonality of the annual maximum flows (Vogel and Sankarasubramanian, 2000; Smith, 1992). Anthropogenic signals/drivers such as warming temperature, urbanization, and regulation (i.e., reservoir operation) have also been attributed to the shifting seasonality in floods (Regonda et al., 2005; Villarni, 2016 and references therein). Berghuijs et al. (2016) explored the influence of precipitation/snow characteristics, considering it as the drivers of flood generating mechanisms, on the seasonality of the annual maximum flow (AMF). Their study suggested that a combination of predictors - extreme rainfall seasonality, snow dynamics, and soil moisture - influence the timing of the mean annual flood across the CONUS. Changes in the seasonality, particularly due to earlier melt, have been observed in the seasonal streamflow at lower elevations in western US (McCabe and Clark 2005, Regonda et al., 2005). Gamble (1997) considered 84 drainage basins in the southeastern United States and reported that the drainage basin area influences the annual peak-flood seasonality only for one out of the five regions that the study investigated. His study interpreted a strong association between drainage area and spring annual peak flood at Georgia coastal plain basins as a result of high soil moisture and frequent extratropical cyclone passage. For New England, Magilligan and Graber (1995) investigated the influence of climate control and geomorphic variables on floods timing and found that the basin size, altitude, and distance from coasts affect the strength of flood seasonality across 36 gauges in New England. However, the role of the basin characteristics in influencing the changes in the seasonality of AMF is not fully understood yet, as they have been found to impact the AMF process (e.g., Smith, 1992; McCabe and Clark, 2005). Recently, Ye et al. (2017) analyzed the seasonality of AMF in 259 natural catchments in the USA and found that basins with synchronous (negatively or positively) moisture (precipitation) and energy (temperature) controls (i.e., moisture and energy in phase) are dominated by climate controls, whereas basins with asynchronous moisture and energy controls (i.e., moisture and energy out of phase) are dominated by antecedent soil moisture storage. Petersen et al., (2012) also found that seasonality of streamflow is influenced by the covariability between moisture and energy with basins. Villarini (2015) addressed the impact of urbanization and regulation on the seasonality of floods and found that both have an effect on the strength of the flood seasonality with wider seasonal distribution under regulation.

Climate variables across the CONUS have experienced a significant change in their frequency and magnitude over the past century. Frei et al. (2013) found evidence of increased occurrence and frequency in extreme precipitation events across the northern United States, potentially leading to extreme streamflow events. The US Global Change Research Program's Climate Science Special Report mentioned an increase of 1.8°F (1°C) in the annual average temperature over the CONUS during 1901-2016 (NCA4: Wuebbles et al., 2017). Furthermore, the correlation between precipitation and temperature has weakened in the last fifty years (Das Bhowmik et al., 2017). To the best of our knowledge, limited/no study has investigated in understanding how changes in climate variables (precipitation/temperature) and basin characteristics influence the change in the seasonality of floods based on a large number of natural watersheds over the CONUS. Thus, the objectives of the current study are:

1. To provide a comprehensive understanding of the change in AMF seasonality over the CONUS using 975 natural HCDN watersheds that have minimal anthropogenic influence

2. To understand how changes in climate and basin characteristics on the change of AMF seasonality at a regional scale.
3. To synthesize the findings from objectives 1 and 2 for developing a regional perspective on changes in flood seasonality across the CONUS.

To understand the changes in AMF seasonality over the HCDN stations, the current study considers two attributes of the seasonality measures: the seasonality index (SI) and the mean date of occurrence (DO). These attributes are based on the circular statistics originally proposed by Markham (1970). Several studies have considered the circular statistics for quantifying the flood seasonality, which gives a basis to quantify the flood seasonality over the CONUS (Burn, 1997; Villarni, 2016; Ye et al., 2017; Blöschl et al., 2017; Berghujis et al., 2019). To address the second objective, the current study performs a regression analysis to attribute the changes in seasonality to the changes in climate variables and basin characteristics - basin elevation and drainage area. Contrary to the previous studies on changes in flood seasonality (Villarini, 2015; Li et al., 2016), this study considers 975 natural watersheds from the USGS Hydroclimate Data Network (HCDN), which are minimally influenced by anthropogenic disturbances. Previous studies have considered these HCDN watersheds for associating streamflow with climate variability and change (Sankarasubramanian and Vogel, 2002; Oh and Sankarasubramanian, 2012; Seo et al., 2016). We synthesize our findings in 8 larger regions by grouping the changes in seasonality from the USGS-defined 18 water resources regions over the CONUS.

This article is organized as follows: Section 2 provides a brief overview of the data and methods considered by the current study. Following that, we present the results related to the change in AMF seasonality across the HCDN basins and statistically identify the significant drivers of the change in AMF seasonality. Finally, we summarize the findings with a discussion.

2. Data and Methodology

2.1. Streamflow Data

The annual maximum peak flow data from 975 stations were obtained from the USGS-HCDN database, which represents the streamflow records for basins that are minimally influenced by anthropogenic factors such as reservoir storage and groundwater pumping (Slack et al., 1993; Vogel and Sankarasubramanian, 2005). For additional details regarding the HCDN basins, we encourage readers to read Sankarasubramanian and Vogel (2002).

2.2. Basin Characteristics Data

Two basin characteristics (drainage area and elevation) for the 975 stations were extracted from a watershed characteristics database developed by Kroll et al. (2004). The watershed scale, considered as drainage area, is a significant factor in controlling the variability in floods (Smith, 1992; Vogel and Sankarasubramanian, 2000). The elevation is primarily considered since it significantly induces the form of precipitation, thereby causing the lag in their response during the melt season (Regonda et al., 2002). The daily precipitation and temperature for the HCDN basins were obtained by spatially averaging the gridded observed daily precipitation and temperature from the archive of the Bureau of Reclamation (originally developed by Maurer et al., 2002; https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html). The daily observations were processed to obtain the mean monthly maximum daily precipitation and the mean monthly daily temperature series over the HCDN basins (see subsection 3.2 in detail).

2.3. Estimation of Seasonality Measures

Flooding of a catchment can be quantified by investigating the timing and regularity (i.e., frequency) of the AMF using the seasonality measure (Burn, 1997), which provides two attributes – the seasonality index (SI) of the AMF and the mean date of occurrence of the AMF (DO), based on the circular statistic suggested by Markham (1970). To estimate the SI and DO, the date of occurrence of the AMF is first converted into the Julian date, where January 1st (December 31) is considered as day 1 (day 365/366). The Julian date of occurrence of i^{th} AMF is then converted into the angular value θ_i (in radians) using equation (1).

$$\theta_i = (\text{Julian date})_i \left(\frac{2\pi}{\bar{m}}\right) \quad (1)$$

where $\bar{m}$ is the number of days per year (365/ 366 days), and n is AMF events in a catchment $(\theta_i, i = 1, \ldots, n)$. Second, the seasonality index (SI), which is a dimensionless measure of the spread of the AMF, and the mean date of occurrence (DO), which is the mode of occurrence in a calendar year, are estimated using equations 2 and 3.

$$\text{SI} = \sqrt{\bar{x}^2 + \bar{y}^2} \quad (2)$$

$$\text{DO} = \begin{cases} arctan\left(\frac{\bar{y}}{\bar{x}}\right) \times \frac{\bar{m}}{2\pi} & \bar{x} > 0,\ \bar{y} \geq 0 \\ \left[arctan\left(\frac{\bar{y}}{\bar{x}}\right) + \pi\right] \times \frac{\bar{m}}{2\pi} & \bar{x} \leq 0 \\ \left[arctan\left(\frac{\bar{y}}{\bar{x}}\right) + 2\pi\right] \times \frac{\bar{m}}{2\pi} & \bar{x} > 0,\ \bar{y} < 0 \end{cases} \quad (3)$$

where $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} cos(\theta_i)$; $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} sin(\theta_i)$ (4)

The SI ranges from 0 to 1, where 1 indicates that the AMF occurs on the same Julian date every year while zero indicates that the occurrence of AMF is equally likely throughout the year (Berghujis et al., 2019). Previous studies (Burn, 1997; Petersen et al., 2012; Almanaseer and Sankarasubramanian, 2011) have shown that basins with an SI below 0.15 have no pronounced seasonality. Thus, a higher value of SI denotes a greater regularity in the AMF time of occurrence.

2.4 Changes in the SI and DO

The current study estimates the changes in SI and DO for two periods; hence, the identification of the change-point year is crucial. Several studies have subdivided the observed AMF by selecting a change-point year for quantifying the temporal changes in flood patterns between two periods. Coopersmith et al. (2014) and Dhakal et al. (2015) considered 1980 as the change-point year while analyzing the AMF and the annual maximum precipitation, respectively. Ye et al. (2017) adopted a varying change-point year (1970, 1975, and 1980) to analyze the changes in flood seasonality and found a limited difference in the same with the change-point year between 1970-1980. The current study performed a change point analysis (for details, see Lavielle, 2005) to identify the representative change-point year of AMF for 975 stations (Figure SI-1 in Supplementary Information). Based on the analysis, the change-point year was considered as 1970 for this study, with the average number of years before and after the change-point year being 35.54 and 40.14 years, respectively. Subsequently, the SI and DO values for the two periods, prior to 1970 and post 1970, at each HCDN station were estimated to evaluate the changes in seasonality and to quantify the shift in DO.

$$\Delta SI = SI^{post1970} - SI^{prior1970} \tag{5}$$

$$\Delta DO = \begin{cases} \left(DO^{post1970} - DO^{prior1970}\right) & if \left|DO^{post1970} - DO^{prior1970}\right| \leq \pi \\ \left(DO^{post1970} - DO^{prior1970}\right) + 2\pi & if \left(DO^{post1970} - DO^{prior1970}\right) < -\pi \\ \left(DO^{post1970} - DO^{prior1970}\right) - 2\pi & if \left(DO^{post1970} - DO^{prior1970}\right) > \pi \end{cases} \tag{6}$$

A positive difference in SI between post-1970 and pre-1970 indicates that the AMFs have become concentrated, while a negative difference in SI denote AMFs have dispersed/diffused/spread post-1970. Similarly, an increase and decrease in the DO indicate later flood arrival (LFA) and early flood arrival (EFA), respectively. To illustrate the association between AMF variability (concentrated or diffused) between two periods and the corresponding change in SI, we plotted the AMFs against calendar days for two stations with substantial increase (Figure 1a) and decrease in SI (Figure 1b). For the first station (located at Big Pipe Creek at Bruceville, Maryland (MD)) in region 1, the SI has increased by 0.439 by post-1979; whereas, for the second station (located at Cowanesque River near Lawrenceville, Pennsylvania (PA)) in region 1, it has decreased by 0.52. Figures 1a and 1b confirm that AMF occurrence is dispersed (concentrated) as post-1970 value of SI becomes smaller (larger) than pre-1970 value of SI. We note that a larger value of SI indicates an increase in the time from the first occurrence to the last occurrence of AMF. Hence, change in SI indicates a range of AMF occurrence in a calendar year. In the current study, if the absolute change in the SI from pre-1970 to post-1970 is more than 0.15, the basin is assumed to have experienced a significant change in its AMF occurrence. Similarly, a change in the DO for more than one month (i.e., $|\Delta DO| \geq 0.5164$ ≈30 days) in its absolute value was considered as significant in terms of AMF time of arrival. Further, the study has divided 975 HCDN stations into eight groups based on the hydroclimate regions in which these stations are located. Group 1 consists of the Water Resources Region (WRR) 1 and 2, Group 2: WRR3 and WRR6, Group 3: WRR4 and WRR5, Group 4: WRR7, WRR9, and WRR10, Group 5: WRR8, WRR11, and WRR12, Group 6: WRR13, WRR14, WRR15 and WRR16, Group 7 is WRR17 and Group 8 is WRR18. For the ease of understanding, above eight groups are referred to as Mid-Atlantic and New England (Group 1); Southeast and Tennessee (Group 2); Ohio and Great Lakes (Group 3); Upper Mississippi and Missouri (Group 4); Texas Gulf, Arkansas, and Lower Mississippi (Group 5); Colorado and Great Basin (Group 6); Northwest (Group 7); and California (Group 8).

2.5 Associating the drivers with the changes in flood seasonality – Regression analysis

To address the second objective of this study, we developed a regression model with the changes in AMF seasonality, SI, as the predictand and a set of climate variables and basin characteristics as the predictors. Selection of potential predictors for flood seasonality relied on our current understanding of the predictors of flood generation. Event rainfall, antecedent soil moisture, snowpack are traditionally considered as predictors of the magnitude of flood (Parajka et al. 2010, Froidevaux et al. 2015, Berghuijs et al. 2016). However, there is an absence of sufficient knowledge regarding the potential predictors for flood seasonality in literature since limited flood records typically restrict a comprehensive analysis attributing the changes in climate and land use changes to the changes in flood characteristics (Franks and Kuczera 2002, Kundzewicz et al. 2014). Blöschl and Montanari (2010) found that changing climate conditions potentially impacted the magnitudes of maximum annual flood in the Danub river at Vienna, Austria in the late nineteenth century. Cunderlik and Ouarda (2009) reported a weak association between climate variability and/or change and the timing of flood with an early occurrence of snowmelt floods. However, Berghuijs et al. (2016) found that rainfall characteristics alone are unable to explain the regional patterns of seasonality and interannual variability of annual maximum flows, indicating a prominent role of antecedent storage and snowmelt on flood seasonality. We initially explored the previous month streamflow based on the DO as a surrogate for antecedent storage; however, it did not improve the relation, and hence we dropped it in developing regression. Further, our interest is in explaining the change in flood seasonality as opposed to mechanisms that cause flood seasonality. We also considered drainage area as it has been shown to explain the variability in AMF (Smith, 1992; Vogel and Sankarasubramanian, 2000). Additionally, we considered elevation as another predictor in explaining the spatial variability in SI as higher elevations as it impacts the form the precipitation (i.e., rain/snow) (McCabe et al., 2007). Similar to Ye et al., (2017), we also considered aridity index as an index of long-term water and energy balance and also correlation between monthly precipitation and temperature as a variable representing moisture and energy being in-phase (i.e., positive correlation) and out-of-phase (i.e., negative correlation) within the year. However, both aridity index and correlation between monthly precipitation and temperature did not play a significant role in developing the best-fitting regression (results not shown), hence not included in the results. We provide additional comments about this in the discussion section.

Considering these, two climatic attributes, changes in the mean monthly maximum daily precipitation (ΔP) and the mean monthly daily temperature (ΔT), between the post-1970 and pre-1970 periods have been considered as the predictors along with drainage area (DA) and elevation (Elev). For calculating ΔP and ΔT for each basin, first, the month in which DO falls pre-1970 for a given basin was identified. Following this, the daily precipitation/temperature for that month was extracted and the maximum value was noted for each year. The mean of daily maximum precipitation/temperature pre-1970 and post-1970 was then estimated and the difference in the mean monthly precipitation/temperature (ΔP/ΔT) was calculated for each basin. Hereafter, changes in the mean monthly maximum daily precipitation (ΔP) and the mean monthly daily temperature (ΔT) are referred to as changes in precipitation and changes in temperature, respectively. Further, for each WRR group, two separate regression relationships have been developed between the predictand (either with basins that experienced an increase in their SI or basins that experienced a decrease in their SI within a region) and the predictors and the best-fit model was identified based on all the possible combinations of the four predictors using the Akaike Information Criteria. An attribute/predictor is considered to influence the change in the SI when the slope of regression is found to be statistically significant, with a *p*-value lesser than 0.1. Further details regarding the regression analysis are discussed in the results section and in Table 1.

3. Results

3.1 Results for change in the seasonality

Results related to the changes in the DO (ΔDO) between the pre-1970 and the post-1970 periods for 975 HCDN stations across eight WRR groups are shown in for lower elevation (≤1000m)(Figures 2a) and higher elevation (>1000m) (Figure 2b). Stations exhibiting EFA (ΔDO ≤30 days) were plotted in red, LFA (ΔDO >30 days) in green, and stations with no significant changes in their DO post-1970 (i.e., within one month) were shown as gray. Similarly, changes in the SI (ΔSI) are plotted in Figures 3a and 3b for lower and higher elevations, respectively. Significant increase (decrease) in the SI is marked with a green-triangle (purple-triangle) in Figure 3, whereas a moderate but significant change is marked by either green or purple circles. An absolute value of 0.15 was considered as a significant change in the SI between two periods. Further, to understand the changes in AMF seasonality and flood arrival since 1970, the study plots the percent change in AMF occurrence between post- and pre-1970 for twelve months (Figures 4a to 4h for the eight WRR regions). Change in the AMF occurrence for a given month is estimated as the delta change in the spatially averaged SI values across the stations whose DO earlier rested on that particular month. A positive (negative) change in Figure 4 indicates that post-1970, the AMF occurrence for a given month has increased (decreased), signifying a higher (lower) number of floods post-1970. Additionally, actual values of DO and SI for pre-1970 and post-1970 are plotted in Figures 5 and 6 respectively for each region. Basins that have DO within 30 days fall within the white portion (Figure 5), which is similar to basins shown in gray circles in Figure 2, but Figure 5 provides the season of occurrence for both pre-1970 and post-1970 for each group along with LFA and EFA based on the pre-1970 season of occurrence. Similar to Figure 5, Figure 6 shows the actual SI values for pre-1970 and post-1970 for each group with the white region indicating no changes in SI ($|\Delta SI| < 0.15$) with basins falling under increase/decrease in SI. Basins are classified based on low/high elevation in Figures 5 and 6.

Overall, based on Figures 2 and 5, very few basins experience change in DO beyond one month (around 15%). Basins west of the continental divide (Groups 6-8) don't show any change in DO except higher elevation basins in CA, which exhibit a LFA. Basins east of the continental divide show both LFA and EFA (Figures 2 and 5) in higher and lower elevations but looking at the pre-1970 and post-1970 comparative plots (Figure 5) show the changes in DO is within 30-60 days in Groups 3-5. In Group 1, Mid-Atlantic and New England, changes in DO occurs mostly in lower elevation with both LFA and EFA (Figure 5). In Group-2, Southeast and Tennessee, AMF exhibits EFA and LFA only in higher elevation basins with limited changes in lower elevation in basins. Our overall observation over the CONUS, compared to the western US, significant changes in DO occurs mostly in the eastern US particularly in Groups 1-2.

We found that around 45% (14%) of the stations in the mid-Atlantic and New England exhibit a decrease (increase) in SI post-1970. AMF occurs mostly in the winter months in the mid-Atlantic and New England region, with few stations along the Appalachian exhibiting late flood arrival (LFA) from winter to spring post-1970 (Figure 2a and Figure 4a). Within Group 1, majority of the higher elevation basins in the Appalachian range exhibit a decrease in their SI with no changes in the DO, though a few basins witness early flood arrival (EFA). Lower elevation basins located in the Northeast with decreasing SI experienced shift in AMF occurrence to June from March during post-1970 (Figure 4a). Under Group-2, an increase in the SI is observed for the large coastal in the lower elevation basins of the Southeast with the AMF occurring in the winter. Whereas, higher elevation basins located over the Southern Appalachian Mountains and lower elevation basins over Florida exhibit a decrease in their SI. This primarily happens with the AMF occurrence increasing in the winter (January and February) and decreasing in the spring and fall (April to September) for stations across the Southwest and Tennessee regions where the SI registers an increase (Figure 4b). For basins with decreasing SI across the Southwest and Tennessee regions, AMF occurrence decreases in the winter and increases in the spring.

We found that basins across the Ohio and Great Lakes region (Group 3) are mostly winter dominated, with almost half of the basins exhibiting a reduction in their SI post-1970. A decrease in the SI over Ohio and the Great Lakes occurs due to the decrease in AMF occurrence in the winter months (Jan-March) and an increase in AMF occurrences from May to December (Figure 4c). An almost equal number of basins (between 10-20%) across the Upper Mississippi and Missouri region (Group 4), a spring-melt dominated region, experienced mostly decrease in their seasonality index. With the exception of four basins experiencing increase in SI, lower elevation basins exhibiting a decrease in their SI are typically located in the eastern part of the upper Mississippi river basin and over the lower Missouri river (Figure 3a). Decrease in SI occurs in lower elevation primarily due to the shift in AMF occurrence from spring to summer months reduced. However, higher elevation basins under Group 4 has experienced an increase in the SI (Figure 3b) and this happens due to increased AMF occurrence in the spring season (Figure 3d).

Half of the basins in the Texas Gulf, Arkansas, and Lower Mississippi (Group 5) experience mostly a decrease in SI occurs (Figure 3). Decrease in SI mostly occurs due to the reduction in spring flood occurrence (Figure 4e). The majority of the basins that exhibit a decrease in their SI also observed early flood arrival. Increase in SI mostly occurs in higher elevation basins. Basins located in Group-6 (Colorado and Great Britain), which is a spring-dominated region, typically did not exhibit any change in the seasonality of AMF. Similar results were found for the snowmelt dominated basins located in the Northwest (Group 7) and California (Group 8) regions, typically exhibiting a no-change in the SI. However, a decrease in SI is observed for a few higher elevation basins in the Northwest and CA regions, which was also reported by Pryor and Schoof (2008). Such basins experiencing decrease in SI show shift in the AMF occurrence from the spring season to fall season. (Figure 4g, 4h). To summarize, the changes in SI is more predominant over the east of the continental divide, whereas the SI decreases in the west particularly in the higher elevation.

3.2 Changes in Flood Seasonality – Attributing the Drivers

Referring to Figures 2-4, the selected HCDN basins over the CONUS can be subdivided into three categories based on the changes in their SI and DO: 1) change in $|SI| < 0.15$ and $|\mathrm{DO}| < 30$ days: these stations were assumed to experience no seasonality change in their AMF, 2) increase in $\mathrm{SI}\ (\text{i.e., flood peaks are concentrated in the later period}) > 0.15$ or $\mathrm{SI\ increase} < 0.15$ (i.e., flood peaks are diffused in the later period) and $|\mathrm{DO}| > 30$ days, 3) $\text{decrease in SI by more than } 0.15$ or $|\mathrm{DO}| > 30$ days and SI decreased by less than 0.15. Considering that a few stations (15%) exhibit changes in their DO and the changes in SI is the primary factor to quantify the AMF seasonality, the stations from category 1 (change in $|\mathrm{SI}| < 0.15$ and $|\mathrm{DO}| < 30$ days) were excluded from regression analysis that identifies drivers of changes in SI over the CONUS. The majority of the stations that exhibit changes in DO are from the mid-Atlantic and New England region (30%) located near the coastal regions or from the Texas Gulf, Arkansas, and Lower Mississippi region (27%). Two regression models are developed for each WRR group with the predictors being either the increase in SI across the stations in category 2 (i.e., increase in SI > 0.15, or SI increase < 0.15, and $|\mathrm{DO}| > 30$) or decrease in SI across the stations in category 3 (i.e., decrease in SI by more than 0.15, or $|\mathrm{DO}| > 30$ days and SI decreased by less than 0.15). Table-1 provides synthesis from the regression analysis with a set of identified influential attributes for each WRR group.

The study found that the decrease in SI for the stations located in the mid-Atlantic and New England region potentially resulted from an increase in temperature (Table 1). In general, an increase in the temperature results in reduced runoff potential which eventually diffuses the seasonality of the AMF. An increase in temperature in the winter is linked with early snowmelt for higher elevation basins located in the mid-Atlantic and New England region. However, given the increase in SI across the mid-Atlantic and New England region is influenced by the increase in temperature at the lower elevation basins resulting in potential delay in flood arrival (LFA). For basins in Group2 (Southeast and Tennessee regions), our analysis show that a decrease in precipitation is associated with a decrease in SI in the winter, while an increase in temperature leads to increase in SI, which occurs mostly in the lower elevation basins (Figures 3a, 6b). Analysis of the drivers for the Southeast and Tennessee regions is consistent with Kunkel et al. (2010) who show the increase in the winter precipitation and temperature over the region.

Under Group 3, higher elevation basins show an increase in precipitation resulting in a decrease in SI. Lawrimore et al. (2014) noted an increase in snowstorms in the winter; hence, winters have become colder across the Ohio and Great Lakes region. This has caused higher snowmelt in spring, leading to an increase in flow during the spring and summer seasons. We also found that a decrease in spring precipitation potentially results in the decrease in SI for basins located over the upper Mississippi and Missouri region (Group 4). A decrease in spring precipitation and an increase in summer precipitation has together resulted in the dispersion of AMF (as shown in Figure 4d), thereby resulting in a decrease in SI. Basins with an increase in SI for group 4 are potentially influenced by the increase in spring precipitation (earlier reported by Kunkel et al., 2010) which leads to the flood arrival in May. An increase in spring precipitation in the northern US has been reported in the Fourth National Climate Assessment report with greater increase in winter and spring precipitation in the northern and eastern US as compared to the South and the West (Kunkel et al., 2010, Easterling et al., 2017 in Climate Science Special Report: Fourth National Climate Assessment, Volume I). For basins located in the Texas Gulf, Arkansas, and Lower Mississippi region (Group 5), a decrease in precipitation results in a decrease in the SI during spring months. For Northwest basins (Group 7), decrease in SI occurs with higher elevation basins. For basins in California (Group 7), decrease in precipitation across the higher elevation basins) is associated with a decrease in SI, even though a change in the DO was not witnessed. For basins across California that historically experience spring-melt and exhibit an increase in SI, early snowmelt is triggered by the increase in winter temperature and precipitation (Table 1), but the number of basins that experience a significant change in SI is very small (11 showing increase in SI and 8 showing decrease in SI). To summarize, the changes in SI under the considered two categories were attributable to the drivers – ΔP, ΔT, area and elevation – over the eastern US (Groups 1-4). Since the number of basins experiencing a significant change in SI is lesser for Groups 5-8, we could not attribute the change in SI to the selected drivers.

4. Discussion and Concluding Remarks

The current study investigated the changes in AMF seasonality and attributed those changes to four predictors – changes in the climate (ΔP and ΔT), basin characteristics (elevation, and drainage area) – over 975 HCDN stations across the CONUS. To summarize, changes in DO is not substantial across the CONUS. With regard to changes in SI, eastern basins (Groups 1-3) are experiencing substantial changes in their SI as compared to basins in the western/central US. Major findings on SI, presented in Figures 2 and 3 and Table 1, for each group are as follows:

a) In the Mid-Atlantic and New England regions, SI mostly decreases potentially due to increase in temperature at higher elevations.

b) Over the Southeast and Tennessee regions, the SI has both increased and decreased in a significant number of basins. Increase in SI is associated with increased temperature. Decrease in SI is more pronounced at lower elevations arising from decreased precipitation.

c) In the Ohio and Great Lakes region, the SI mostly decreases due to potential decrease in winter precipitation leading to higher spring flow.

d) Upper Mississippi and Missouri regions experience decrease in SI in lower elevation basins due to decrease in precipitation. Increase in SI occurs in higher elevations due to increase in temperature.

e) Over the Texas Gulf, Arkansas, and Lower Mississippi region, floods arrive early for most basins, but the change in SI is not significant and associated with any of the considered predictors.

f) Most stations over Colorado and the Great Basin region shows no change in their SI and DO.

g) Over the Northwest, SI decreases in few basins at higher elevations indicating increased variability (i.e., diffused) in flood arrival during the later period.

h) In California, few higher elevation basins exhibit decrease in SI due to reduced precipitation, whereas around 8 basins show increase in SI.

Our analysis on the role of the four predictors – ΔP, ΔT and natural logarithms of elevation, and drainage area – is summarized for each group in Tables 1. Except in the case of New England and Mid-Atlantic regions, in general, decrease in SI (diffused) is associated with decrease in ΔP (Groups 2, 3, 4 and 8). Physical basis for the role of ΔP contributing to the decrease in SI could be explained as follows: decrease in precipitation during the post-1970 period results in reduced moisture availability which could result in increased variability in AMF occurrence (i.e., decreased SI) as the basin might have not been saturated enough to produce pre-1970 pattern during the post-1970 period. Thus, decrease in precipitation results in decreased SI, which occurs in Southeast and Tennessee regions (Group 2), Upper Mississippi and Missouri regions (Group 4) and over California (Group 8) (Table 1). For eight basins from California, increase in precipitation is associated with increase in SI. Otherwise, reduced precipitation is consistently associated with decrease in SI (i.e., diffused). Increase in winter and spring precipitation across the northern and eastern US has been documented in the previous studies (Kunkel et al., 2010; Easterling et al., 2017), which could be attributed to the decrease in SI in the eastern basins.

For basins with increased SI (concentrated), increase in ΔT during post-1970 seems to be the primary driver, which occurs in Mid-Atlantic and New England (Group 1), Southeast and Tennessee (Group 2), and California (Group 3) regions. This could be explained physically as follows: Increase in ΔT during the post 1970 period indicates an increased energy availability, which limits the role of storage by increasing the opportunity to early melt and evapotranspiration, thereby resulting in reduced variability in AMF peaks across all the regions. Thus, under these situations SI increases post 1970 compared to pre 1970 period for Mid-Atlantic and New England (Group 1), Southeast and Tennessee (Group 2), and California (Group

8) regions. Only under Group 1, increase in ΔT in higher elevation basins results in a decrease in SI. Among the basin characteristics, compared to drainage area, elevation plays a more critical role in influencing the changes in SI. Basins under higher elevation shows a decrease in SI, which is true for all the regions except for the Texas Gulf, Arkansas, and Lower Mississippi basins (Group 4), where an increase in SI has been seen. Higher elevation basins under groups 2 and 4 also show an increase in their SI as they experience a more pronounced melting season. Increased role of elevation primarily arises in altering the form of precipitation. The role of the drainage area was found to be minimal in altering the SI of AMF. We also included both aridity index and correlation between monthly precipitation and temperature, which indicate the long-term and within-year moisture and energy balance respectively. However, they did not play a significant role in developing the best-fitting regression hence not shown in the results. Compared to past studies (Ye et al., 2017) which primarily focused on identifying the predictors at the national scale, moisture and energy balance indicators – aridity index and in-phase/out-of-phase seasonality – did not play a significant role in the regional synthesis. One potential reason is that both these moisture and energy balance indicators may not vary significantly across the basins with the grouped water resources regions. Further, our study also considered almost twice the naturalized basins (975 catchments in our study vs 438 catchments in Ye et al., 2017), which provided an opportunity to identify drivers from a regional synthesis. Our study underscores the importance of regional analyses which highlights the significant role of change in precipitation and temperature and elevation being the primary drivers in influencing the change in AMF seasonality within the grouped regions.

Understanding the changes in AMF seasonality is crucial for projecting the AMF under future climate change conditions. For instance, any effort in projecting future changes requires identification of the predictors corresponding to the month during which the AMF occurs (Delgado et al., 2014; Condon et al., 2015; Schlef et al., 2018). The current study provides a regional perspective on the predictors that contribute to the changes in AMF seasonality and identifies changes in precipitation and temperature as the major drivers. Given that most basins do not experience changes in their DO, we considered predictors based on SI, which denotes the variability in AMF occurrence during the post-1970 period. For estimating the changes in flood risk, precipitation and temperature are the two major variables that are commonly considered (Condon et al., 2015), even though other attributes such as climatic indices like ENSO indicators (Schlef et al., 2018) and atmospheric predictors (Delgado et al., 2014) have also been considered. Although such exhaustive analyses of predictors are beyond the scope of this study, one could associate regional findings from this study for analyzing the impacts of the identified predictors for quantifying the changes in flood risk (e.g., Pizarro and Lall, 2002; Sankarasubramanian and Lall, 2003). The role of basin characteristics, particularly elevation, is also critical in quantifying the flood risk since it controls the change in SI by the influencing the form of precipitation (i.e., rain/snow). Considering these, one could consider the climate and basin characteristics in quantifying regional flood risk in a hierarchical modeling setup (Chen et al., 2014; Kwon et al., 2008) to explain the changes in flood seasonality. These critical efforts could potentially provide reliable information and frameworks to quantify flood risk under future climate conditions.

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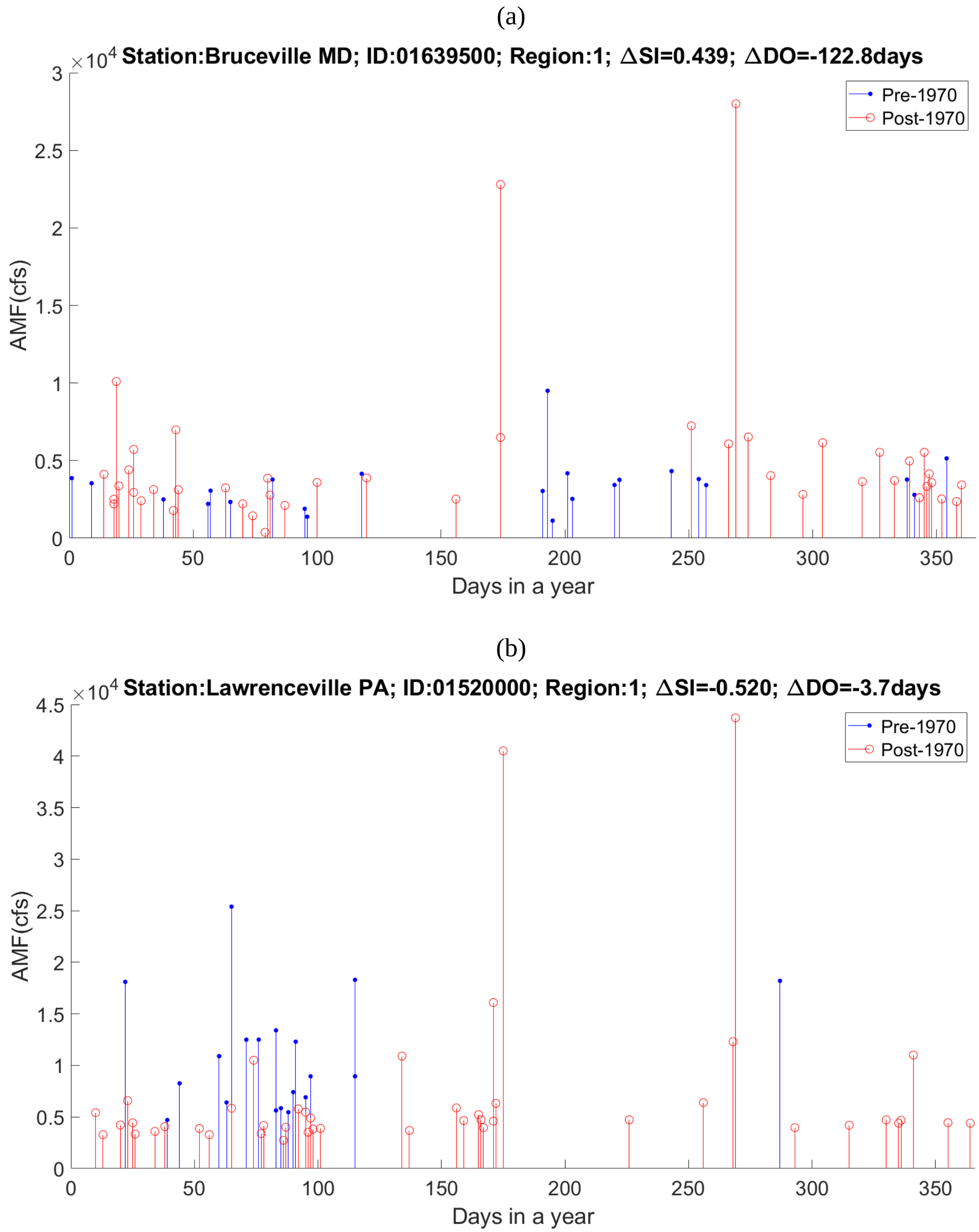


Figure 1. Scatter plot of AMF values (in cfs) against calendar days for two stations with (1a) increase in SI (concentrated) and (1b) decrease in SI (diffused) before and after 1970.

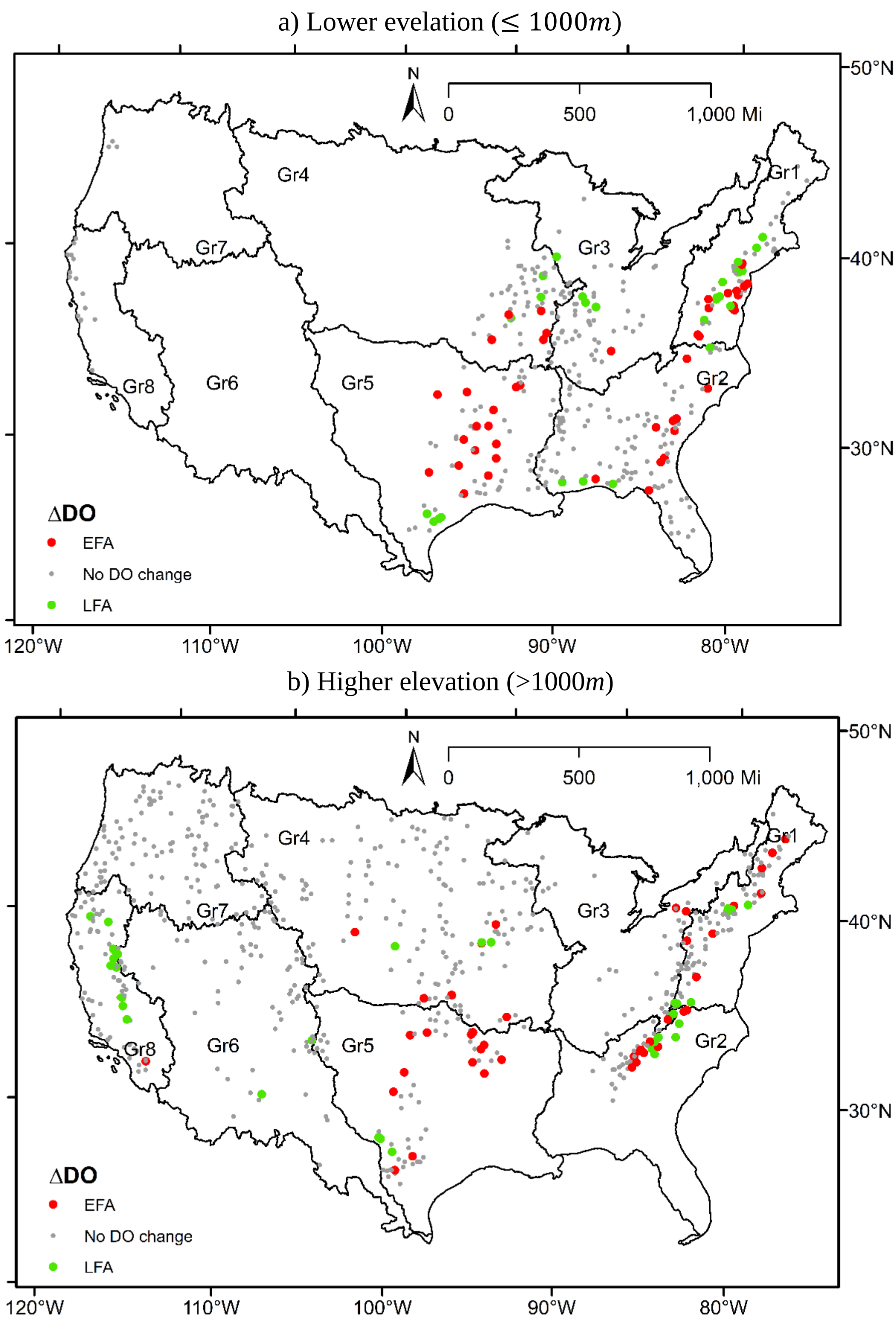
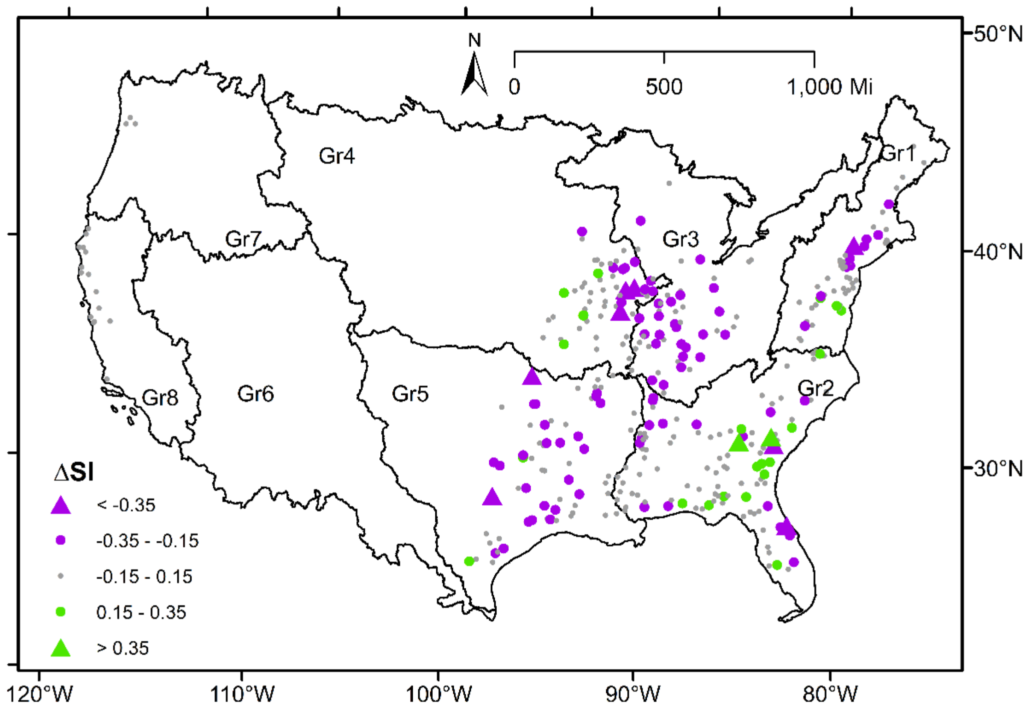


Figure 2. Changes in the dominant season of occurrence (ΔDO) of annual maximum floods between pre- and post-1970 over HCDN stations under eight groups. HCDN stations are segregated based on lower and higher elevations (Figures 2a and 2b respectively) Red, green and gray circles indicate stations with the early arrival of floods (EFA), late arrival of floods (LFA), and no change in DO, respectively.

a) Lower evelation ($\leq 1000m$)



b) Higher elevation (>1000m)

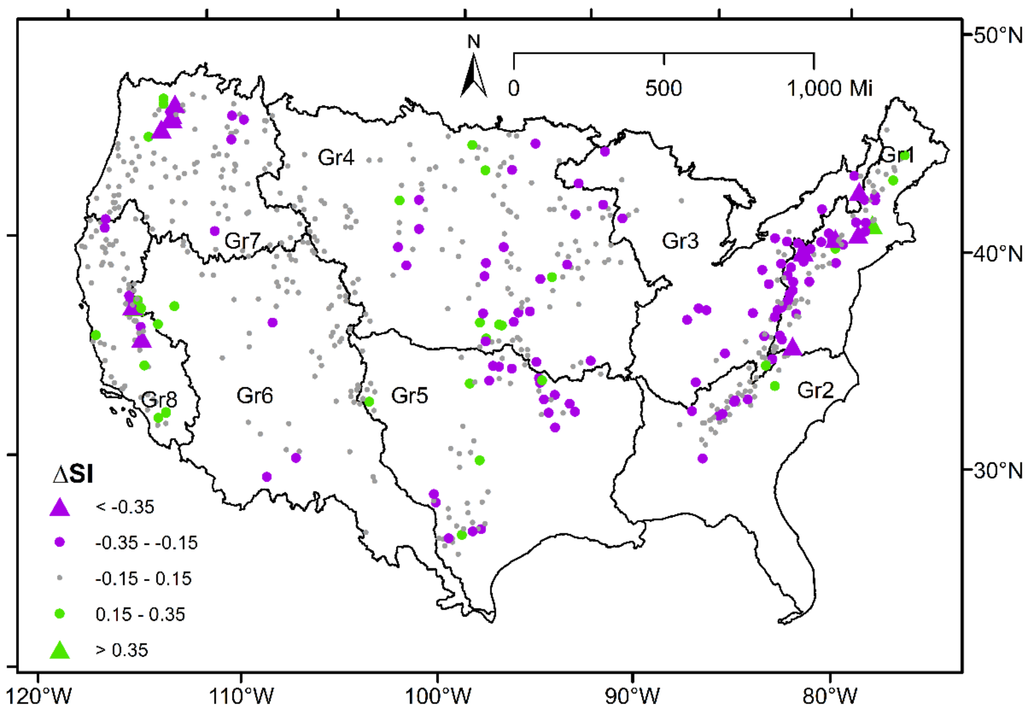


Figure 3. Changes in seasonality index (ΔSI) of annual maximum floods between pre-1970 (SI1) and post-1970 (SI2) over HCDN stations under eight groups. HCDN stations are segregated based on lower and higher elevations(Figures 3a and 3b respectively). Green-triangle and green-circle indicate stations where floods are more concentrated (increase in SI); while purple-triangle and purple-circle indicate stations where floods arrive more diffused (decrease in SI). Stations with no changes in the seasonality of floods over post-1970 (no change in SI) are identified in grey-dots.

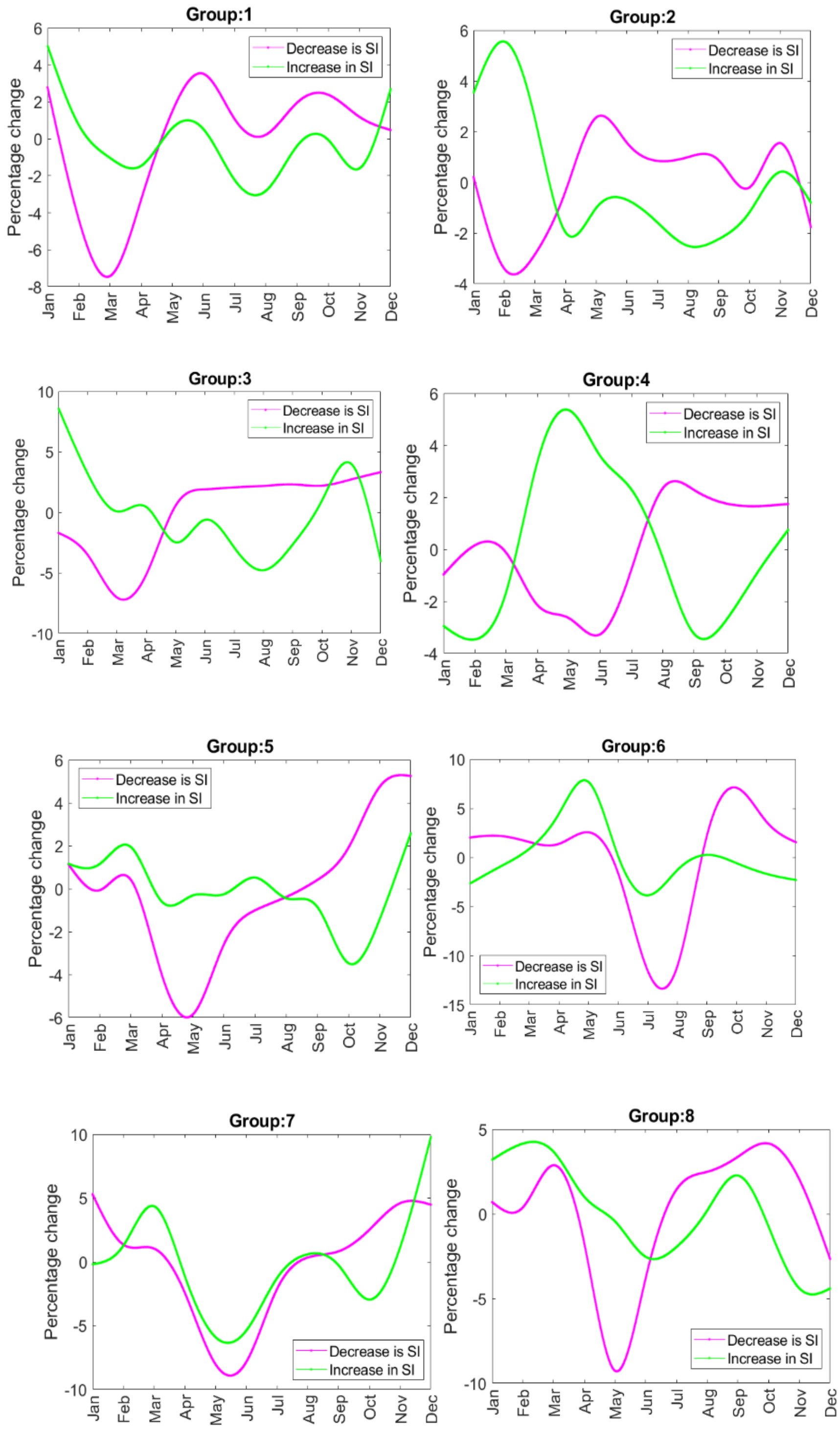


Figure 4. Percent change in AMF occurrence between post- and pre-1970 for eight regions and twelve months. Positive change means an increase in occurrence for the month after 1970. Change in AMF occurrence for a given month is estimated as the delta change in spatially averaged SI values across stations whose DO earlier rested on that particular month. A positive (negative) change indicates that post-1970, the AMF occurrence for a given month has increased (decreased)

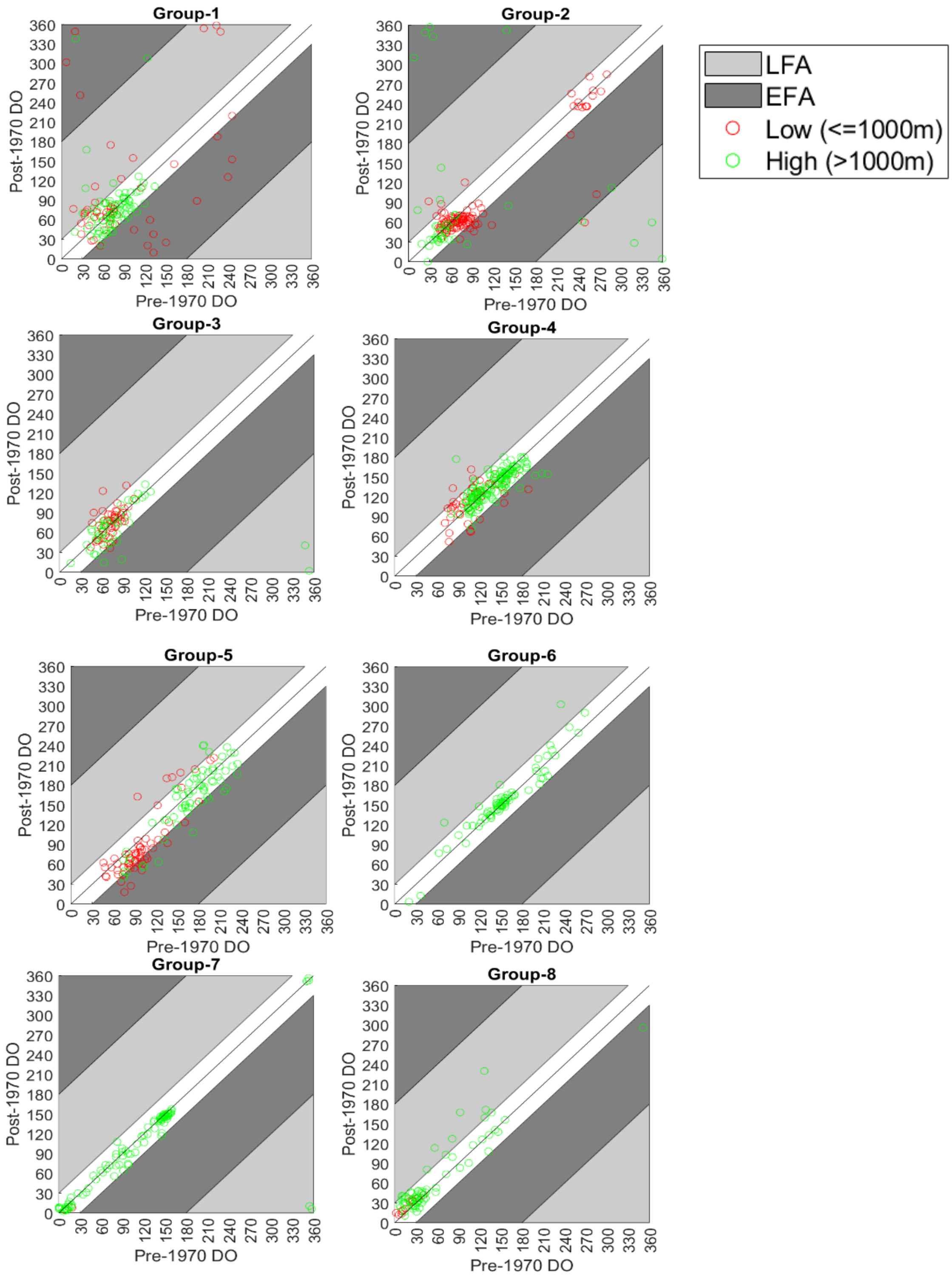


Figure 5. Values of DO of each basin pre- and post-1970. Basins falling in light gray shaded area exhibit later flood arrival (LFA) while basins in dark grey shaded area have early flood arrival (EFA) post-1970, whereas basins in the white area does not have significant changes in dO (less than 30 days). Blue circle corresponds to basins with low elevation (less than or equal to 1000m) and green circle represends basins with high elevation (greater than 1000m).

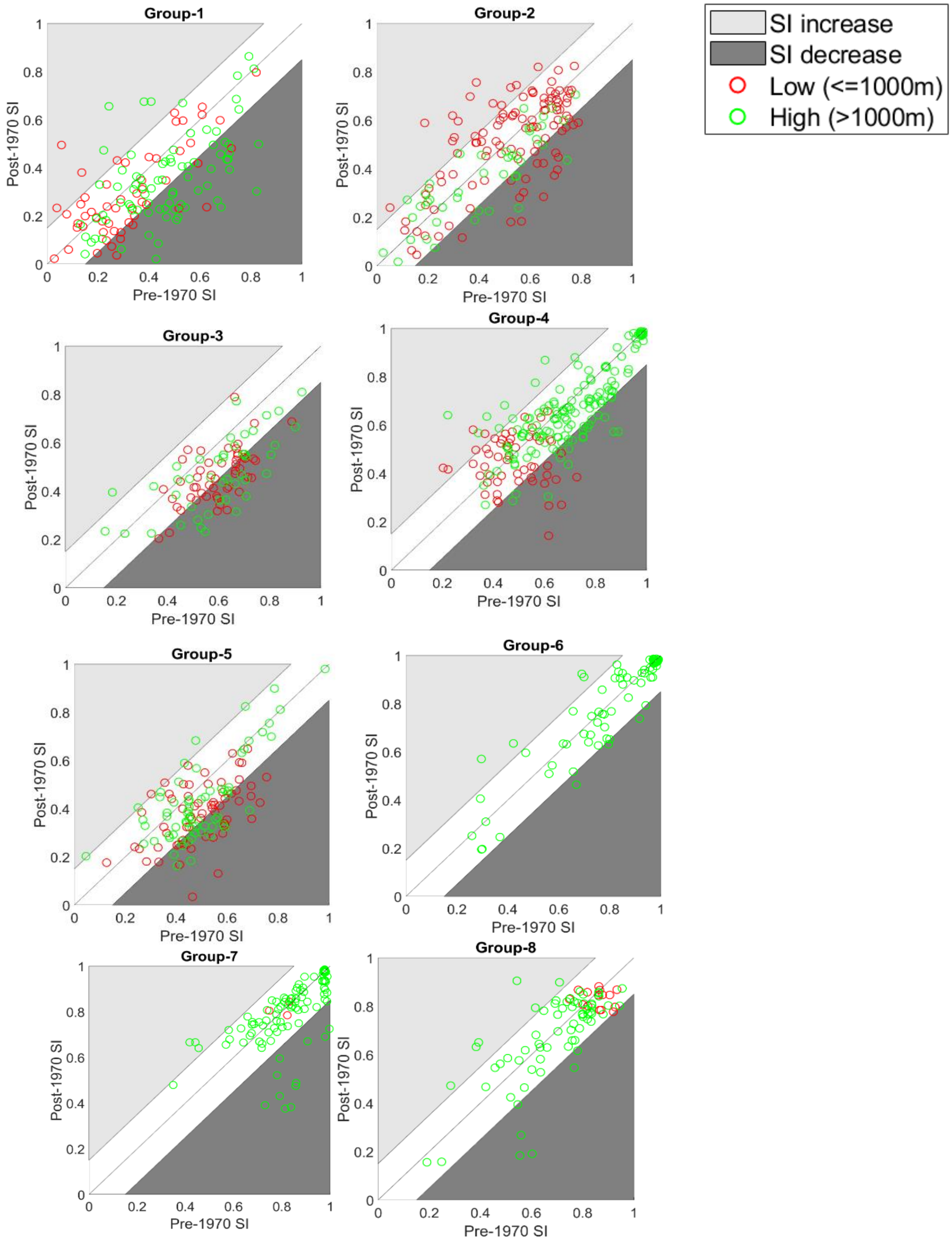


Figure 6. Values of SI of each basin pre- and post-1970. Blue circle corresponds to basins with low elevation (less than or equal to 1000m) and green circle represends basins with high elevation (greater than 1000m). Basins in light gray area exhibit increase in SI, basins falling in dark gray have decrease in SI, while basins located in the white area does not exhibit significant change in SI (less than 0.15 in absolute value).

Table-1. Hydroclimatic and watershed related attributes influencing changes in the seasonality index (SI) and/or mean date of occurrence (DO) of the AMF post-1970 for each group. The number of basins (#) considered in the regression, along with the change in |SI| above 0.15 and the change in DO, are provided. Significant regression coefficients and their p-values (in parenthesis) are provided from the best-fitting linear regression.

Group	**Total stations**	**The slope of selected attributes and p-value**		**Influencing factors**
		Decrease in SI (diffusion)	Increase in SI (concentration)	
1	136	#:61 ΔT: -0.059 (0.04) Elev: -0.091 (0.05)	#:19 ΔT: 0.263 (0.01)	Mostly winter dominated; both early and late flood arrival occurs • A decrease in SI occurs with increased ΔT and at higher elevation basins • An increase in the SI occurs with increased ΔT
2	151	#:38 ΔP: 0.005 (0.1) Elev: 0.049 (0.08)	#:25 ΔT: 0.057 (0.1) Elev: -0.090 (0.1)	AMF occur throughout the year; floods arrive early at lower elevations • A decrease in SI occurs with reduced ΔP at lower elevations • An increase in SI occurs with increased ΔT
3	96	#:48 Elev: -0.099 (0.05)	#:2 NA	Mostly winter dominated • Decrease in SI is associated with increase in elevation.
4	203	#:34 ΔP: 0.010 (0.02) Elev: 0.097 (0.1)	#:21 Elev: 0.240 (0.01)	Mostly spring dominated, few stations exhibit early flood arrival • Decrease in SI occurs with reduced ΔP and in lower elevations • Increase in SI occurs at higher elevations
5	130	#:56 NA	#:11 NA	Floods arrive early; no significant drivers
6	73	#:4 NA	#:6 NA	Mostly spring dominated and no significant drivers identified.
7	103	#: 11 Elev: -1.749 (0.03)	#:3 NA	Decrease in SI for spring-melt basins; • Decrease in SI occurs in higher elevations
8	83	#:11 ΔP: 0.018 (0.08) Elev: -0.794 (0.02)	#:8 ΔP: 0.010 (0.1) ΔT: 0.136 (0.1)	Mostly winter dominated and floods arrive late in the higher elevations • Decrease in SI occurs with reduced ΔP in higher elevations • Increase in SI occurs with an increase in ΔP and ΔT

Supplemental Information

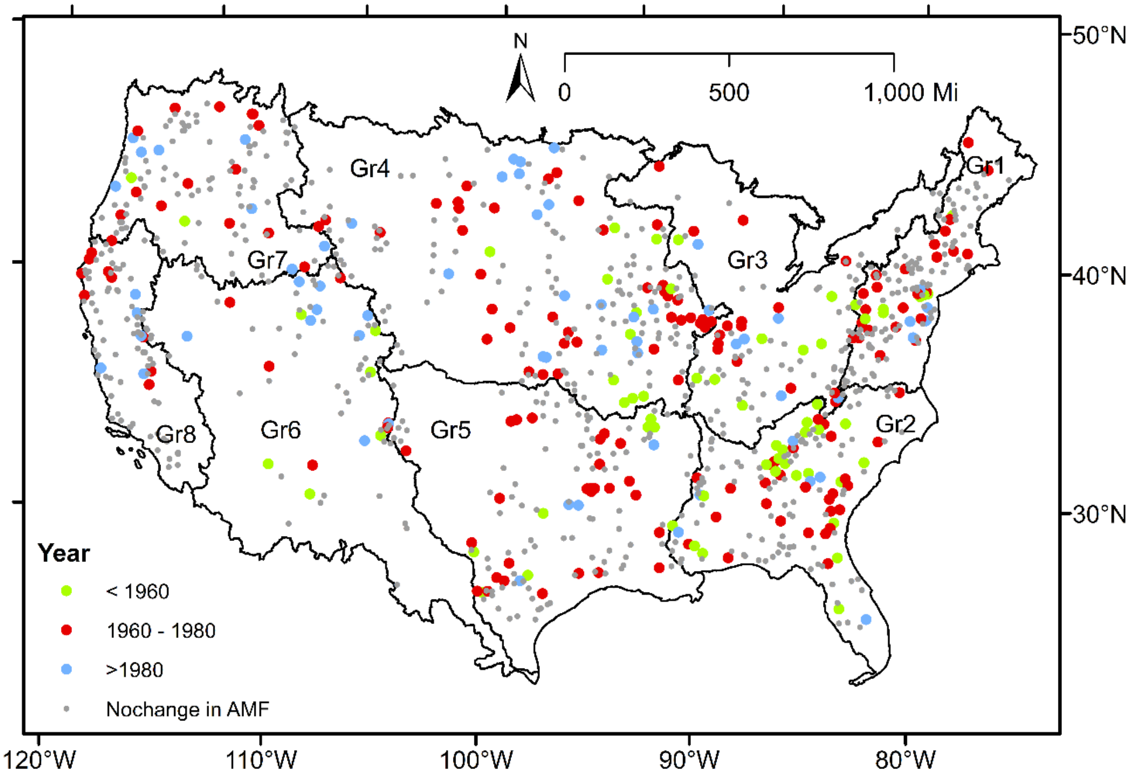


Figure-SI-1. Spatial variation of change-year of Annual Maximum Flow (AMF) for each on the 975 stations. Stations exhibiting no change in AMF were shown in gray.

Details on Figure SI-1: The median of change-year for all of the 975 stations was found to be 1967, whereas for each of the group where significant changes in AMF were noted were as follows: 1965 (Group-1), 1959 (Group-2), 1970 (Group-3), 1984 (Group-4), 1963 (Group-5), 1977 (Group-6), 1975 (Group-7) and 1976 (Group-8).