Hydrological Drought Persistence and Recovery in the CONUS: a Multi-stage Framework Considering Water Quantity and Quality

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Abstract

Hydrological droughts have considerable negative impacts on water quantity and quality, and understanding their regional characteristics is of crucial importance. This study presents a multi-stage framework to detect and characterize hydrological droughts considering both streamflow and water quality changes. Hydrological droughts are categorized into three stages of growth, persistence, retreat, and water quality variables (i.e., water temperature, dissolved oxygen concentration, and turbidity) are utilized to further investigate drought recovery. The framework is applied to 400 streamflow gauges across the Contiguous United States (CONUS) over the study period of 1950-2016. The method is illustrated for the 2012 US drought, which affected most of the nation. Results reveal the duration, frequency, and severity of historical droughts in various regions as well as their spatial consistencies and heterogeneities. Furthermore, duration of each stage of drought (i.e., growth, persistence, and retreat) is also assessed and the spatial patterns are diagnosed across the CONUS. Considering the water quality variables, increased water temperature (4^{o}C on average) and reduced dissolved oxygen concentration (2.5 mg/L on average) were observed during drought episodes, both of which impose severe consequences on ecology of natural habitats. On the contrary, turbidity was found to decrease during droughts, and indicate a sudden increase when drought terminates, due to increase in runoff. Varied drought recovery durations are perceived for different water quality variables, and in general, it takes about two more months for water quality variables to recover from a drought, following the hydrological drought termination.

Keywords: Drought, Drought recovery, Turbidity, Dissolved oxygen, Water temperature, CONUS.

1 Introduction

Drought is among the most devastating natural disasters, which imposes severe impacts on various environmental and ecological aspects of the affected region (Van Loon and Van Lanen, 2012; Mishra et al., 2017). Despite its distinction as a climatic extreme event, there is no unanimous definition for drought because of its different types and distinct origins (Ahmadalipour and Moradkhani, 2017). Meteorological droughts start when precipitation drops below normal level and may lead to hydrological imbalances, which disturbs the normal environmental functioning of a region (Van Loon and Laaha, 2015; Heudorfer and Stahl, 2016). Crausbay, et al. (2017) defined ecological drought by combining drought impacts from ecologic, climatic, hydrologic, socioeconomic, and cultural aspects. In ecological drought, water deficit is defined such that it drives ecosystems beyond their threshold of vulnerability, influencing the ecosystem services and triggering feedbacks in natural and human systems.

Several studies have discussed that the severity and frequency of droughts have increased in many parts of the world as a consequence of the changes in rainfall and streamflow patterns, which may be associated with anthropogenic activities and climate change (Karamouz et al., 2012; Ahmadalipour et al., 2017a, 2017b). Thus, a systematic framework for detecting drought onset-termination can mitigate drought impacts (Karamouz et al., 2011; 2013; Yan et al., 2017).

Although it is necessary to understand drought recovery mechanism and duration, few studies have investigated these topics over large spatial domains. (Pan et al., 2013; DeChant and Moradkhani, 2014), while others elaborated on restoring function in plants (Martorell et al., 2014; Secchi et al., 2014). Schwalm et al. (2017) stated that recovery time is the duration that "an ecosystem requires to revert to its pre-drought condition". Ecological drought recovery was presumed to coincide with hydrological drought termination (Anderegg et al., 2015). In riverine ecosystems, water quality is an important ecological factor, which has been neglected in the majority of drought recovery assessments. Understanding drought recovery duration is essential; if a region experiences a new drought episode before complete recovery from an antecedent drought event, the ecosystem would experience more severe ecological impacts (Sawada and Koike, 2016). Categorizing a drought episode into different stages can shed light on drought propagation and provide a better understanding of drought recovery. There have been few attempts to utilize variable spatiotemporal thresholds for categorizing droughts into different stages (Bonsal et al., 2011; Parry et al., 2016a, 2016b). Most of the assessments merely focused on water availability (quantity), while the recovery of water quality has not been investigated. More specifically, the possible lag time between drought recovery in terms of water quantity and quality has not been studied.

The fresh water quality is correlated to streamflow, biogeochemical, and anthropogenic influences. Several studies explored water quality variations during hydrological drought episodes at different spatial scales (Van Vliet and Zwolsman, 2008; Hrdinka et al., 2012; Hellwig et al., 2017). Mosley (2015) outlined three driving forces for water quality changes during a drought episode, explicitly, 1) hydrological drivers, dilution, and mass balance, 2) the role of increased temperature, and 3) increased residence times. Many studies concluded on increasing water temperature during hydrological drought episodes (Sprague, 2005; Baures et al., 2013; Hanslík, et al., 2016). Higher water temperature intensifies biological activity, leading to a higher rate of nutrient uptake and more oxygen release. Drought or low flow condition cause higher water temperature and less nutrient inflow to water bodies (Hellwig et al., 2017; Mosley 2015). This leads to favorable changes in physical and hydrological conditions for biological growth increasing the likelihood of eutrophication. Thus, eutrophication will increase not only due to changes in nutrient concentration, but also due to hydrological and physical conditions becoming more suitable. Recently, Sinha et al. (2017) showed that the precipitation changes induced by climate change will substantially increase the riverine total nitrogen loading across the U.S., which will exacerbate eutrophication, especially over the northeastern parts. The solubility of gasses, such as oxygen, depends on water temperature and theoretically, higher temperature causes less solubility of oxygen. Previous studies showed that in most cases when water temperature increases, dissolved oxygen decreases, indicating solubility is the dominant process for the concentration of dissolved oxygen (Mulholland et al., 1997; Mimikou et al., 2000; Murdoch et al., 2000). Additionally, decreased streamflow during hydrological drought episodes causes lower velocities and longer residence times (Mosley 2015). Therefore, sedimentation and higher interaction of groundwater and surface water lead to lower turbidity during drought episodes (Hrdinka et al., 2012; Mosley et al., 2012). Most of the above-mentioned analyses have been carried out at regional scales, and there have been just few attempts for investigating water quality changes during drought episodes over the CONUS.

There are two primary groups of drought identification methods, both of which require long time series of hydro-meteorological data. The first method is the probabilistic-based approach, which provides drought intensity according to the deviation from normal condition. Most of the standardized drought indices follow this approach, which have been employed in numerous studies (McKee et al., 1993; Vicente-Serrano et al., 2010; Irannezhad et al., 2017). The second drought identification method is the threshold-based approach: drought onset happens when the variable of interest falls below a predefined threshold (KO and Tarhule, 1994; Shiau and Shen, 2001; Wong et al., 2013). Moreover, there are two threshold level families: the constant (i.e., a constant percentile of annual long-term cumulative frequency distribution) and the variable threshold level. The variable threshold method is more appropriate when seasonal patterns should be taken into account, and is broadly used in recent studies (Sung and Chung, 2014; Van Loon and Laaha, 2015; Heudorfer and Stahl, 2016). Since the environmental functions are related to seasonal cycles, droughts are considered as deviations from seasonal cycles and the variable threshold method is implemented in this study.

This paper integrates hydrological drought concepts and its environmental impacts, and represents a multi-stage framework to detect and characterize hydrological droughts considering water quality parameters. The overarching objectives of this study are to fill the following gaps, which have not been adequately addressed in previous assessments:

1) Developing a framework for hydrological drought detection, and categorizing drought episodes into different stages of growth, persistence, and retreat.
2) Investigating water quality variations during hydrological drought episodes.
3) Analyzing drought recovery considering both water quality and quantity criteria.
4) Assessing spatiotemporal and probabilistic characteristics of hydrological drought including frequency, severity, and recovery duration.

2 Materials and Method

In hydrological drought studies, drought recovery is defined as the time when the hydrological variable of interest reverts to its normal condition (Mo, 2011; Pan et al. 2013; DeChant and Moradkhani, 2014). The ecological perspectives reveals that a complete drought recovery may require longer time, and it is essential to consider more criteria in addition to water quantity for drought recovery. In this study, drought recovery is defined as a phase starting within the drought episode and extending beyond drought termination until the riverine ecosystem reverts to its pre-drought condition. To capture drought recovery duration, drought episodes should be identified. Figure 1 presents the methodology, which consists of three main steps explained in the following sections.

2.1 Hydrological drought threshold determination

The characteristics of a region, data availability, and the study objectives are the factors which affect the threshold calculation method. Daily quantile based on the long time series is considered as the optimum value for streamflow threshold because it is capable of capturing the low flow regime of a basin (Heudorfer and Stahl, 2016). To calculate daily streamflow threshold level, daily quantiles are computed for the streamflow duration curve over the entire observation period (1950-2016). Kjeldsen et al. (2000) suggested the range of 70th-95th percentile as the threshold level. In this study, the 80th percentile (Fleig et al., 2006; Heudorfer and Stahl, 2016) is considered as the threshold level and the time series of the 365 threshold levels are generated. In other words, a set of 365 80th percentile values are calculated from the available observed data for each station. This threshold level is applied for all the stations to maintain the comparability of characteristics of detected droughts over the study area. Applying the 80th percentile threshold may result in many short periods of streamflow deficit, which are not necessarily separate drought episodes. Therefore, a centered moving average of 30 days is applied to smooth the jagged threshold curve (Heudorfer and Stahl, 2016).

2.2 Identifying drought stages

Comparing the daily observed flow with the threshold to detect hydrological droughts may cause a sequence of short drought episodes, which are not separated (Tallaksen et al., 1997; Van Loon and Laaha, 2015). Many studies eliminated any drought event shorter than 15 days

(Hisdal et al., 2004; Fleig et al., 2006). Additionally they applied a pooling method with the inter-event period of 10 days to integrate separate events (Tallaksen et al., 1997; Fleig et al., 2006), which was found to be not effective, and failed in detecting multi-seasonal drought events. Therefore, a method is developed here to unify these discrete events by categorizing a hydrological drought episode into three stages of growth, persistence, and retreat (combining the methods utilized by Bonsal et al., 2011 and Parry et al., 2016a). The drought persistence period is the main criterion for hydrological drought assessment. Having identified drought persistence, drought growth and retreat can then be investigated. The following steps explain each hydrological drought stage (see supplementary Figure S1):

- **Persistence:** the period that streamflow remains below the normal threshold level for at least 30 consecutive days. If there are more than one period fulfilling this condition during a drought episode, the longest period is considered as the drought persistence stage.
- **Growth:** moving backwards from the beginning of drought persistence, drought onset is the point when streamflow falls below the threshold level for less than 15 days in a T-day window (explained in the drought recovery section). Drought growth stage starts from drought onset until the beginning of drought persistence.
- **Retreat:** moving forward from the end of drought persistence stage, drought termination is the time when streamflow falls below the threshold level for less than 15 days in a T-day window (explained in the drought recovery section). Drought retreat stage starts following the end of drought persistence until drought termination.

2.3 Drought recovery

In this study, drought recovery starts from the beginning of the retreat stage and continues until T-day after drought termination. The T-day after drought termination (when streamflow has reverted to its pre-drought condition) is added to drought retreat for drought recovery, because the basin needs more time to meet normal water quality condition. The T–day period is defined as the required time for all water quality parameters to recover (to revert to their normal conditions). Thus, a river is assumed to recover from a drought when the streamflow and water quality parameters return to their normal (i.e., pre-drought) condition. Water quality is assumed recovered when there is no significant difference between the median of variable of interest and its threshold (combining methods by Caruso, 2001, 2002; and Van Vliet and Zwolsman, 2008). The Kruskal–Wallis test (Kruskal and Wallis, 1952), as a nonparametric method, is employed at 0.05 significance level to investigate such difference. The historical hydrological droughts in each streamflow station were considered, and the T-day period is calculated in order to comply with the regional characteristics of each basin. Like streamflow threshold, the normal water quality condition (threshold) is defined as the long-term daily average of each water quality variable for the study period, which is then smoothed by thirty-day centered moving average.

Figure 1 – The framework for analysis of drought recovery given water quantity and quality parameters

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2.4 Study Area and Data

The Contiguous United States (CONUS) is selected as the study area because of its widely variable climate, which leads to the existence of perennial and ephemeral rivers in different regions. There are eighteen river basins across the CONUS, which are delineated based on the USGS 2-digit hydrologic unit codes (excluding Alaska, Hawaii, and Caribbean) as shown in Figure 2. Hydrologic Units (HU) are areas of land from which surface water drains to a particular point. Among all the streamflow stations across the CONUS, a small fraction of them monitor water quality parameters. We considered all the stations operated by USGS over the CONUS and selected the ones that meet our criteria. The criteria for selecting stations are as follows:

1- Streamflow data availability for at least 30 consecutive years during the study period (1950-2016);

2- Recording at least one water quality parameter with 5 consecutive years of observed data and total duration of 10 years; and

3- Being least affected by anthropogenic influences (i.e., dams, abstraction and return flows)

Assessing all stations for the above criteria, we included all the active stations with over 30 years of streamflow observation that collects at least one of the water quality parameters. Therefore, 400 USGS (the US Geological Survey) stations were selected considering the study period (1950-2016), recording at least one water quality parameter, and being least affected by anthropogenic influences (such as dams, abstractions, and return flows from irrigation systems and power plants). Water temperature, dissolved oxygen, and turbidity are assessed as vital water quality parameters (SWAMP, 2010), and rest of the water quality parameters are neglected due to their short record or poor spatial coverage. Missing data for streamflow and water quality parameters are estimated by the USGS therefore significant gaps of observed data are filled. Figure 2 shows the location of the 400 selected stations, all of which measure water temperature; whereas some stations do not record either dissolved oxygen or water turbidity.

Figure 2- Study area, river basin boundaries, and location of the selected streamflow/water quality stations. All the stations record streamflow observations, and the water quality variables are specified using three colors.

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3 Results

3.1 Verification of the hydrological drought detection framework: The 2012 US drought

The drought detection method applied in this study is verified for the historic drought event (Rippey, 2015). An unusually dry winter in 2011-2012 coincided with warm and dry spring and summer, and affected most parts of the CONUS. It led to catastrophic drought impacts over the affected states and caused $40 billion damage, mostly due to agricultural losses (Rippey, 2015). Nearly two-thirds of the nation dealt with drought on September 2012 according to the US Drought Monitor (USDM). The USDM (Svoboda et al., 2012), detected a severe to extreme drought episode affecting all over the CONUS with higher persistence duration in south and Midwest. The results of our analysis also detect a hydrological drought event in 38 states, with a duration of 11 months on average (ranging from 4 to 15 months). The onset, termination, and duration of the 2012 US drought are shown in Figure 3 for each of the affected states. Figure 3 shows that in Midwestern and Southeastern states, the 2012 drought tended to persist longer and drought recovery took more time for these regions, while drought recovery in the Pacific Northwest took shorter time.

In this study, drought growth is defined as the period that the hydrological variable (e.g.,. streamflow) falls below threshold for at least 15 days in 60 days. Drought persistence is the period that streamflow remains below the threshold for over 30 consecutive days. In other words, drought growth focuses on capturing the onset of a drought and its initial stages, whereas drought persistence is the period that drought intensifies and lasts until amelioration and then proceeds to the recovery stage. Therefore, the persistence period of drought is generally longer than the growth stage. For example, in the 2012 US drought, prolonged period of high air temperature in late spring resulted in soaring atmospheric evaporative demand in central US that quickly translated to severe and extreme drought conditions, drying the soil moisture and substantially reducing the streamflow, especially in central US (Hobbins et al., 2016; Otkin et al., 2017). Therefore, for the 2012 drought the growth stage was very short, making its detection very challenging and subsequently causing considerable impacts (McEvoy et al., 2016; Yan et al., 2017).

Figure 3 – Chronology of drought stages for the 2012 drought over the affected US states.

A thorough examination of water quality changes over this drought episode is executed. Water temperature shows the maximum deviation from threshold occurred in the river basins that are located in lower latitude (see Figure S2). Additionally, Figure 3 reveals that in the sates that are located in lower latitudes, drought persistence tends to be longer. Dissolved oxygen shows the same pattern where California, Arizona, Texas and South Carolina experienced the most deviation from the normal condition with relatively longer persistence. On the other hand, turbidity tends to deviate most for this drought episode in mountainous areas that are located in dry climate. Southeast US and generally the areas located on east coast show the least deviation of turbidity compared to other regions.

3.2 Spatial analysis of drought stages

Figure 4 (top) shows the number of hydrological drought episodes over the CONUS during the study period (1950-2016). It is worth mentioning that, in order to keep the maps easier to follow, all the presented results are interpolated using inverse distance weighted interpolation method. The figure reveals that generally, the Pacific Northwest, Mid-Atlantic, and Great lakes basins experienced droughts more frequently than other basins. The Upper Colorado and Ohio River basins also experienced relatively frequent drought episodes. In general, Western US indicates a tendency towards more frequent hydrological drought events. Another drought characteristic investigated in the figure is drought duration. Figure 4 (bottom) shows the average duration of drought over the CONUS. Texas, South Atlantic and Missouri show longer drought duration compared to other regions. Comparing drought frequency and drought duration, the regions with more frequent droughts tend to have shorter drought episodes.

Figure 4- Spatial distribution of number of drought (top) and average drought duration in days (bottom) during the historical period of 1950-2016.

Besides the total duration of drought (shown in Figure 4), the duration of each stage of drought is also assessed. Figure 5 illustrates the duration of drought growth, persistence, and recovery across the CONUS for the study period. Figure 5a shows the average duration of drought growth (days). As seen in this figure, the South Atlantic, Texas gulf, and Missouri basins indicate longer drought growth duration compared to other regions. Generally, prolonged drought growth periods cause drought identification complex, since the streamflow deviation is not significant and it usually does not get attention until it reaches the persistence period. Another parameter presented in the figure is duration of drought persistence (Figure 5b). The figure illustrates that drought, on average, persists less than 2 months in most of the Eastern US. Whereas in California, Upper Colorado, Texas, and Souris-Red-Rainy basins, droughts tend to persist more than three months. Lastly, mean drought recovery duration is presented in Figure 5c. It can be seen that there are regions located in South Atlantic, mid-Atlantic, Texas, and Arkansas River basins with average drought recovery duration of 6 months. Whereas, California, Pacific Northwest, Great lakes, and Ohio River basins tend to recover from drought in less than 4 months. Comparing the average duration of drought stages (Figure 5a, b, and c) discloses that drought recovery takes longer time than drought growth and persistence. Moreover, the regions corresponding to longer drought growth require more time for drought recovery.

Figure 5- Mean duration (in days) of a) drought growth; b) persistence; and c) recovery in the historical period of 1950-2016.

3.3 Drought impacts on water temperature

Figure 6 shows temporal changes of water temperature, dissolved oxygen, and turbidity during three hydrological drought episodes affecting three selected stations in South Carolina in 2009, Kansas in 2014, and Oregon in 2012. These stations are chosen since they represent the mean pattern of the river basin they are located, and they provide the same length of records for water quality. A statistical analysis on all stations reveals that a hydrological drought is associated with an increase in water temperature (see Table 1). Kruskal–Wallis test is applied to detect whether there is a significant difference (at p-value<0.05) between the median of water temperature during a drought episode and the water temperature threshold level. Additionally, Figure 6 reveals that water temperature threshold follows a seasonal pattern and it tends to be higher (/lower) in the warmer (/colder) seasons. It is worth mentioning that the same pattern is seen all over the study area. Results of the Kruskal-Wallias test indicated that for most drought episodes (more than 85% of all stations) there is a significant difference between water temperature during drought episodes and the normal water temperature threshold. Additionally, the mean, median and the maximum water temperature in all stations were higher than the mean, median and the maximum water temperature threshold, respectively. Figure 6 (first column) shows that water temperature during 2-month (/4-month) drought episodes in South Carolina and Oregon (/Kansas) are mostly above the normal water temperature threshold level (normal condition). The figure illustrates that water temperature reverts to its normal range 42, 68, and 27 days after drought termination in South Carolina, Kansas, and Oregon, respectively. On average, among all stations over the CONUS, water temperature reverts to its pre-drought normal state 52 days after drought termination (the required time for water temperature to recover from a hydrological drought). The spatial distribution of the average time required for water temperature to recover from a hydrological drought is presented in Figure 7-a.

Figure 6- Drought impacts on water temperature, dissolved oxygen, and turbidity during three hydrological drought episodes occurred in South Carolina in 2009 (first row), Kansas in 2014 (middle row), and Oregon in 2012 (bottom row). The red bar shows drought duration (onset to termination) and the green bar indicates the required time for water quality to recover.

Table 1 – Minimum, median, and maximum deviation of water temperature, dissolved oxygen, and water turbidity during drought for each river basin.

This study showed that water temperature increased during hydrological drought episodes, which is in agreement with many previous assessments (Chessman and Robinson, 1987; Caruso, 2001; Zielinski, 2009). Our analyses on all studied stations demonstrated that water temperature considerably increases from the beginning of the persistence stage of drought and it remains above the normal threshold even after drought termination. If the growth stage lasts for more than 40 days, water temperature may increase even during the growth stage. In most cases, water temperature reaches its maximum deviation when the maximum departure is happened in streamflow. The minimum, median, and maximum deviation of water temperature from the normal threshold for each river basin are presented in Table 1. The table shows that the basins located in lower latitudes experienced higher water temperature rise. It is worth mentioning that the maximum water temperature increase coincided with the most severe drought episode in all river basins.

Figure 7- Spatial distribution of average time needed for; a) water temperature, b) dissolved oxygen, and c) turbidity to recover from drought after the hydrological drought termination (i.e. after the streamflow has reached normal conditions).

3.4 Drought impacts on turbidity

Decreased turbidity is detected during drought episodes using the Kruskal–Wallis test (Figure 6 right column). The test indicated that for most of the stations (90% of them), the median observed turbidity during drought was significantly lower (p-value <0.05) than the normal turbidity threshold. There were few stations that the difference between the medians was not significant. However, for all stations, the mean and median of observed turbidity during drought episodes were lower than the mean and median of the normal turbidity threshold, respectively (see Table 1). Low turbidity is generally desired for most water consumption purposes (specifically domestic demand). On the other hand, since drought terminations mostly coincide with a sudden increase of flow (i.e. higher runoff causes higher turbidity), the turbidity thrusts up during the drought termination. This implies that more time is required for the turbidity to recover after hydrological drought termination. Figure 6 (right column) shows that after a 2-month (/4-month) drought episodes in South Carolina and Oregon (/Kansas), turbidity needs 67 and 24 (/40) days to recover, respectively. On average, among all stations over the CONUS, turbidity requires 42 days to recover after hydrological drought termination. Spatial distribution of turbidity recovery time reveals that it takes less than 60 days for most of the regions to recover from drought (Figure 7c). There are some scattered areas in Arkansas, Pacific Northwest, southeast Missouri, and great Lakes river basins with recovery times more than 60 days.

Our analysis detected that turbidity is usually lower than the normal threshold during hydrological droughts, which is in agreement with the findings of several previous studies (Caruso, 2001, 2002; Golladay and Battle, 2002; Goransson et al., 2013). The improvement of water turbidity can be attributed to less storm events that causes decreased runoff, which is associated with less erosion of solid transports to the watercourses during drought. Lower streamflow during the hydrological drought also causes slower velocity, which increases sedimentation and decreases turbidity. Table 1 showed that for the river basins located in dry climate with mountainous characteristics (e.g. Lower Colorado and Great basins), the maximum deviation of turbidity is higher than other river basins. Such higher deviation implies the tendency of these basins to terminate droughts with a sudden increase in streamflow (Paulson et al., 1985; Mensing et al., 2008; Asadi Zarch et al. 2011). It has been discussed that turbidity can have various impacts on ecology and natural habitats. High concentration of particulate matter during drought recovery period decreases light penetration, and consequently reduces productivity and natural habitat quality. It also increases sedimentation, which makes siltation more likely, and can result in harming the habitat for fish and aquatic life (Lake, 2011).

3.5 Drought impacts on dissolved oxygen

Dissolved oxygen alteration is investigated in all stations using the Kruskal–Wallis test to examine if the median of observed dissolved oxygen is significantly different from the threshold. The test shows that there is a significant difference between the medians of dissolved oxygen during drought episodes and the normal dissolved oxygen threshold (p-value < 0.05). During drought, the mean and median of dissolved oxygen in all stations were lower than the mean and median of dissolved oxygen threshold, respectively (see Table 1). Figure 6 (middle column) illustrates that after a drought episode with 2 (/4) months duration, dissolved oxygen recovery lasts for 15 and 64 (/47) days in south Carolina and Oregon (/Kansas), respectively. On average, among all stations over the CONUS, dissolved oxygen requires 51 days to recover after hydrological drought termination. Dissolved oxygen recovery takes more than 2 months in southeast Missouri, Texas, and South-Atlantic river basins (see Figure 7b). Moreover, Figure 6 shows that the dissolved oxygen follows a seasonal pattern and it reaches to the lowest (/highest) level during warmer (/colder) seasons. This pattern is seen all over the study area. This diagram shows the reverse relationship between water temperature and dissolved oxygen and explains the decreases of dissolved oxygen level during drought episodes due to the increases in temperature.

Our analysis also identified a decline in dissolved oxygen when a hydrological drought takes place, which is in agreement with findings of many studies showing a decrease in dissolved oxygen during hydrological droughts (Boulton and Lake, Ylla et al., 2010; 1992; Hellwig et al., 2017). Generally, in river basins with perennial rivers and higher streamflow, the variability range of dissolved oxygen is limited due to the deeper flow in rivers, which leads to less reaeration. On the other hand, most ephemeral rivers with shallow flow are located in lower latitude. Dissolved oxygen requires longer recovery time in these river basins because of higher water temperature and less oxygen solubility in spite of better reaeration. Therefore, in most river basins, water temperature is the dominant process (rather than reaeration and biological activity) that controls dissolved oxygen level. During drought persistence stage, dissolved oxygen shows a similar pattern to water temperature, and the maximum deviation of dissolved oxygen happens in the persistence stage. Many aquatic species can survive only within a specific temperature range and a minimum dissolved oxygen level. Therefore, considering dissolved oxygen and water temperature is essential for maintaining the ecology and biology of water resources systems (Mathews and Marsh-Mathews, 2003; Lake, 2011). Droughts have caused flora and fauna fatalities in different parts of the world, for instance in Australia (Leigh at al., 2015), southern US (Buskey et al., 2001), and California (Brumbaugh et al., 1994; Israel and Lund, 1995). The reported reasons for aquatic fatalities due to droughts were decline in dissolved oxygen level, vanishing the natural habitat of species, loss of streams connectivity, and alteration of food (Lake 2003, 2011; Leigh at al., 2015).

4 Discussion

Applying the hydrological drought detection method, a total of 9247 drought episodes were identified in 400 stations across the CONUS during 1950-2016. Figure 8 shows the relationship between drought duration, recovery time (required time for streamflow and water quality to revert to its pre-drought state), and annual flow across three different river basins with diverse climate (i.e. Pacific Northwest, Arkansas, and South Atlantic). The figure illustrates that there is a significant inverse relationship between drought duration and the annual flow in all three river basins (R^2> 0.5 and p-value<0.05). Therefore, annual streamflow deficits are probably more intense during prolonged drought events compared to shorter drought episodes. Similar results are found for recovery time and annual flow, and severe annual streamflow deficits are more likely to result in longer recovery time. However, recovery time is positively correlated to drought duration for these river basins (R^2> 0.5 and p-value<0.05), and similar pattern is found in all the river basins over the CONUS. The positive correlation found between drought duration and annual flow is in agreement with the findings of Spinoni et al. (2014) and Austin et al.

(2018). These studies also showed that if a drought episode lasts longer, drought severity increases and the affected area deals with exacerbated water stress. Thomas et al. (2014) investigated hydrological droughts and recovery time for south and southeastern USA, and concluded that for longer and more severe hydrological droughts, longer drought recovery duration should be expected. These findings are in consensus with the findings of the present study, indicating an inverse relationship between recovery time and annual flow and a direct relationship between drought duration and recovery time.

Figure 8 – Relationship between drought duration and annual flow (left), recovery time and annual flow (middle), and drought duration and recovery time (right) over the Pacific Northwest (top), Arkansas (middle) and South Atlantic (bottom) river basins.

Figure 9 shows hydrological drought severity over the CONUS for the study period. Severity indicates the ratio of accumulated streamflow deficit to streamflow in normal condition during drought episodes (elaborated in equation 1).

$$Drought\ Severity = \frac{\sum_{I=onset}^{Termination} Observed\ Streamflow_i - Threshold_i}{\sum_{i=onset}^{Termiantion} Threshold_i} * 100$$

$$if\ (Observed\ Streamflow_i - Threshold_i) < 0 \quad \text{(Equation 1)}$$

The figure shows that California, Great basin and South Atlantic river basins experienced more severe droughts during the study period. Texas and Souris basins also experienced severe droughts. Comparing Figure 9 (drought severity) and Figure 4 (number of droughts) reveals an inverse relation between drought severity and frequency in areas located in the Pacific

Northwest, California, Great Basin, Upper Colorado, Texas, Arkansas, Ohio, New England, Upper Mississippi, and Mid-Atlantic river basins. This inverse relationship implies that the regions affected by more frequent droughts, experienced less severe droughts, in general. This is found in the Pacific Northwest, Upper Colorado, and mid-Atlantic river basins. Whereas, those parts of the CONUS that experienced less frequent droughts (e.g. California, Texas and South-Atlantic river basins), suffered from more severe droughts. Griffin and Anchukaitis (2014) showed that for the period of 2012-2014, California experienced the most severe drought condition in the last century. Our analysis also finds Southern California among the regions that the most severe hydrological droughts have happened during the study period. Additionally, California experienced a hydrological drought in 2012, which lasted for almost a year (Figure 3), and that drought episode was accompanied by two major hydrological droughts in the following years. Anderson et al. (2013) and Long et al. (2013) showed that Southern US experienced more severe drought episodes compared to Northern regions during the period of 2000-2012. Figure 9 also corroborates that these areas (i.e. Florida, Southern Plains, and Southwestern US) experienced more severe hydrological droughts compared to the rest of the US.

Figure 9 – Spatial distribution of normalized drought severity over the CONUS during 1950-2016. Severity is defined as the ratio of accumulated streamflow deficit to streamflow in normal condition during drought episodes

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Figure 10 illustrates the correlation between the deviation of water quality parameters (during drought episodes) and drought severity over 18 river basins. In general, water temperature and dissolved oxygen are more correlated with drought severity than turbidity. Dissolved oxygen and drought severity are highly correlated in California, Lower Colorado, Texas, Rio Grande and South Atlantic river basins, all of which are located in the lower latitudes. Turbidity and drought severity correlation is the highest in Missouri and Arkansas, both located in arid climate. Comparing Figure 10 with Figure 7 reveals that in the river basins that require longer recovery time for dissolved oxygen, the correlation between dissolved oxygen and drought severity is highest. Similar pattern is found for turbidity recovery time in the Great Lakes, Missouri, and Arkansas, where the correlation between drought severity and turbidity is the highest, compared to other water quality parameters. Figure 10 shows that the southern US regions (basins 2-7 and 16) indicate higher correlation between water quality variations and drought severity, with dissolved oxygen indicating the highest correlation, which reveals the higher vulnerability of aquatic life to drought severity in southern US.

Figure 10 – The correlation coefficient between drought severity with water temperature, dissolved oxygen, and turbidity variations and over 18 river basins of the U.S.

The empirical cumulative distribution functions (CDFs) are developed to probabilistically analyze drought duration in the study period. Figure 11 shows the CDF of drought duration for Ohio, Missouri, and South Texas-Gulf river basins. These river basins are selected as they show the lowest, highest, and mean drought duration, respectively. The figure shows that with 75% probability, drought durations are 180, 220, and 300 days in Ohio, Missouri, and Texas river basins, respectively. Additionally, historical hydrological droughts indicated a median (50%

probability) duration of 110, 125, and 140 days for Ohio, Missouri and Texas river basins, respectively. In another interpretation, if a drought episode begins in these river basins, it is 55, 68 and 75% probable that it lasts for 200 days or less in Texas, Missouri and Ohio, respectively. In conclusion, it is more likely for Texas to experience more long-term drought events compared to other river basins.

Figure 11- Cumulative probability distribution (CDF) of drought duration in Ohio, Missouri, and South Texas-Gulf coast basins, representing least, most, and mean drought duration among all US basins, respectively

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5 Summary and Conclusions

It is essential to understand drought impacts on freshwater resources quality and their recovery duration. To this end, this study developed a framework for hydrological drought detection in order to categorize droughts into three stages of growth, persistence, and retreat, investigated water quality variations during droughts, analyzed recovery time for each water quality parameter, and finally assessed spatiotemporal and probabilistic characteristics of drought episodes. The method was applied on 400 streamflow and water quality stations over the CONUS with daily observation. The historic 2012 US drought was selected to validate the presented methodology. On average, drought persistence was found to last less than 2 months in most of the Eastern US. Whereas in California, Upper Colorado and Texas river basins, drought tends to persist more than three months. Results showed that, drought frequency is negatively correlated with drought severity and duration, whereas drought duration and recovery time are positively correlated. In terms of water quality, results showed that increased temperature, decreased turbidity, and lower dissolved oxygen were observed during hydrological droughts. Average recovery time for water temperature, turbidity and dissolved oxygen were 52, 42 and 51 days following hydrological drought termination, respectively. Furthermore, turbidity recovery time was found to be less than 60 days after drought termination for most of the CONUS, whereas, dissolved oxygen recovery indicated to be more than 2 months (maximum 69 days) in the lower latitude river basins.

Acknowledgement

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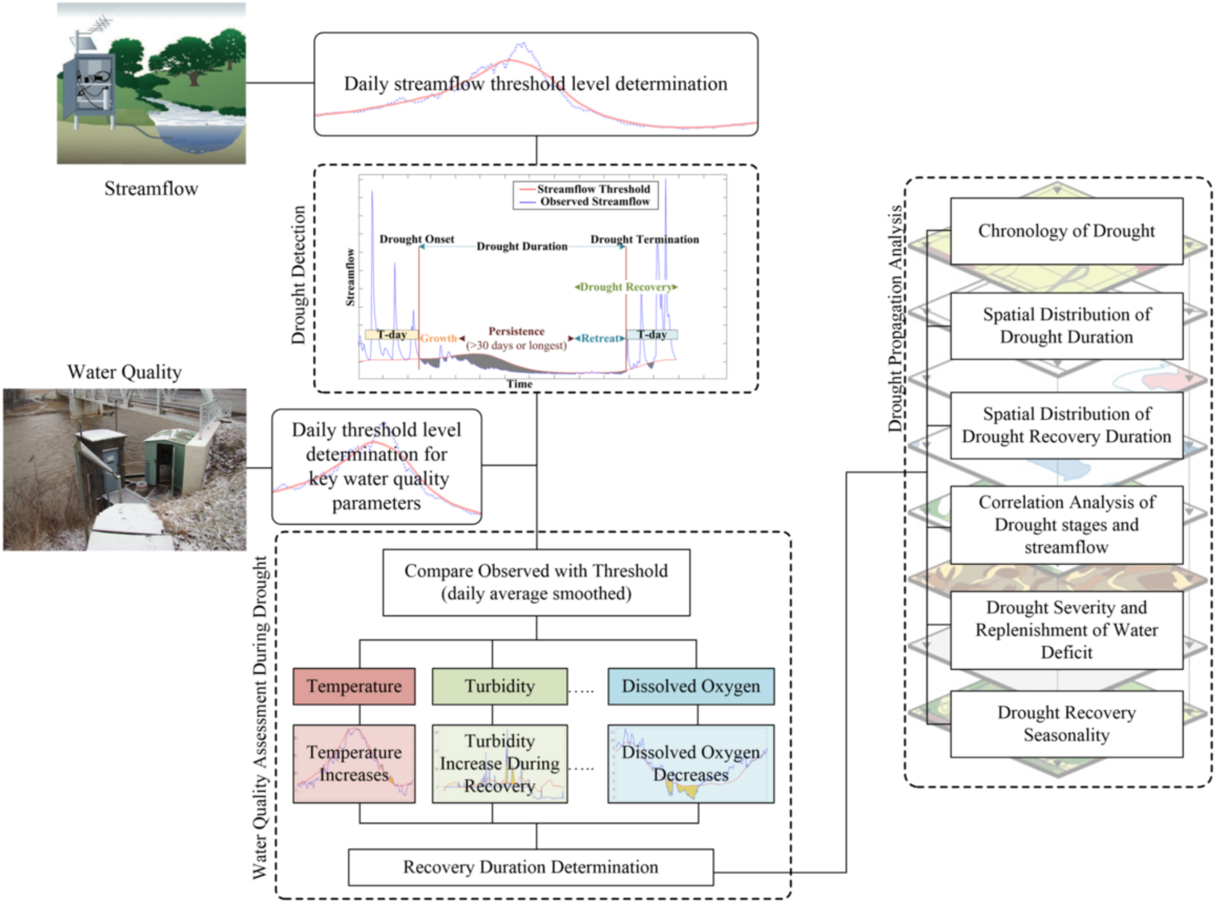
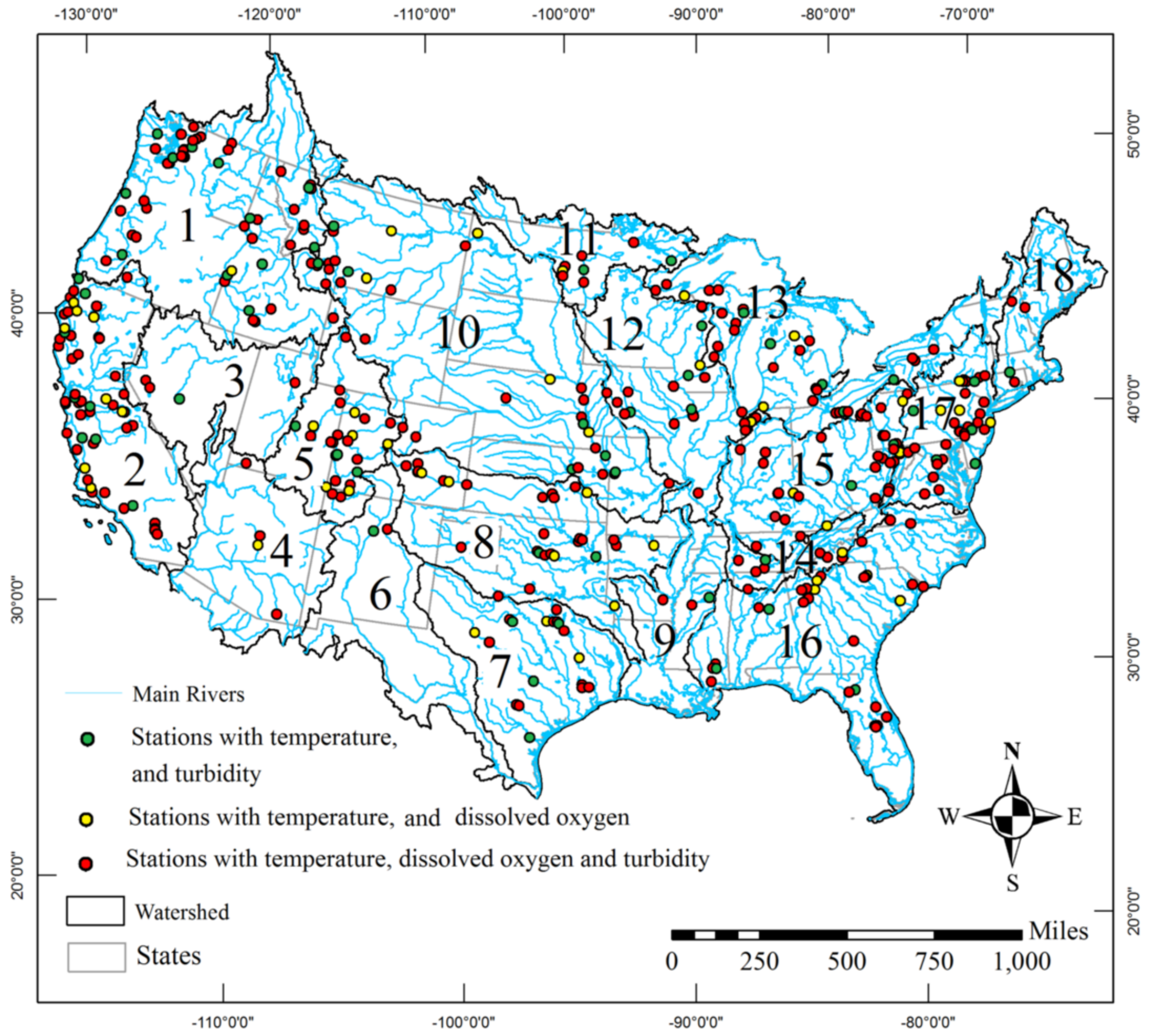
Figure S1- A conceptual diagram of drought growth, persistence, retreat, and recovery stages. In this study, persistence is when the flow remains below threshold for 30 days or more; moving backward/forward from persistence begin/end, drought onset/termination is when there is 15 or less days with flow below the threshold level in a T-day window (T = 60 days for this study). The gray shaded area shows streamflow deficit.

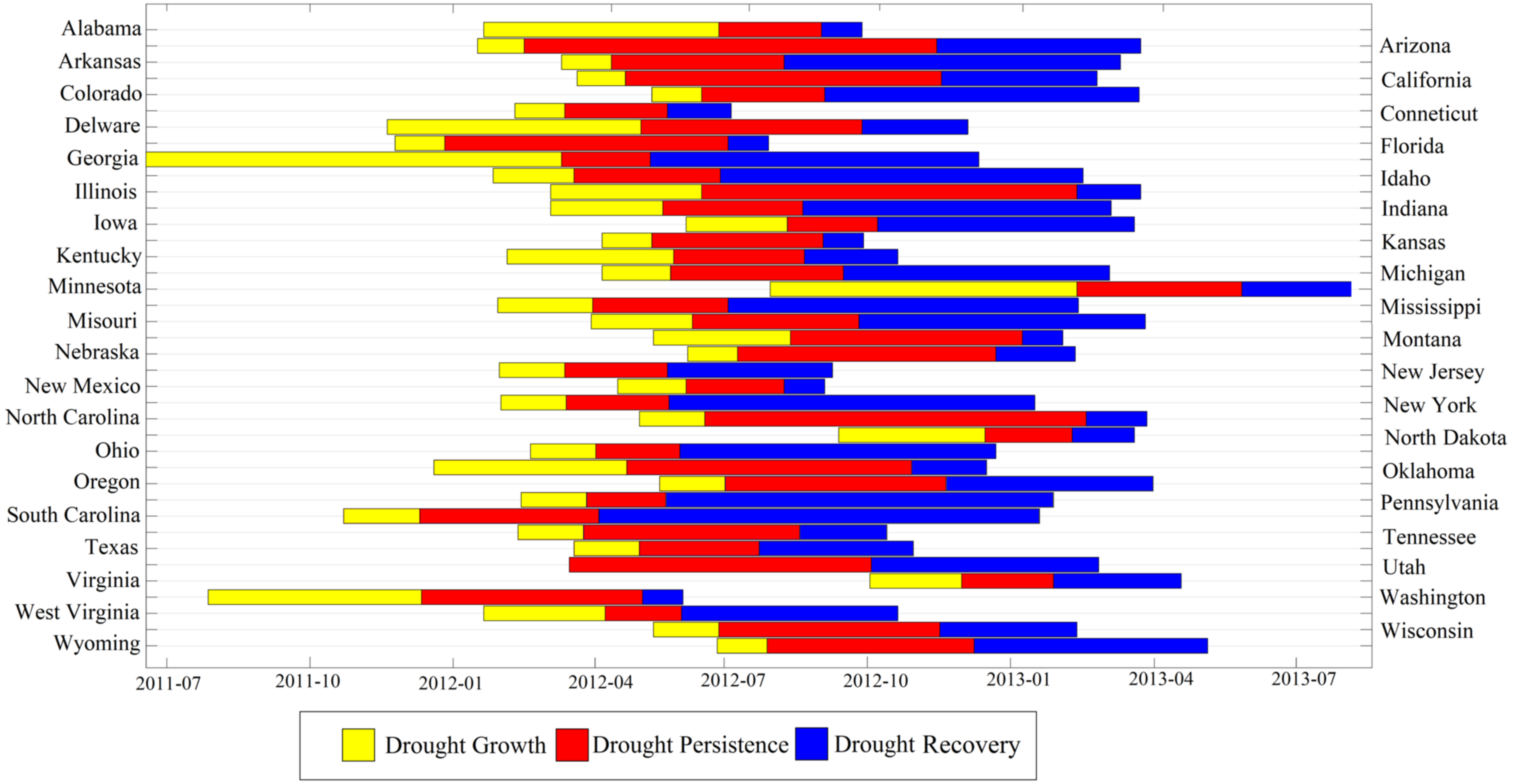
Figure S2- Spatial distribution of water temperature, dissolved oxygen and turbidity deviations from thresholds over the 2012 drought episode



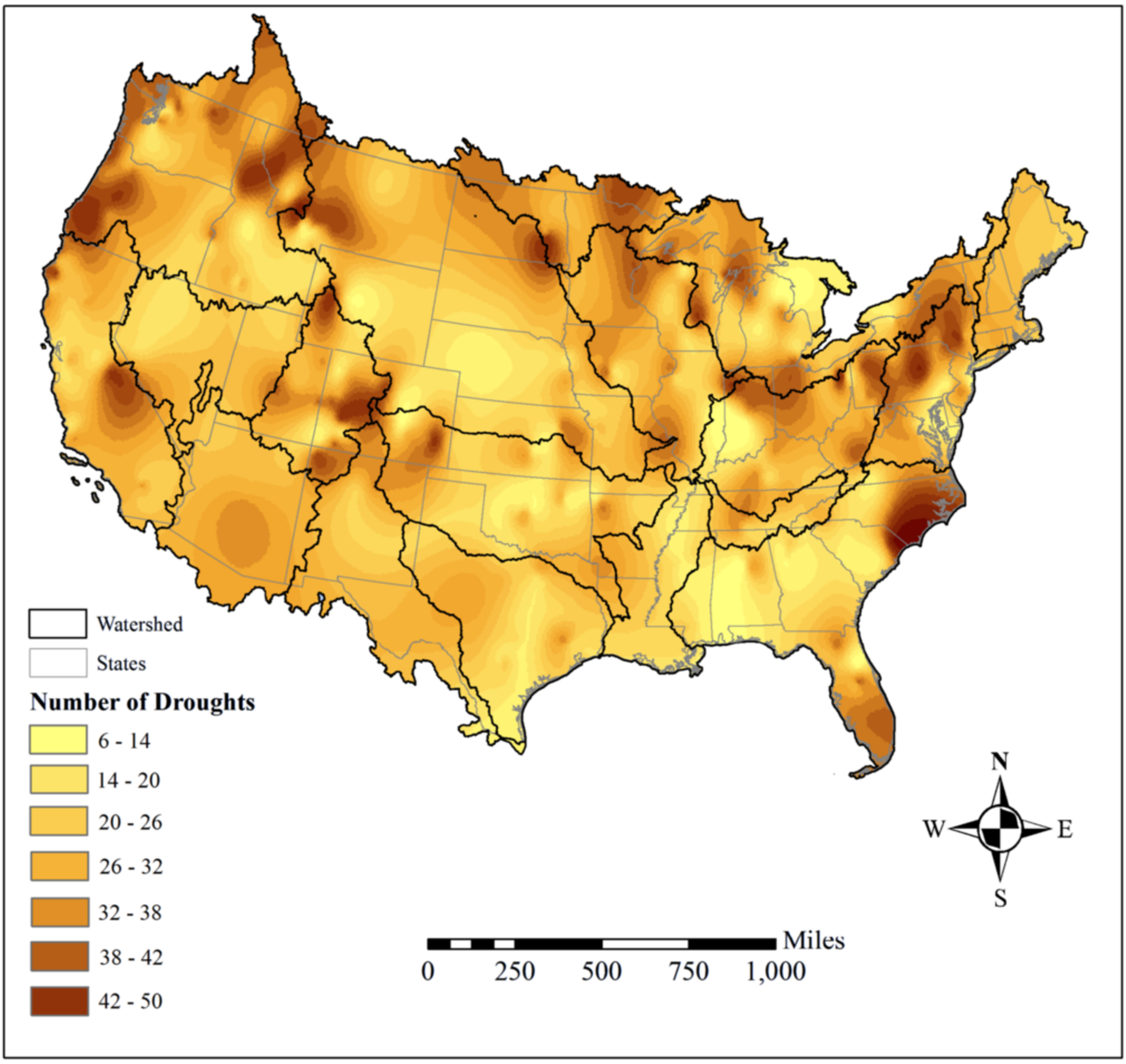
Streamflow
Daily streamflow threshold level determination
Drought Detection
Streamflow Threshold
Observed Streamflow
Streamflow
Drought Onset
Drought Duration
Drought Termination
Drought Recovery
T-day
Growth
Persistence
(>30 days or longest)
Retreat
T-day
Time
Water Quality
Daily threshold level determination for key water quality parameters
Water Quality Assessment During Drought
Compare Observed with Threshold (daily average smoothed)
Temperature
Turbidity
.....
Dissolved Oxygen
Temperature Increases
Turbidity Increase During Recovery
.....
Dissolved Oxygen Decreases
Recovery Duration Determination
Drought Propagation Analysis
Chronology of Drought
Spatial Distribution of Drought Duration
Spatial Distribution of Drought Recovery Duration
Correlation Analysis of Drought stages and streamflow
Drought Severity and Replenishment of Water Deficit
Drought Recovery Seasonality

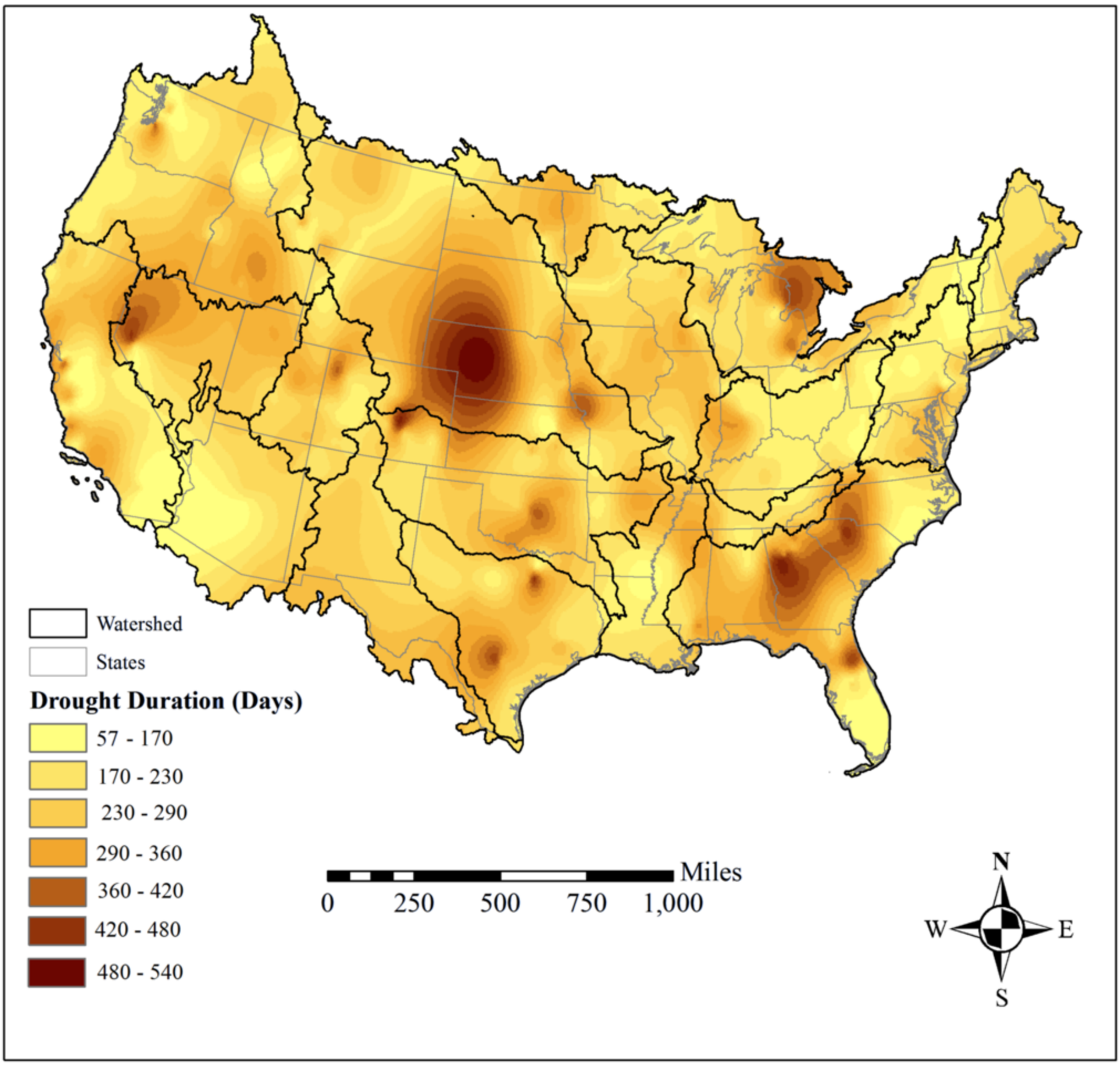


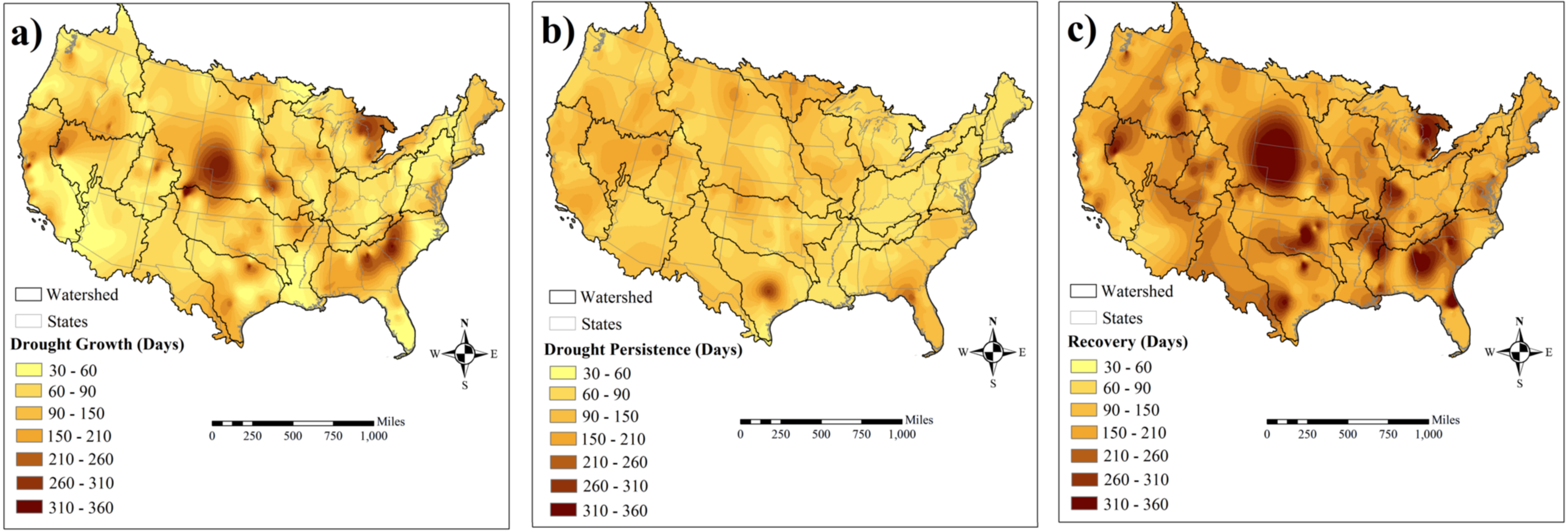
1 Pacific Northwest Basin
2 California Basin
3 Great Basin
4 Lower Colorado Basin
5 Upper Colorado Basin
7 Texas Gulf Coast Basin
8 Arkansas-White-Red Basin
9 Lower Mississippi Basin
10 Missouri Basin
11 Souris-Red-Rainy Basin
13 Great Lakes Basin
14 Tennessee Basin
15 Ohio Basin
16 South Atlantic-Gulf Basin
17 Mid-Atlantic Basin

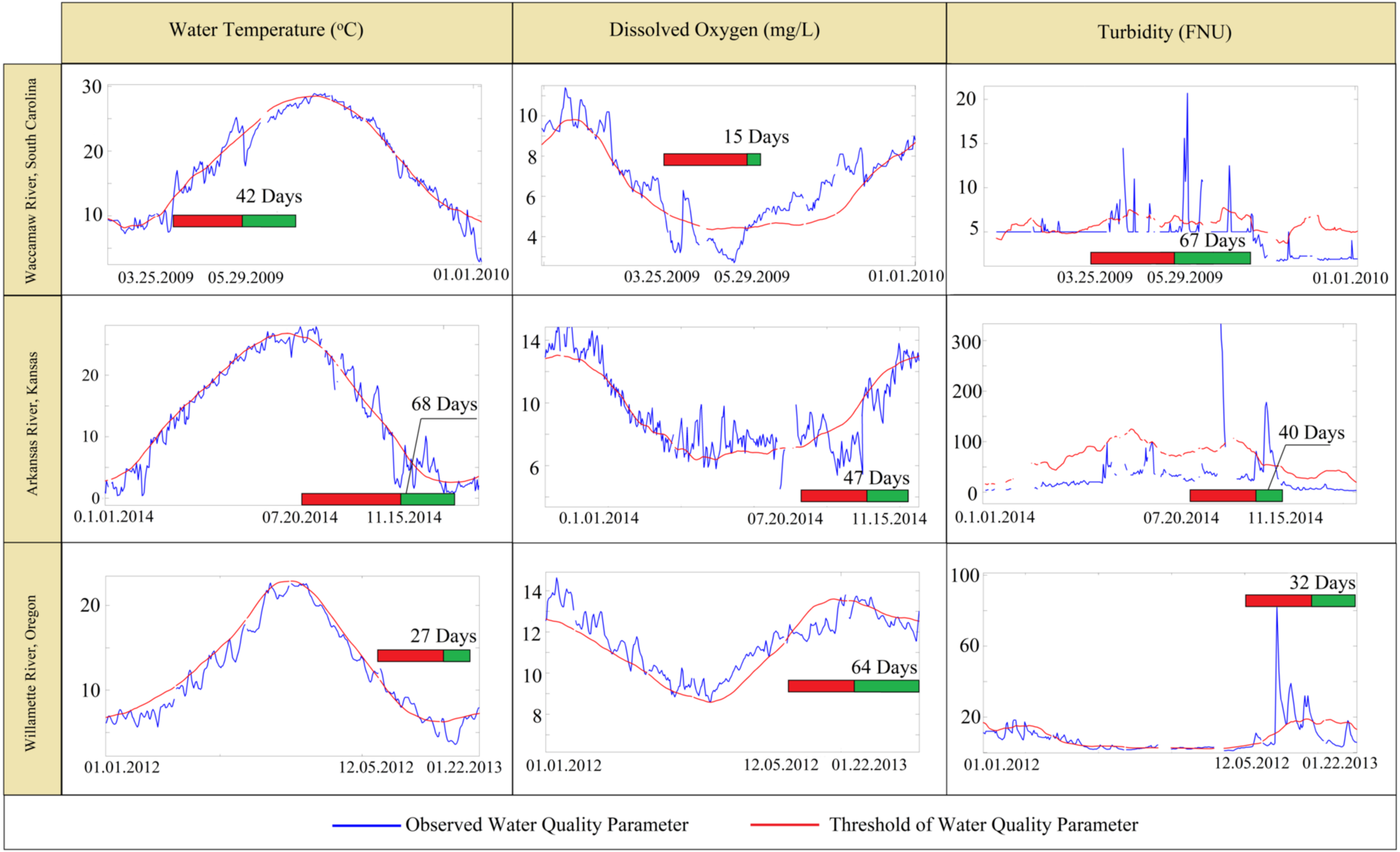


Alabama
Arizona
Arkansas
California
Colorado
Conneticut
Delware
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Michigan
Minnesota
Mississippi
Misouri
Montana
Nebraska
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
South Carolina
Tennessee
Texas
Utah
Virginia
Washington
West Virginia
Wisconsin
Wyoming
2011-07
2011-10
2012-01
2012-04
2012-07
2012-10
2013-01
2013-04
2013-07
Drought Growth
Drought Persistence
Drought Recovery

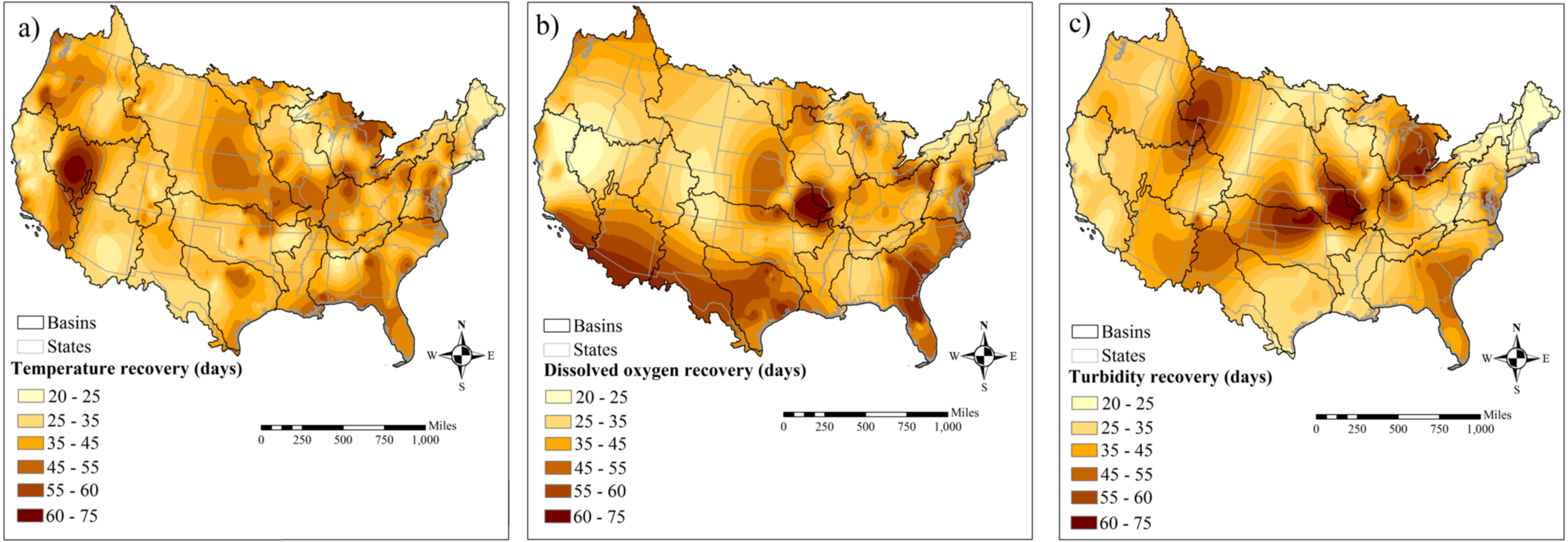

Watershed
States
Number of Droughts
6 - 14
14 - 20
20 - 26
26 - 32
32 - 38
38 - 42
42 - 50
Miles
0
250
500
750
1,000
N
W
E
S

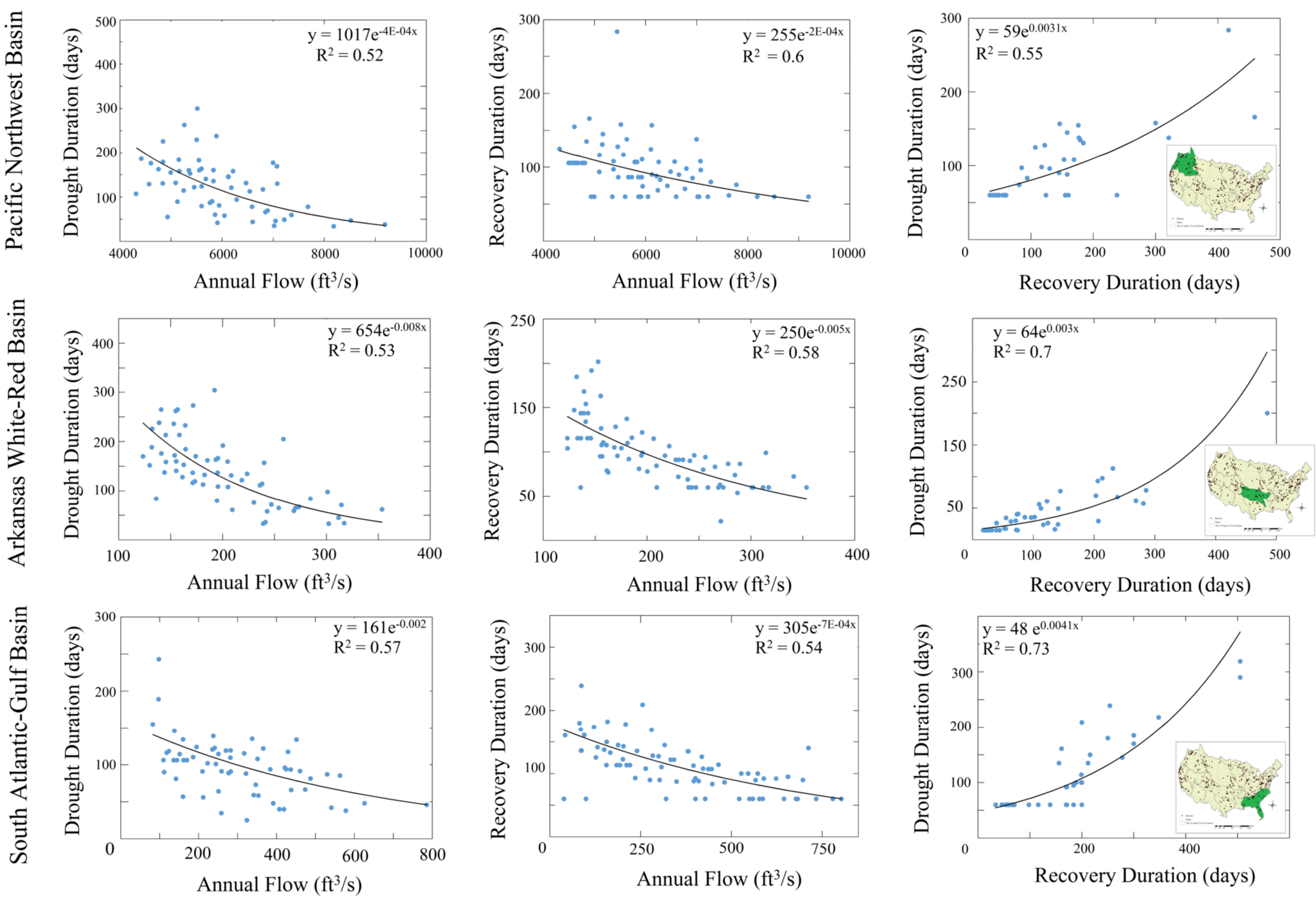

Watershed
States
Drought Duration (Days)
57 - 170
170 - 230
230 - 290
290 - 360
360 - 420
420 - 480
480 - 540
Miles
0
250
500
750
1,000
N
W
E
S

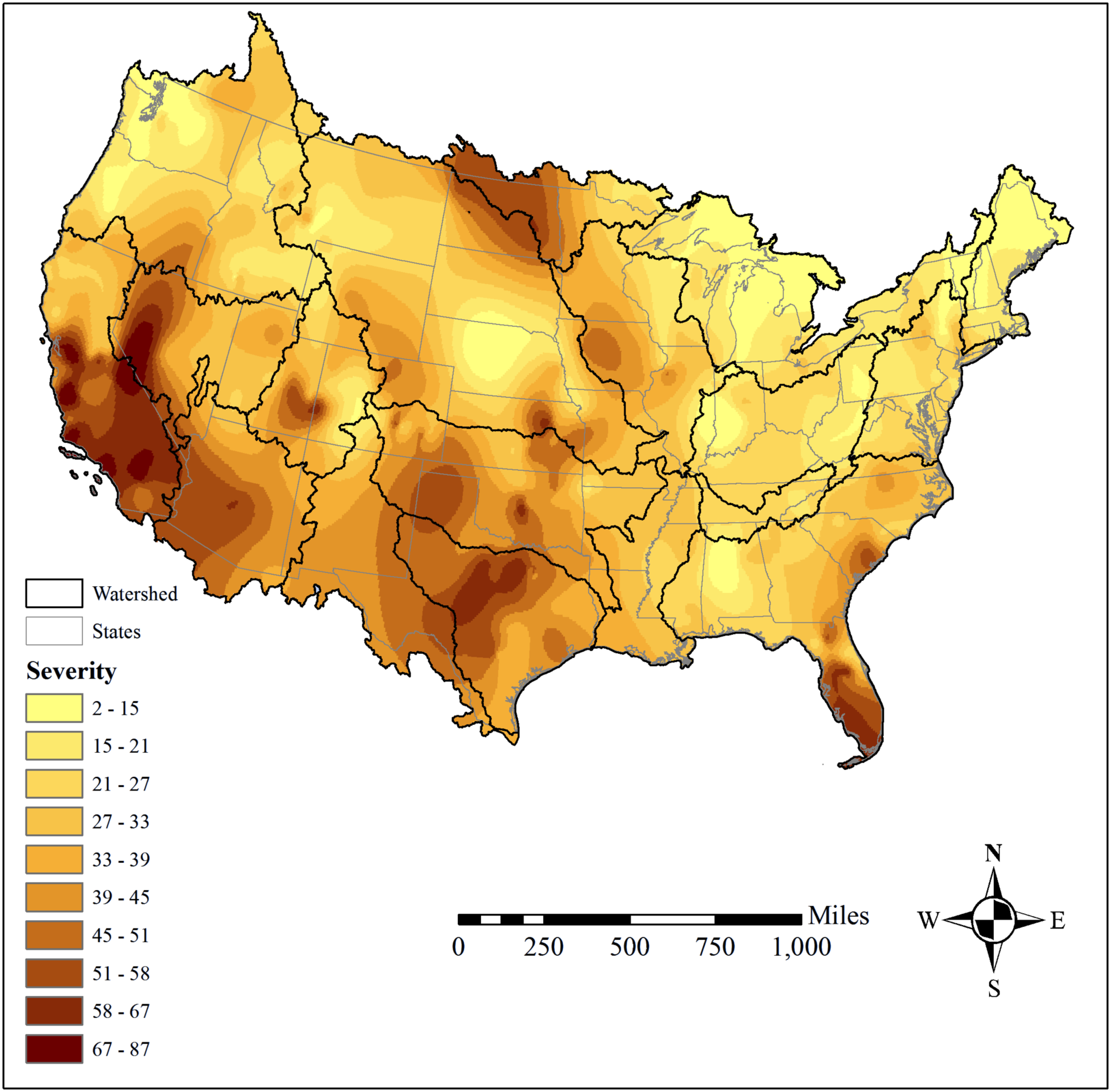

a)
Watershed
States
Drought Growth (Days)
30 - 60
60 - 90
90 - 150
150 - 210
210 - 260
260 - 310
310 - 360
N
W
E
S
Miles
0
250
500
750
1,000
b)
Watershed
States
Drought Persistence (Days)
30 - 60
60 - 90
90 - 150
150 - 210
210 - 260
260 - 310
310 - 360
N
W
E
S
Miles
0
250
500
750
1,000
c)
Watershed
States
Recovery (Days)
30 - 60
60 - 90
90 - 150
150 - 210
210 - 260
260 - 310
310 - 360
N
W
E
S
Miles
0
250
500
750
1,000

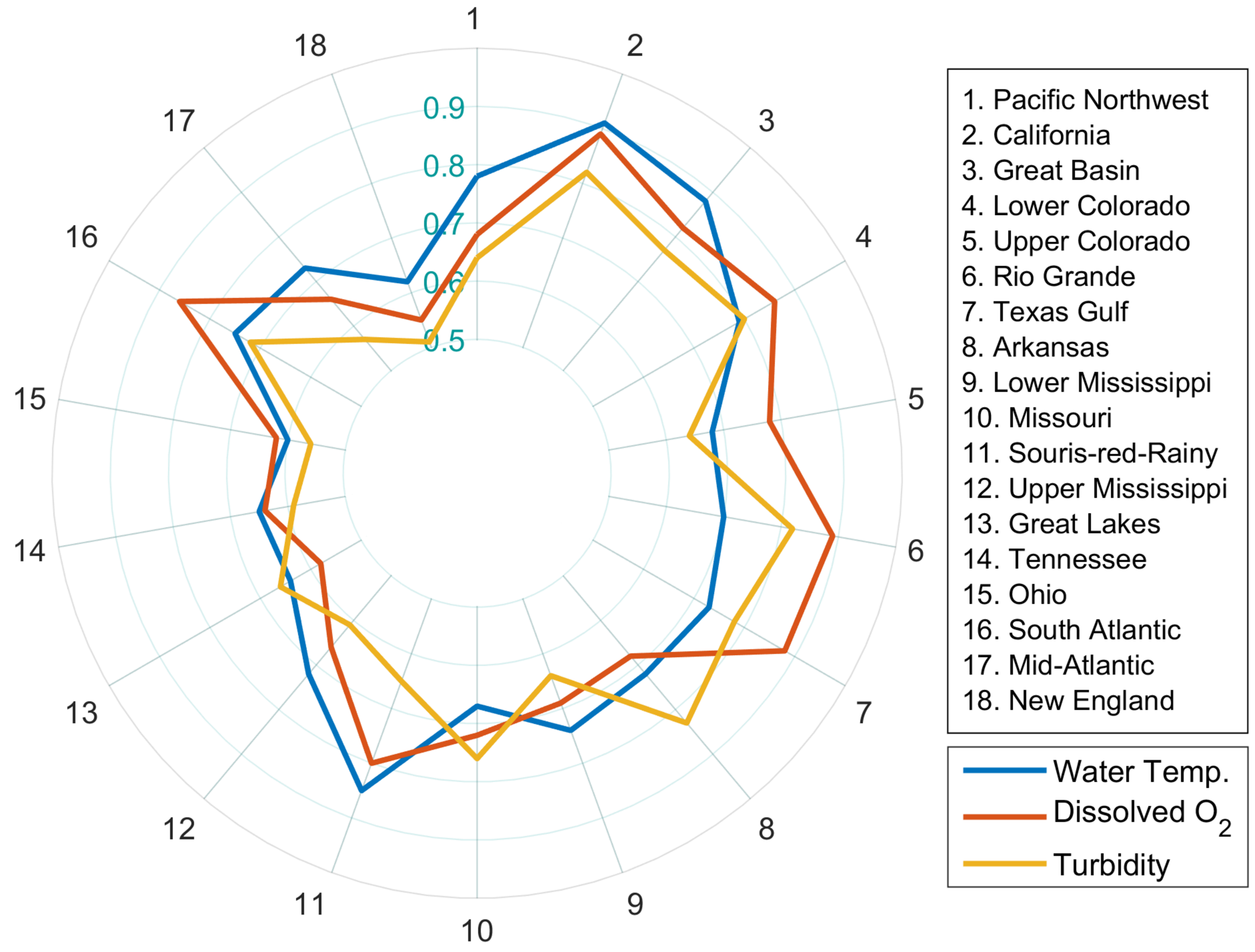


Water Temperature (°C)
Dissolved Oxygen (mg/L)
Turbidity (FNU)
Waccamaw River, South Carolina
Arkansas River, Kansas
Willamette River, Oregon
42 Days
15 Days
67 Days
68 Days
47 Days
40 Days
27 Days
64 Days
32 Days
03.25.2009
05.29.2009
01.01.2010
0.1.01.2014
07.20.2014
11.15.2014
01.01.2012
12.05.2012
01.22.2013
Observed Water Quality Parameter
Threshold of Water Quality Parameter


a)
Basins
States
Temperature recovery (days)
20 - 25
25 - 35
35 - 45
45 - 55
55 - 60
60 - 75
Miles
0 250 500 750 1,000
N
W
E
S
b)
Basins
States
Dissolved oxygen recovery (days)
20 - 25
25 - 35
35 - 45
45 - 55
55 - 60
60 - 75
Miles
0 250 500 750 1,000
N
W
E
S
c)
Basins
States
Turbidity recovery (days)
20 - 25
25 - 35
35 - 45
45 - 55
55 - 60
60 - 75
Miles
0 250 500 750 1,000
N
W
E
S


Pacific Northwest Basin
Arkansas White-Red Basin
South Atlantic-Gulf Basin
Drought Duration (days)
Recovery Duration (days)
Annual Flow (ft³/s)
y = 1017e^-4E-04x
R² = 0.52
y = 255e^-2E-04x
R² = 0.6
y = 59e^0.0031x
R² = 0.55
y = 654e^-0.008x
R² = 0.53
y = 250e^-0.005x
R² = 0.58
y = 64e^0.003x
R² = 0.7
y = 161e^-0.002
R² = 0.57
y = 305e^-7E-04x
R² = 0.54
y = 48 e^0.0041x
R² = 0.73


Watershed
States
Severity
2 - 15
15 - 21
21 - 27
27 - 33
33 - 39
39 - 45
45 - 51
51 - 58
58 - 67
67 - 87
Miles
0
250
500
750
1,000
N
W
E
S



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
0.9
0.8
0.7
0.6
0.5
1. Pacific Northwest
2. California
3. Great Basin
4. Lower Colorado
5. Upper Colorado
6. Rio Grande
7. Texas Gulf
8. Arkansas
9. Lower Mississippi
10. Missouri
11. Souris-red-Rainy
12. Upper Mississippi
13. Great Lakes
14. Tennessee
15. Ohio
16. South Atlantic
17. Mid-Atlantic
18. New England
Water Temp.
Dissolved O_2
Turbidity

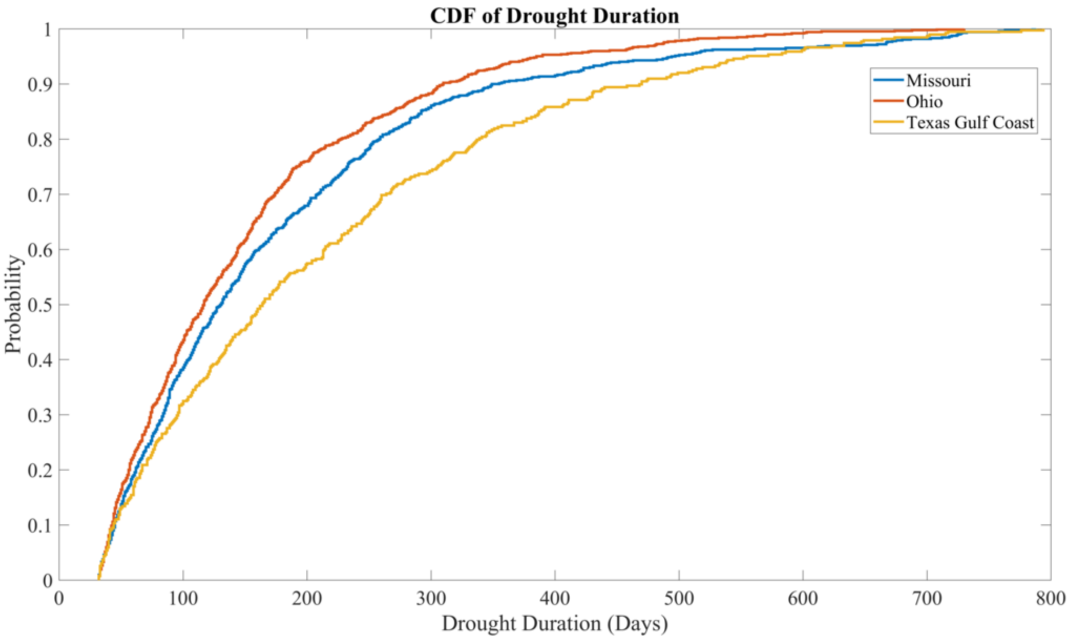

CDF of Drought Duration
Probability
Drought Duration (Days)
Missouri
Ohio
Texas Gulf Coast
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
100
200
300
400
500
600
700
800

Table 1 – Minimum, median, and maximum deviation of water temperature, dissolved oxygen, and water turbidity during drought for each river basin.

	Temperature (^oC)			**Dissolved Oxygen (mg/L)**			**Turbidity (FNU)**		
	Min	Median	Max	Min	Median	Max	Min	Median	Max
1. Pacific Northwest	1	1.5	2.8	1	1.5	2.3	14	25	50
2. California	2	2.8	5.8	1.3	1.8	2.8	18	32	55
3. Great Basin	2	2.5	4.8	1.2	1.6	2.7	36	68	110
4. Lower Colorado	2.2	3	5.6	1.4	1.7	2.8	40	72	95
5. Upper Colorado	1.5	2	3.2	1.1	1.5	2.3	35	68	114
6. Rio Grande	2.2	3.2	5.7	1.4	1.8	2.6	42	61	103
7. Texas Gulf	2.1	3	5.9	1.3	1.7	3	29	36	68
8. Arkansas	1.5	1.9	5.5	1	1.4	2.8	33	66	120
9. Lower Mississippi	2.5	3	4.8	1.3	1.6	2.6	15	29	48
10. Missouri	1.3	2.8	4.3	1.2	1.5	2.2	44	72	113
11. Souris-Red-Rainy	1.2	1.9	2.8	1.1	1.4	1.8	16	30	62
12. Upper Mississippi	1.5	1.9	3	1.2	1.5	2.1	18	28	52
13. Great Lakes	1.4	2.1	2.7	1	1.4	2.2	17	31	56
14. Tennessee	2	3	3.3	1.2	1.6	2.5	14	26	50
15. Ohio	1.2	2.2	3	1.1	1.4	2.3	11	26	46

16. South Atlantic	2.2	2.9	4.9	1.4	1.9	2.9	10	21	39
17. Mid-Atlantic	1.5	2.3	3.1	1.2	1.5	2.3	11	20	44
18. New England	1.2	1.8	2.6	1.1	1.4	2.1	15	31	56