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Key Points:

- Characterizing shifts in intensity, duration, and frequency of water shortage events is needed to improve the vulnerability assessments
- Assessing the vulnerability to water shortage and relationships with aridification is required at the monthly to decadal timescales
- Population growth and climate change may increase decadal events in the drier regions and interannual events in the wetter regions

Supporting Information:

Supporting Information may be found in the online version of this article.

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Vulnerability to Water Shortage Under Current and Future Water Supply-Demand Conditions Across U.S. River Basins

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Abstract Climate change, population growth, urbanization, and interactions thereof may alter the water supply-demand balance and lead to shifts in water shortage characteristics at different timescales. This study proposes an approach to improve the vulnerability assessments of U.S. river basins to the shortage at the interannual to decadal timescales by characterizing shifts in intensity, duration, and frequency (IDF) of water shortage events from current (1986–2015) to future (2070–2099) periods. The results indicate that under the driest future climate projection, the frequency and intensity of over-year ($D > 12$ months) events at the monthly scale and decadal ($D > 10$ years) events at the annual scale tend to increase in the Southwest, Southern, middle Great Plain, and Great Lakes regions. Conversely, the frequency of interannual ($D < 12$ months) events at the monthly scale and annual ($D > 1$ year) and multi-year ($D > 3$ years) events at the annual scale is likely to increase in the West Coast regions. Besides, river basins with a higher rate of aridification are likely to experience more frequent over-year ($D > 12$ months) events, while river basins with a decrease in aridification were projected to undergo more frequent interannual ($D < 12$ months) events due to an increase in the variability of extreme weather anomalies within a year. The findings of this study provide new insights to understand and characterize vulnerability to water shortage under current and future water supply-demand conditions and can inform the development of effective mitigation and/or adaptation strategies.

Plain Language Summary Water Shortage is an inevitable and complex phenomenon that has plagued civilization throughout history. Future changes in climate and population may cause a decrease in freshwater availability and an increase in water demand leading to more frequent water shortage conditions. The enhanced characterizations of changes in water shortage conditions from interannual to decadal events are requisite to the appropriate management and planning of future water resources, and improved implementation of regional adaptation and mitigation strategies under significant shifts in water supply-demand balances. We proposed an approach to assess how shifts in the demand-supply balance can alter the intensity, duration, and frequency of water shortage conditions at the monthly and annual scales. The findings reveal that under the driest future climate projection for the United States river basins, prolonged water shortage conditions in drier basins and interannual water shortage events in wetter basins are likely to be the main concerns in the future and should gain more attention in the water resource planning and management.

1. Introduction

Water availability plays a critical role in a wide range of environmental, agricultural, industrial, and recreational activities. However, urbanization, population growth, and climate change may lead to shifts in water supply-demand conditions in river basins and culminate in short-term or chronic water shortages (Brown et al., 2019; Engström et al., 2020; Heidari, Arabi, Ghanbari, & Warziniack, 2020; Heidari, Arabi, Warziniack, & Kao, 2020; Mahat et al., 2017; Naz et al., 2016; Warziniack & Brown, 2019; Xing et al., 2018). Water shortage occurs when water demand exceeds water supply (Foti et al., 2012; Salas et al., 2005; Yevjevich, 1967). Water shortage events have recently increased across multiple U.S. river basins with longer duration, higher intensity, and greater spatial extent than has occurred over the last decades (Martin et al., 2020).

Enhanced characterization of shifts in water shortage conditions is increasingly discussed in response to climate change and rapid population growth (Cheng et al., 2014; Heidari, Arabi, Ghanbari, & Warziniack, 2020;

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Salas et al., 2018). Although diverse methods have been used in previous studies for the assessment of future water shortage conditions across the United States, four important considerations should be addressed to improve the vulnerability assessment of water supply systems to water shortage in the future:

First, a few studies discussed the effects of shifts in both water supply and water demand on the characterization of future water shortage events across the United States (Guo, Huang, Huang, Wang, Fang, et al., 2019; Guo, Huang, Huang, Wang, Wang, & Fang, 2019; Heidari, Arabi, Ghanbari, & Warziniack, 2020; Salas et al., 2018; Tu et al., 2018) and more research is needed to support actionable managements to mitigate negative impacts. Previous studies mostly describe water shortage in terms of deficiencies in water supply systems, in which water demand is a constant threshold of water supply (Guo, Huang, Huang, Wang, Fang, et al., 2019; Guo, Huang, Huang, Wang, Wang, & Fang, 2019; Tu et al., 2018). However, socioeconomic drivers such as population growth can significantly increase water demand and lead to an unequal balance between water supply and demand in the future (Salas et al., 2018).

Second, previous studies mostly assessed the vulnerability of the United States water supply systems to only long-term water shortage conditions (Brown et al., 2013, 2019; Foti et al., 2012, 2014; Mahat et al., 2017; Mehran et al., 2017; Warziniack & Brown, 2019). However, the effects of changes in the water supply-demand balance must be assessed at different timescales from interannual to decadal (Cayan et al., 2010; Gober & Kirkwood, 2010; Jaeger et al., 2017; MacDonald, 2010; Mann & Gleick, 2015; McDonald et al., 2011; Rosegrant & Cai, 2002; Sun et al., 2008; Yigzaw & Hossain, 2016). Interannual changes in the variability of weather and water consumption in the future may cause unequal supply-demand balance within a year (Gutzler & Nims, 2006; Yu et al., 2014). The assessments of water shortage conditions at various timescales allow characterizing of both prolonged and short-term events (Maliva & Missimer, 2013). Many regions that are prone to prolonged water shortage conditions may not have the food, water, and economic resources to overcome multi-year water shortage conditions (Maliva & Missimer, 2013). Besides, even in regions where water is abundant, water scarcity during short time periods within the year may be on the rise due to climate change and rapid population growth (Jaeger et al., 2017). Interannual water shortage conditions can lead to significant impacts, especially on agricultural regions during the growing seasons (Otkin et al., 2018).

Third, a few studies investigated the relationship between aridification and water shortage events across the United States river basins (Andreadis & Lettenmaier, 2006; Piemontese et al., 2019). Long-term changes in the relationship between climate and water budgets of river basins may lead to aridification or desertification (Heidari, Warziniack, et al., 2021; Maliva & Missimer, 2013). Aridification can be defined as the long-term severe lack of freshwater availability in a region. Severe water shortage events can develop very rapidly if climate change leads to aridification in a region (Andreadis & Lettenmaier, 2006; Piemontese et al., 2019). Understanding mechanisms behind the water shortage conditions is required for the enhanced water resource management and planning (Andreadis & Lettenmaier, 2006; Hagenlocher et al., 2019; Svoboda et al., 2002; Tu et al., 2018).

Fourth, previous studies have mainly focused on only the frequency of water shortage occurrence. Foti et al. (2014) assessed the vulnerability of the U.S. water supply system to the shortage as the probability that annual water supply is less than annual water demand. Brown et al. (2019) and Warziniack and Brown (2019) quantified the frequency of water shortage as the number of months over a given multiyear time period when shortages occur. Engström et al. (2020) assessed the exposure of each state within the CONUS to water scarcity and represented only the frequency to show how often a state is in water shortage conditions. However, the effects of changes in the water supply demand balance must be characterized on shifts in intensity, duration, and frequency relationships of water shortage events. Although IDF curves have been commonly used for the characterization of the designed event for water supply systems, these relationships may need to be modified in a changing environment under nonstationary conditions (Hallack-Alegria & Watkins, 2007; Heidari, Warziniack, Brown, & Arabi, 2021; Mann & Gleick, 2015; Rajsekhar et al., 2015; Ramazanipour et al., 2011; Salas et al., 2005). The improved estimation of future IDF relationships can enhance the management and planning of future water resources (Buurman & Babovic, 2016; Heidari, Arabi, Ghanbari, & Warziniack, 2020).

Recently, Heidari, Arabi, Ghanbari, and Warziniack (2020) developed a probabilistic approach for enhanced characterization of intensity, duration, and frequency (IDF) relationships of water shortage events at a

sub-annual scale under considerable shifts in water supply and demand conditions. The approach uses the mixture Gamma-Generalized Pareto (Gamma-GPD) model to simultaneously improve the characterization of both non-extreme and extreme events. In this study, the application of the developed probabilistic approach was demonstrated for the CONUS at a 4-digit hydrologic unit code (HUC4) basin scale under the IPSL-CM5A-MR model obtained from the Multivariate Adaptive Constructed Analogs (MACA) data set as the driest climate model with the highest projected decrease in average precipitation (Joyce & Coulson, 2020). This model was selected in order to assess significance and importance of the proposed approach under considerable shifts in water supply and demand conditions.

Thus, this study assesses future shifts in intensity, duration, and frequency (IDF) of water shortage conditions at interannual, annual, multi-year, and decadal scales across the CONUS in response to significant shifts in water supply and water demand conditions under the driest climate change scenario. Specifically, the objectives are to: (a) assess shifts in IDF properties of water shortage events across U.S. river basins from current to future conditions; (b) evaluate the frequency amplification factors of water shortage events; (c) identify factors that govern changes in water shortage frequency (or intensity) across regions in CONUS; and (d) characterize the relationship between aridification and water shortage events of U.S. river basins at various timescales. The findings of this study can help decision makers to assess and improve the ability of various water supply systems to shortage and address the considerations in water resource planning and management under considerable shifts in water supply and demand conditions.

2. Materials and Methods

In this section, we demonstrate our proposed approach to characterize the vulnerability of the United States river basins to water shortage under the worst-case scenario for the end-century conditions. Current climate conditions (1986–2015) of U.S. river basins were projected using the combination of the Daymet (Thornton et al., 1997) and the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al., 2008) data sets. Future climate conditions (2016–2099) were estimated using the driest MACA climate model with radiative concentration pathways (RCPs) 4.5 and 8.5 from the downscaled Multivariate Adaptive Constructed Analogs (MACA) data sets (Abatzoglou & Brown, 2012). The forcing climate variables were used as inputs to the variable infiltration capacity (VIC version 4.1) model to project the monthly water yields across the CONUS at the HUC4 river basin scale (Figure S1). The monthly water demand of each basin was estimated in light of population growth and climate change. Then, the water supply of each basin was obtained using the Water Evaluation and Planning (WEAP) model. The estimated water supply and water demand were used to characterize changes in characteristics of water shortage events from current (1986–2015) to future (2070–2099) conditions. Additionally, the statistical relationships between the water shortage conditions and aridification were assessed. Finally, regions with a level of shortage in the future were categorized into supply-based, demand-based, and supply/demand-based regions. Changes in the average duration, intensity, and frequency of water shortage events were characterized under shifts in only water demand conditions (demand-based), only water yield conditions (supply-based), and both supply and demand conditions (supply/demand-based). In the following sections, we applied the term baseline to denote the current period (1986–2015) as a basis for comparison with the future (2070–2099) climate conditions.

2.1. Hydroclimatic Projection

The daily precipitation and temperature of U.S. river basins for the current conditions (1986–2015) were obtained from the Daymet data set (Thornton et al., 1997) and then biased corrected using the Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate data set (Daly et al., 2008) at the monthly scale. The daily wind speed of U.S. river basins for the current conditions was also calculated from the North American Regional Reanalysis (NARR) data set (Mesinger et al., 2006). Readers are referred to Oubeidillah et al. (2014) and Naz et al. (2016) for more detailed information about the historical climate projection.

The future precipitation, minimum and maximum temperature, and wind speed of U.S. river basins were obtained from the downscaled Multivariate Adaptive Constructed Analogs (MACA) data sets (Abatzoglou & Brown, 2012). The MACA climate data set includes 20 downscaled climate models at the grid size of

~4 km (1/24°) with the RCPs 4.5 and 8.5. Joyce and Coulson (2020) selected five MACA climate models for the CONUS to represent a possible range of temperature and precipitation over the 21st century including the wettest, driest, hottest, and the least warm models and one model located near the middle of these ranges (Joyce & Coulson, 2020; Heidari, Arabi, Warziniack, & Kao, 2020; Heidari, Arabi & Warziniack, 2021). Heidari, Arabi, Warziniack, and Kao (2020) found that there is a consistent spatial pattern of changes in hydroclimatic conditions of U.S. River basins across the five selected MACA climate projections. As a common spatial pattern, climate change will cause a wetting trend over the western and eastern CONUS but a drying trend over the central and southern CONUS. However, they showed that the magnitude of changes are various across the five climate models by particularly largest changes under the driest climate model (IPSL-CM5A-MR).

In this study, we selected the IPSL-CM5A-MR model that has on average the highest decreases in precipitation and evaporation and the highest increases in potential evapotranspiration and temperature at the conterminous scale (Joyce & Coulson, 2020). This model was chosen in order to represent the worst-case scenario for the future climate conditions and better understand and assess the significance and importance of the proposed approach under significant shifts in water supply conditions. Besides, we selected RCP 4.5 and 8.5 to compare the effects of the medium and high concentration pathways on the future water shortage conditions. RCP 4.5 approximately results in a radiative forcing of 4.5 W/m² at year 2100, while RCP 8.5 leads to a radiative forcing of 8.5 W/m² at year 2100 and results to the greatest warming and likely the most critical change in precipitation (Rupp et al., 2013).

Note that a global and comprehensive assessment of the United States water shortage conditions under various climate change projections is not the purpose of the current study. However, a good representation of current climate conditions is a vital need required to realistically simulate future climate conditions. Figure S2 compares the 30-year average of annual projected precipitation and temperature of the IPSL-CM5A-MR climate model and the baseline climate model (the combination of PRISM and Daymet) over the historical period (1986–2015) at the HUC4 basin scale. The 30-year average of precipitation and temperature for the climate model has a high correlation with the baseline historical model under both RCPs 4.5 and 8.5. The IPSL-CM5A-MR climate model with RCPs 4.5 and 8.5 shows a strong linear correlation (from 0.9928 to 0.9985) for both annual precipitation and temperature. Readers are referred to Heidari, Arabi, Warziniack, and Kao (2020), and Joyce and Coulson (2020) for more detailed information about the future climate projections.

The current and future climate projections were then inputted to the semi-distributed macroscale Variable Infiltration Capacity (VIC) version 4.1.1 hydrologic model (Cherkauer & Lettenmaier, 2003; Liang et al., 1994) at a daily time step to simulate the water yield of U.S. river basins at the grid size of ~4 km (1/24°). The VIC hydrological model simulates land-atmosphere fluxes and the water and energy balances at the land surface. Grid cells represent the spatial variability of precipitation, vegetation, and topography (Cherkauer & Lettenmaier, 2003). The VIC model has some key assumptions including that the atmosphere is the only source of incoming water for each grid cell, and that grid cell is independent of other cells. It means that there are no horizontal water and energy exchanges between grid cells (Demaria et al., 2007). Topography, soil characteristics, vegetation, and land surface classification are other key hydrological inputs to the VIC model.

The VIC model has been commonly applied in previous studies to project streamflow over different large river basins in North America at various spatial and temporal scales (Andreadis & Lettenmaier, 2006; Brown et al., 2019; Heidari, Arabi, Warziniack, & Kao, 2020; 2021; Naz et al., 2016; Oubeidillah et al., 2014).

In this study, the aggregated monthly runoff obtained from the USGS National Water Information System gauge observations (WaterWatch data set) (Brakebill et al., 2011) was used to calibrate the VIC model for each HUC4 basin. The WaterWatch monthly runoff data can lead to the homogenous application of the VIC model to all relevant grid cells. Organized and calibrated VIC input data for the US Geological Survey (USGS) eight-digit hydrologic subbasins (HUC8) across the entire CONUS were obtained from Oubeidillah et al. (2014). To calibrate the VIC model, the simulated monthly total streamflow (surface runoff plus baseflow) of each HUC8 basin was matched with the monthly runoff from the USGS WaterWatch runoff

data set. The daily water yield outputs from the VIC model were then aggregated to monthly values for each HUC4 river basin.

Figure S3 compares the observed versus simulated annual water yield for each HUC4 river basin within the CONUS over the 1986–2015 period. The VIC model shows a strong linear correlation (0.9894) between observed and simulated mean annual water yield. Readers are referred to Oubeidillah et al. (2014), Naz et al. (2016), and Heidari, Arabi, Warziniack, and Kao (2020) for the detailed description of the VIC model set up, calibration, evaluation, and simulation.

2.2. Water Demand Projection

The method used in this study to estimate water demand follows that described by Brown et al. (2013, 2019). The monthly water demand of each HUC4 river basin was estimated by summing projections for six water use sectors including domestic and public, agricultural irrigation, thermoelectric, industrial, commercial, and mining, livestock, and aquaculture. The current water use data were obtained from the USGS water use circulars and for thermoelectric power water use from Diehl and Harris (Diehl & Harris, 2014). The future water withdrawal for each sector was estimated as the product of a water use driver such as population and irrigated area; and a water withdrawal rate such as domestic withdrawals per capita and irrigation withdrawal per unit area.

The A1B scenario from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment set of global socioeconomic scenarios was chosen to project future changes in population and income levels using the AIM global emissions model (Brown et al., 2013; Nakicenovic, 2000). The A1B scenario closely extends the current trends in population and economic growth and simulates a high level of technological change and rapid spread of efficient technologies by assuming a balanced emphasis on all energy sources. The population of the United States has been estimated to approximately increase to about 67% from current to future conditions with an annual growth rate that gradually declines by about 62% (Brown et al., 2013).

Irrigated area has been estimated to rise in the East and decrease in the West (Brown et al., 2013); and per capita total electricity consumption has been projected to increase about 7% from current to future conditions with an annual growth rate that gradually declines by 100%. Impacts of climate change on water demand were included in domestic, public, irrigation, and thermoelectric demand (Brown et al., 2013). Projected changes under the driest climate model can affect water use in several sectors (Brown et al., 2019; Georgakakos et al., 2014), as rising potential evapotranspiration rates, plus decreasing precipitation can lead to a significant increase in agriculture and landscape irrigation demands.

2.3. Water Supply Assessment

The Water Evaluation and Planning (WEAP) model (Yates et al., 2005) was applied in this study to estimate the water supply allocated to each HUC4 river basin. The WEAP model applies linear programming to allocate water in order to maximize demand satisfaction that is subject to allocation priorities, mass balances, water availability, and other constraints (Brown et al., 2019). The approach of the WEAP model is to satisfy demands and maintain reservoir storage levels. The water demand is satisfied from the current water yield before the utilization of reservoir storage.

The WEAP model used in this study was set up by Brown et al. (2019) at HUC04 watersheds spatial scale. The WEAP model runs at the monthly time step for the period of 1985–2099 to calculate the past and future water supply of each HUC4 river basin. The monthly water yield, water demand, trans-basin diversion capacity, instream flow constraint; reservoir storage capacity, evaporation rate, and volume-elevation curve; and priorities of the different water uses are the key inputs to the WEAP model.

The water supply of a basin was defined as the amount of water available to meet demands for a given month and obtained from the sum of water yield, net trans-basin diversions, reservoir storage from the prior month, and inflow from upstream minus the sum of required instream flow release, reservoir evaporation, and any required release to satisfy downstream demands. Note, the net trans-basin diversion is positive if the basin imports water and negative if the basin exports water. The surplus water supply will be stored in the reservoir when water supply exceeds consumptive use demands.

The highest priority was given to the instream flow requirement and trans-basin diversions and then the next two lower priorities were assigned to within basin consumptive demands, and the lowest propriety was given to the reservoir storage. This order of priority of different water uses was assumed so that a minimal amount of water for environmental and ecosystem needs will be maintained and major water diversion agreements will be satisfied. Readers are referred to Brown et al. (2019) and Warziniack and Brown (2019) for the detailed description of the WEAP model set up, calibration, and evaluation.

2.4. Characterization of Water Shortage IDF Relationships

The probabilistic approach developed by Heidari, Arabi, Ghanbari, and Warziniack (2020) was used in this study to assess shifts in intensity, duration, and frequency (IDF) of water shortage events across the CONUS at the monthly and annual scales. The projected water demand and water supply from Sections 2.2 and 2.3 were used as inputs to identify changes from current to future conditions.

The duration (D), intensity (I), and frequency (F) of a water shortage event were defined as the number of consecutive months/years where water demand exceeds water supply, the cumulative water deficit divided by its duration, and the number of times that a specific event occurs, respectively (Figure S4).

The water shortage events were modeled using the mixture Gamma-GPD distribution. The mixture model helps to simultaneously capture bulk and tails of events (Ghanbari et al., 2019, 2020; Heidari, Arabi, Ghanbari, & Warziniack, 2020). In the Gamma-GPD model, values below the GPD threshold (i.e., location parameter) were modeled by the Gamma distribution, while values above the threshold were modeled by the GPD. The mixture Gamma-GPD cumulative function (F) is given by:

$$F(x|r, a, \xi, \beta, u, \phi_u) = \begin{cases} (1 - \phi_u) \frac{G(x|r, a)}{G(u|r, a)} & x < u \\ (1 - \phi_u) + \phi_u g(x|\xi, \beta, u) & x \geq u \end{cases} \quad (1)$$

where $g(x|\xi, \beta, u)$ is the unconditional GPD function, $G(x|r, a)$ is Gamma distribution function, u is the GPD location parameter (threshold), and ϕ_u is the probability of x being above the threshold.

The joint probability distribution of events for intensity $I > I_0$ and duration $D > D_0$ can be obtained by the product of the conditional distribution of intensity for a given duration and the marginal distribution of duration as:

$$P(I > I_0 \cap D > D_0) = P(I > I_0 | D > D_0) \cdot P(D > D_0) \quad (2)$$

where D_0 and I_0 denote any given values of duration and intensity, respectively. $P(D > D_0)$ is the marginal probability of events with $D > D_0$ and the term $P(I > I_0 | D > D_0)$ is the conditional probability of $I > I_0$ given $D > D_0$. The marginal probability of $D > D_0$ from the mixture Gamma-GPD is given by:

$$P(D > D_0) = F(D > D_0) = \begin{cases} (1 - \phi_u) \frac{G(D > D_0|r, a)}{G(u|r, a)} & x < u \\ (1 - \phi_u) + \phi_u g(D > D_0|\xi, \beta, u) & x \geq u \end{cases} \quad (3)$$

The conditional probability of $P(I > I_0 | D > D_0)$ can be determined in the same way considering that the mixture model should be fitted to just water shortage events with $D > D_0$ as follows:

$$P(I > I_0 | D > D_0) = F(I > I_0 | D > D_0 | r, a, \xi, \beta, u, \phi_u) \quad (4)$$

The annual return period of events under nonstationary conditions with intensity greater than or equal to a target ($I > I_0$) were calculated as a function of the expected interarrival time and cumulative intensity distribution function, expressed as:

$$T_{I>I_0|D>D_0} = \frac{E(D > D_0)}{P(I > I_0 | D > D_0)} * \frac{1}{P(D > D_0)} = \frac{E(D > D_0)}{P(I > I_0 \cap D > D_0)} \quad (5)$$

where $E(D > D_0)$ is the expected interarrival time with $D > D_0$. The expected value of interarrival time between two successive socioeconomic events with $D > D_0$ is given by (Shiau & Shen, 2001; Zhao et al., 2017):

$$E(D > D_0) = E\left(\sum_{i=1}^N DI_i\right) \quad (6)$$

where DI_i is interarrival time between two successive events with $D > D_0$, and N is the number of events equal to or greater than a certain duration.

The change in frequencies under nonstationary conditions can also be quantified by dividing the exceedance probability of a given water shortage event in the future to the current condition as follows:

$$\text{Amplification Factor (AF)} = \frac{P_t(I > I_0)}{P_c(I > I_0)} \quad (7)$$

where AF is the frequency amplification factor of events with $I > I_0$, $P_c(I > I_0)$ and $P_t(I > I_0)$ are the exceedance probability of events with $I > I_0$ for current and future conditions.

The applied probabilistic approach allows enhanced assessments of vulnerability to water shortage at the both interannual and annual time steps in basins undergoing climate and socioeconomic changes. The performance of the mixture model was evaluated using the chi-square goodness-of-fit test, root-mean-square error (RMSE), and the coefficient of determination (Heidari, Arabi, Ghanbari, & Warziniack, 2020). Improved characterization of IDF relationships is critical in the design of water supply systems under non-stationary conditions (Guo, Huang, Huang, Wang, Fang, et al., 2019; Guo, Huang, Huang, Wang, Wang, & Fang, 2019; Heidari, Arabi, Ghanbari, & Warziniack, 2020; Mehran et al., 2015; Salas et al., 2018).

2.5. Characterization of Changes in the Aridity Index

The aridity (or dryness) index is commonly used in previous studies to characterize regions that are more prone to aridification in response to long-term climate change (Yang et al., 2006; Zhang et al., 2017). The aridity index is defined as the ratio of annual potential evapotranspiration (PET) to annual precipitation (P). The river basins with increases in the long-term average aridity index are more likely to face aridification in the future.

The annual precipitation of HUC4 river basins was obtained from the IPSL-CM5A-MR (driest) climate model of the MACA data set. The potential evapotranspiration of HUC4 river basins was calculated using the VIC hydrological model. The Penman-Monteith equation was implemented in the VIC model for the estimation of the PET. The VIC model assumes that PET is from open water meaning that there are sufficient open water supplies. Thus, the PET values are the maximum (potential) evapotranspiration capacity.

In this study, the statistical correlation between changes in aridity index and changes in the intensity and duration of water shortage events at different timescales were calculated at the HUC4 river basin scale to figure out how long-term anomalies such as aridification can be related to interannual to decadal water shortage events. The hypothesis is defined as there is no correlation. Thus, the p -values less than the significance level (0.05) indicate rejection of the hypothesis meaning that changes in aridity index water shortage characteristics are statistically correlated.

3. Results and Discussion

The demonstration study reveals that shifts in IDF relationships of water shortage conditions in response to climate change and population growth vary from one HUC4 river basin to another. Under the driest climate scenario for the CONUS, the majority of HUC4 river basins within the Southwest, Southern, and the middle Great Plain regions were projected to undergo a significant increase in intensities and frequencies of over-year ($D > 12$ months) events at the monthly scale and decadal ($D > 10$ years) events at the annual scale. However, most river basins within the West Coast regions were estimated to experience a decrease in the intensity of water shortage conditions. However, the frequency of interannual ($D < 12$ months) events at the monthly scale and annual ($D > 1$ year) and multi-year ($D > 3$ years) events at the annual scale were projected to increase in the West Coast regions under the driest climate projection for the CONUS.

Note that the characterization of water shortage at the monthly and annual scales makes a significant difference in the definition of water shortage events. The events with duration (D) = n months mean that there

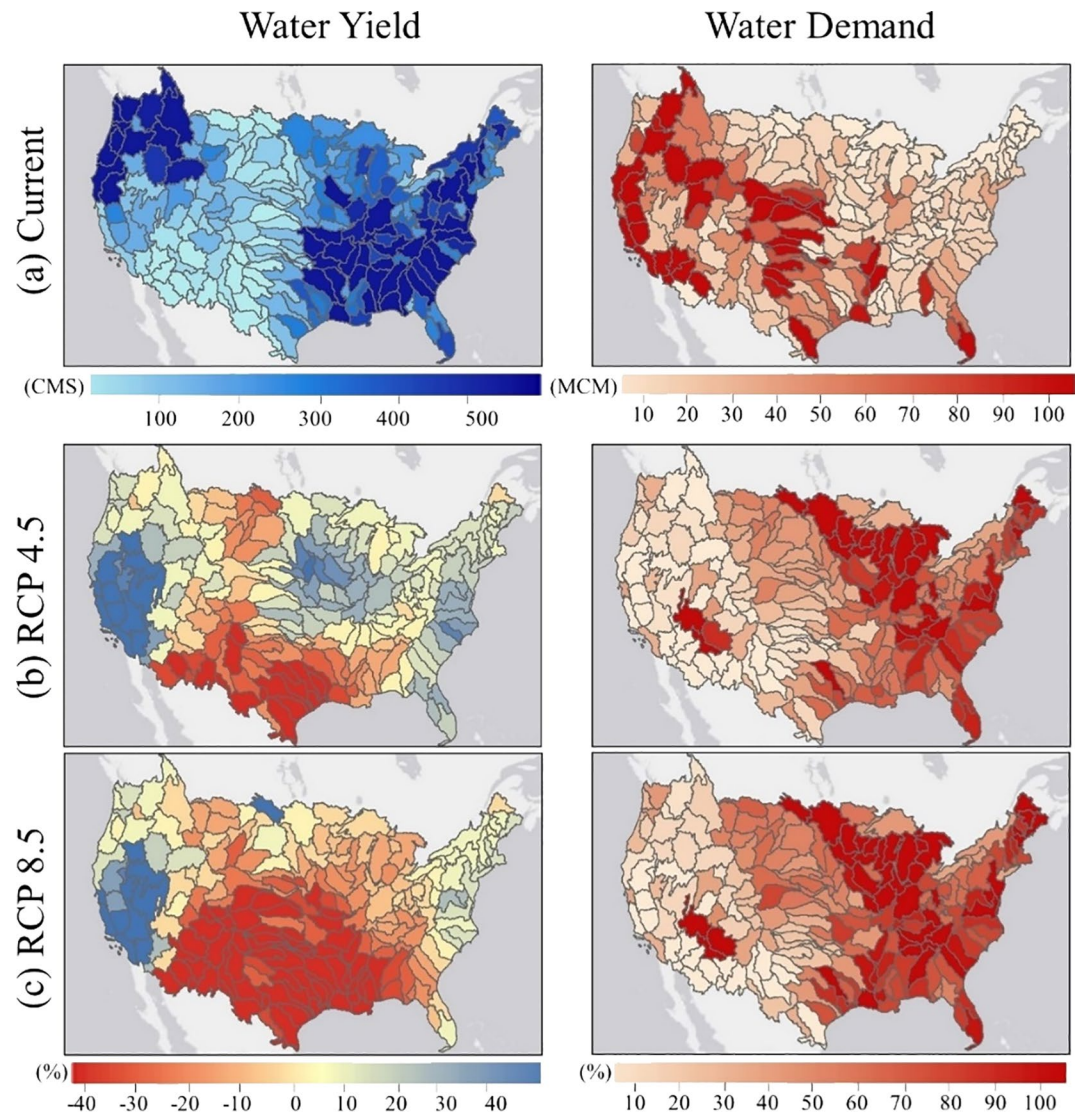


Figure 1. (a) Current monthly water yield and water demand by basin; and projected changes from current (1986–2015) to future (2070–2099) conditions under the driest Multivariate Adaptive Constructed Analog climate model with (b) radiative concentration pathway (RCP) 4.5 and (c) RCP 8.5.

are n consecutive months in which monthly water demand is greater than monthly water supply. However, events with duration (D) = n years mean that there are n consecutive years in which total annual water demand is greater than total annual water supply. For example, events with duration equal to 24 months ($D = 24$ months) are not equivalent to events with duration equal to two years ($D = 2$ years). Thus, even during a two-year event, there may be months with water surplus. As a result, characterization of water shortage events at both monthly and annual scale can help to identify interannual to decadal events that can lead to enhanced decision-making in water resource planning and management.

3.1. Changes in Water Yield and Demand

Figure 1 shows changes in monthly water yield and water demand of HUC4 river basins under the driest climate change scenario with RCPs 4.5 and 8.5. The current water yield and water demand vary substantially across the HUC4 basins with higher water yield in the wetter regions (e.g., Southeast and Northwest United States) and the higher water demand in drier regions (e.g., the West, Southwest, and Midwest United States) (Figure 1a). Note that higher water demand is likely to occur in basins with lower water yield. The

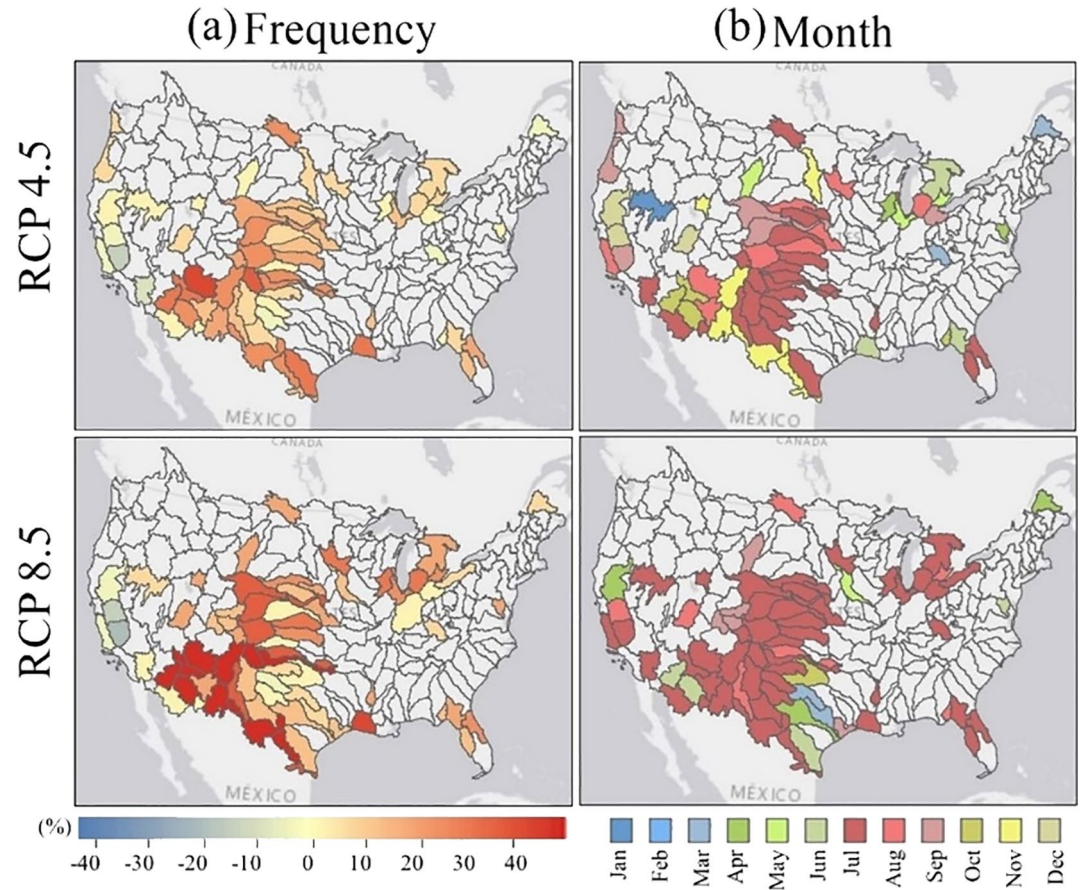


Figure 2. (a) Changes in the frequency of months with water shortage by basin from current (1986–2015) to future (2070–2099) conditions and (b) the months with the highest occurrence of water shortage under radiative concentration pathway (RCP) 4.5 and RCP 8.5.

unit of deficit in this study is million cubic meters (MCM) and the unit of water yield is cubic meters per second (CMS).

Changes in water yield from current (1986–2015) to future (2070–2099) conditions are highly variable from a 30% decrease in the southern United States to more than 50% increase in the western United States under RCP 4.5 (Figure 1b). While the pattern of changes in water yield under the RCP 8.5 is like the RCP 4.5, a decrease in water yield tends to be extended to some river basins in the Southwest, middle Great Plains, and Southeast United States (Figure 1c).

Estimated changes in water demand from current to future conditions are highly variable across the CONUS, that is positive in most HUC4 basins but slightly changes in basins located in the West, Southwest, and Northwest United States under both RCPs 4.5 and 8.5 (Figures 1b and 1c) due to the effect of the projected decrease in the irrigated area (Brown et al., 2013). The highest increase in future water demand is likely to occur in the Ohio Valley and Upper Midwest United States. Decreasing water yield, increasing water demand, or especially their combination can lead to potential conditions for water shortage.

3.2. Changes in IDF Relationships of Water Shortage Conditions at the Monthly Scale

Under the driest climate model, RCPs 4.5 and 8.5, 64 and 73 HUC4 river basins were projected to experience some level of monthly water shortage in the future (Figure 2a). Thus, in this study, we assessed shifts in intensity, duration, and frequency (IDF) of water shortage events across these basins. Although the majority of basins located in the Southwest region were projected to experience a higher increase in the number of

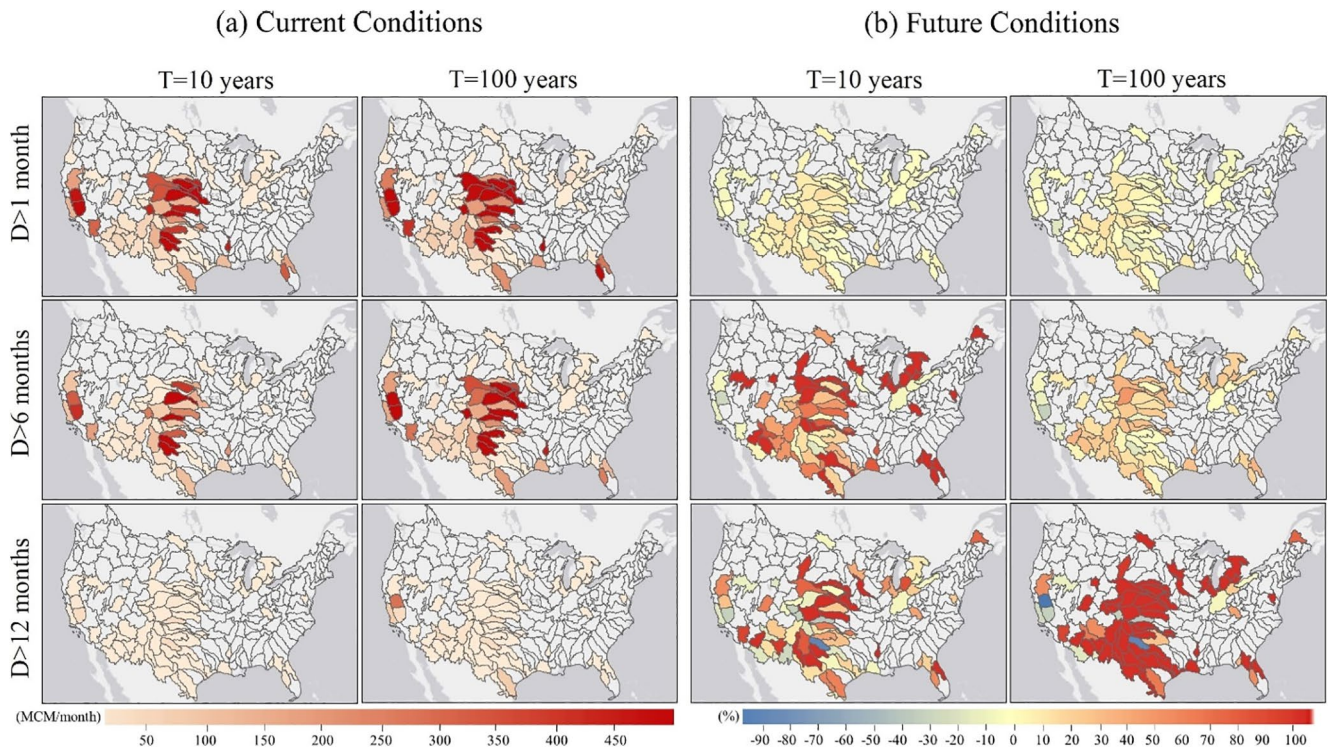


Figure 3. (a) Current intensity and (b) changes in the intensities of events from current (1986–2015) to future (2070–2099) conditions under radiative concentration pathway 8.5 at the monthly scale.

months with water shortage in the future, the HUC4 river basins in the West Coast region were estimated to have a decrease in the number of months with water shortage.

Furthermore, Figure 2b shows the months with the highest occurrence of water shortage conditions in each HUC4 river basin. The majority of water shortage conditions were projected to occur over the summer months (July, August, and September).

We then assessed the IDF relationships of current (1986–2015) and future (2070–2099) water shortage conditions at the monthly scale to estimate shifts in characteristics of interannual and over-year ($D > 12$ months) water shortage events. Figure 3a shows the current IDF relationships of HUC4 river basins across the United States. Under the current conditions and for a given return period (e.g., $T = 10$ years), the intensity decreases as the duration becomes longer. Additionally, for a given duration (e.g., $D > 1$ month), the intensity was projected to slightly change as the return period increases (e.g., from $T = 10$ years to $T = 100$ years). Overall, the West Coast and the middle Great Plain river basins were projected to currently have more intense water shortage conditions (~ 400 mcm/months) at the sub-annual scale.

However, under the future conditions (Figure 3b), the intensity of water shortage events was projected to mostly increase from current to future conditions with a higher rate of increase in events with longer duration and higher return period. Water shortage events with a duration greater than 1 month ($D > 1$ month) and a return period of 10 years ($T = 10$ years) have the lowest increase in intensity. Conversely, events with a duration greater than 12 months ($D > 12$ months) and a return period of 100 years ($T = 100$ years) were projected to have the highest increase in intensity.

For $T = 10$ years, the intensity was projected to significantly increase from $D > 1$ month to $D > 6$ months while for $T = 100$ years, the highest increase in intensity was projected from $D > 6$ months to $D > 12$ months. The result means that at the sub-annual scale, the intensity of water shortage events with a duration greater than 12 months (12 consecutive months with water deficit) is more vulnerable to climate change and population growth compared to the intensity of interannual water shortage events, especially for longer return periods.

For water shortage events with $D > 1$ month, there are minor differences in the intensity of current and future water shortage events. Additionally, the intensity of future events with $D > 1$ month was projected to slightly change as the return period increases (e.g., from $T = 10$ years to $T = 100$ years). The finding indicates that sub-annual events that occur every 10 years are likely to experience the same magnitude of increase in intensity compared to sub-annual events that occur every 100 years.

For water shortage events with $D > 6$ months, the majority of river basins are more likely to experience higher increases in the intensity of more frequent events ($T = 10$ years) compared to the less frequent events ($T = 100$ years). Thus, this reveals that events that occur every 10 years are likely to experience a higher magnitude of changes in the intensity compared to events that occur every 100 years.

Conversely, for water shortage events with $D > 12$ months (12 consecutive months with water deficit), river basins are more likely to experience higher changes in the intensity of less frequent events ($T = 100$ years) compared to the more frequent events ($T = 10$ years). This means that events with a duration greater than 12 months ($D > 12$ months) that occur every 10 years are likely to experience a lower magnitude of changes in intensity than events with a duration greater than 12 months ($D > 12$ months) that occur every 100 years.

The results indicate that less frequent ($T = 100$ years) and longer ($D > 12$ months) sub-annual events and more frequent ($T = 10$ years) and shorter ($D > 6$ months) sub-annual events are likely to experience the highest increase in intensity in the future. Overall, the majority of river basins in the Southwest, Southern, and the middle Great Plain regions were estimated to experience interannual water shortage conditions with higher intensity in the future. However, West Coast river basins are likely to experience a decrease in the intensity of interannual water shortage events up to more than -90% .

Figures S5–S68 show intensity-duration-frequency (IDF) curves of each HUC4 river basin for current and future conditions. The unit of intensity in this study is the million cubic meters per month (MCM/month). In general, the assessment of water shortage at the monthly scale indicates that the interannual water shortage conditions are likely to become more intense in the future. Note that the driest climate model under the RCP 8.5 leads to a higher increase in the intensity of interannual events although the patterns are similar.

Then, we investigated the effects of shifts in future water supply and demand conditions on the frequency of sub-annual water shortage events using the frequency amplification factor (AF). Figure 4 compares the frequency amplification factors of water shortage events with the duration less than 12 months ($D < 12$ months) with water shortage events with the duration greater than 12 months ($D > 12$ months) across the United States for both RCPs 4.5 and 8.5.

Although both RCPs 4.5 and 8.5 show the same spatial pattern of amplification factors, the RCP 8.5 projected a greater amplification factor meaning that water shortage events will become more frequent under the RCP 8.5. In the Southwest, Southern, and middle Great Plain river basins, while the frequency amplification factors of events with $D < 12$ months (interannual events) have slightly decreased, the amplification factor of events with $D > 12$ months (12 consecutive months that monthly water demand exceeds monthly water supply) was projected to increase.

The result reveals that the frequency of over-year events ($D > 12$ months) is likely to increase in the future while interannual events are likely to be less frequent in the future. However, the river basins in the West Coast region are more likely to experience less frequent over-year ($D > 12$ months) events and more frequent interannual ($D < 12$ months) events.

In general, the assessment of water shortage at the monthly scale indicates that the Southwest, Southern, and the middle Great Plain river basins are likely to experience more intense sub-annual water shortage conditions in the future with more frequent over-year events ($D > 12$ months) and less frequent interannual events ($D < 12$ months). Conversely, the West Coast river basins are likely to experience a decrease in the intensity of sub-annual water shortage events in the future with less frequent over-year ($D > 12$ months) events and more frequent interannual ($D < 12$ months) events.

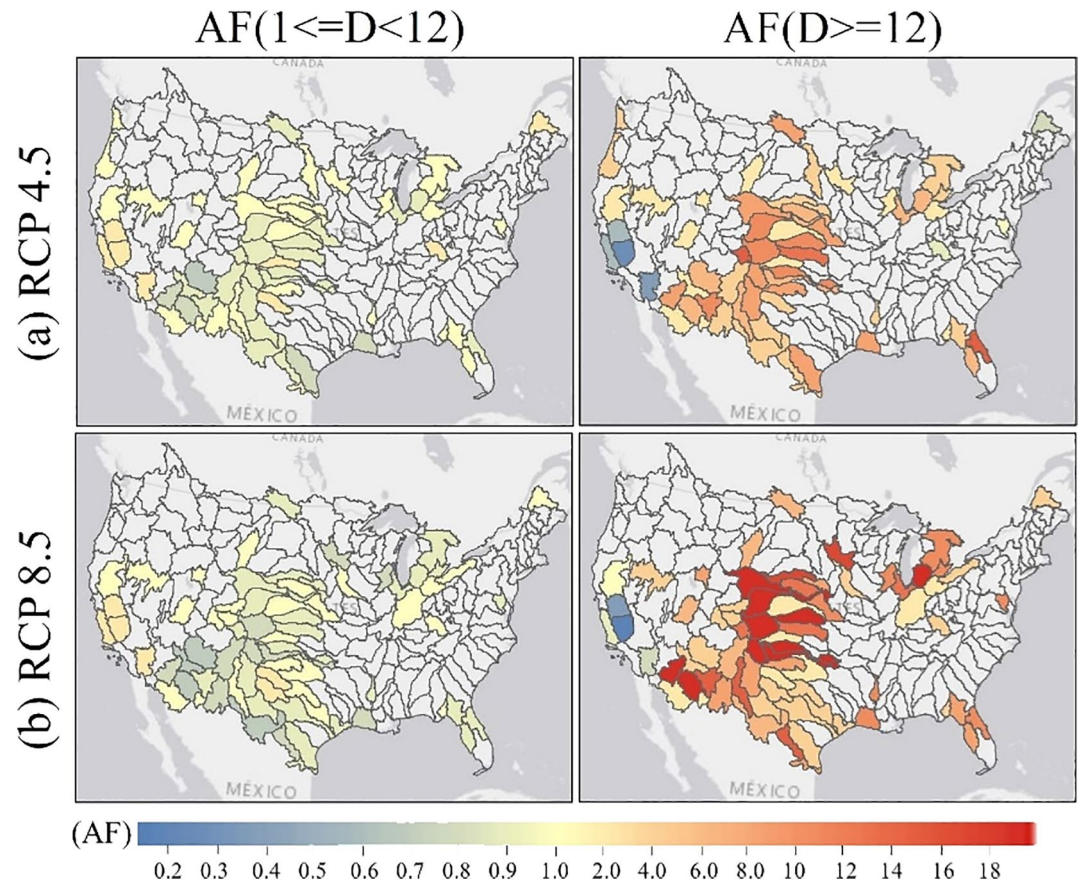


Figure 4. The frequency amplification factor (AF) under (a) radiative concentration pathway (RCP) 4.5 and (b) RCP 8.5 at the monthly scale.

3.3. Changes in IDF Relationships of Water Shortage Conditions at the Annual Scale

We assessed the IDF relationships of current and future water shortage conditions in this section at the annual scale to estimate shifts in characteristics of annual ($D > 1$ year), multi-year ($D > 3$ years), and decadal ($D > 10$ years) water shortage events. Figure 5a shows the current IDF relationships of HUC4 river basins across the United States at an annual scale. In general, water shortage events at the annual scale tend to have a slightly higher intensity compared to water shortage events at the sub-annual scale.

Under the current conditions and for a given return period (e.g., $T = 50$ years), the intensity decreases as the duration becomes longer. Additionally, for a given duration (e.g., $D > 1$ year), the intensity was projected to slightly change as the return period increases (e.g., from $T = 50$ years to $T = 100$ years). Overall, similar to the water shortage at the sub-annual scale, the West Coast and the middle Great Plain river basins were projected to currently have more intense water shortage conditions (~ 400 mcm/year) at the annual scale.

However, under the future conditions (Figure 5b), the intensity of water shortage events was projected to mostly increase from current to future conditions, particularly for water shortage events with longer duration (multi-year and decadal) and higher return period ($T = 100$ years). Water shortage events with shorter duration and a lower return period were projected to experience smaller changes in intensity. Conversely, events with a longer duration (e.g., $D > 10$ years) and a higher return period (e.g., $T = 100$ years) were projected to experience a higher increase in the intensity of water shortage events.

For a given return period (e.g., $T = 50$ years), the decadal events were projected to experience a higher increase in the intensity compared to the multi-year and annual water shortage events. The result means that at the annual scale, the intensity of decadal water shortage events (i.e., $D > 10$ years) is more vulnerable to climate change and population growth compared to the intensity of annual and multi-year water shortage

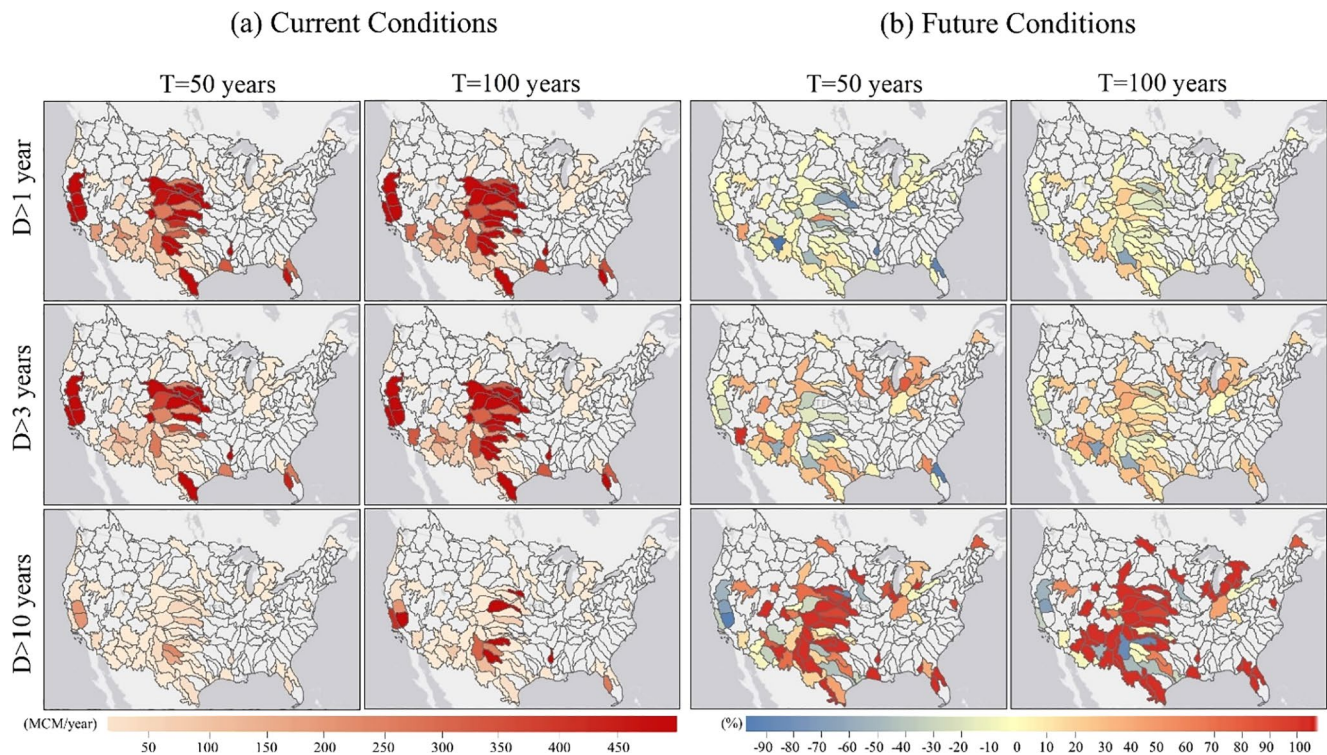


Figure 5. (a) Current intensity and (b) changes in the intensities of events from current (1986–2015) to future (2070–2099) conditions under radiative concentration pathway 8.5 at the annual scale.

events. Subsequently, the intensity of multi-year water shortage events (i.e., $D > 3$ years) can be more affected by climate change and population growth compared to the intensity of annual water shortage events.

For a given duration (e.g., $D > 10$ years), the intensity of future events was projected to slightly alter as the return period increases from $T = 50$ years to $T = 100$ years. Additionally, for water shortage events with $D > 1$ year, there are minor differences in the intensity of current and future water shortage events. The finding indicates that at an annual scale, events that occur every 50 years are likely to experience the same magnitude of increase in intensity compared to annual events that occur every 100 years. The results indicate that less frequent ($T = 100$ years) and longer ($D > 10$ years) water shortage events tend to experience a higher increase in the intensity in the future.

Overall, most river basins in the Southwest, Southern, and the middle Great Plain regions were estimated to experience more intense water shortage conditions in the future, particularly for decadal and multi-year events. However, West Coast river basins are likely to experience a decrease in the intensity of decadal and multi-year water shortage events up to more than -90% . The unit of intensity is the million cubic meters per month (MCM/year). In general, the assessment of water shortage at the annual scale indicates that the multi-year and decadal water shortage events are likely to become more intense in the future.

Then, we investigated the effects of shifts in annual water supply and demand conditions on the frequency of annual, multi-year, and decadal water shortage events using the frequency amplification factor (AF). Figure 6 compares the frequency amplification factors of water shortage events with $1 < D < 3$ years, $3 < D < 10$ years, and $D > 10$ years across CONUS for both RCPs 4.5 and 8.5. RCPs 4.5 and 8.5 approximately show the same spatial pattern of amplification factors.

For events with $1 \leq D < 3$ years, the frequency was projected to mostly decrease ($AF \sim 0.2$) in the Southwest, Southern, and middle Great Plain river basins. However, the West Coast river basins are more likely to experience more frequent water shortage events ($AF \sim 0.2$ to 0.4). For events with $3 \leq D < 10$ years, the frequency was projected to mostly decrease ($AF \sim 0.2$) in the middle Great Plain river basins with a lower

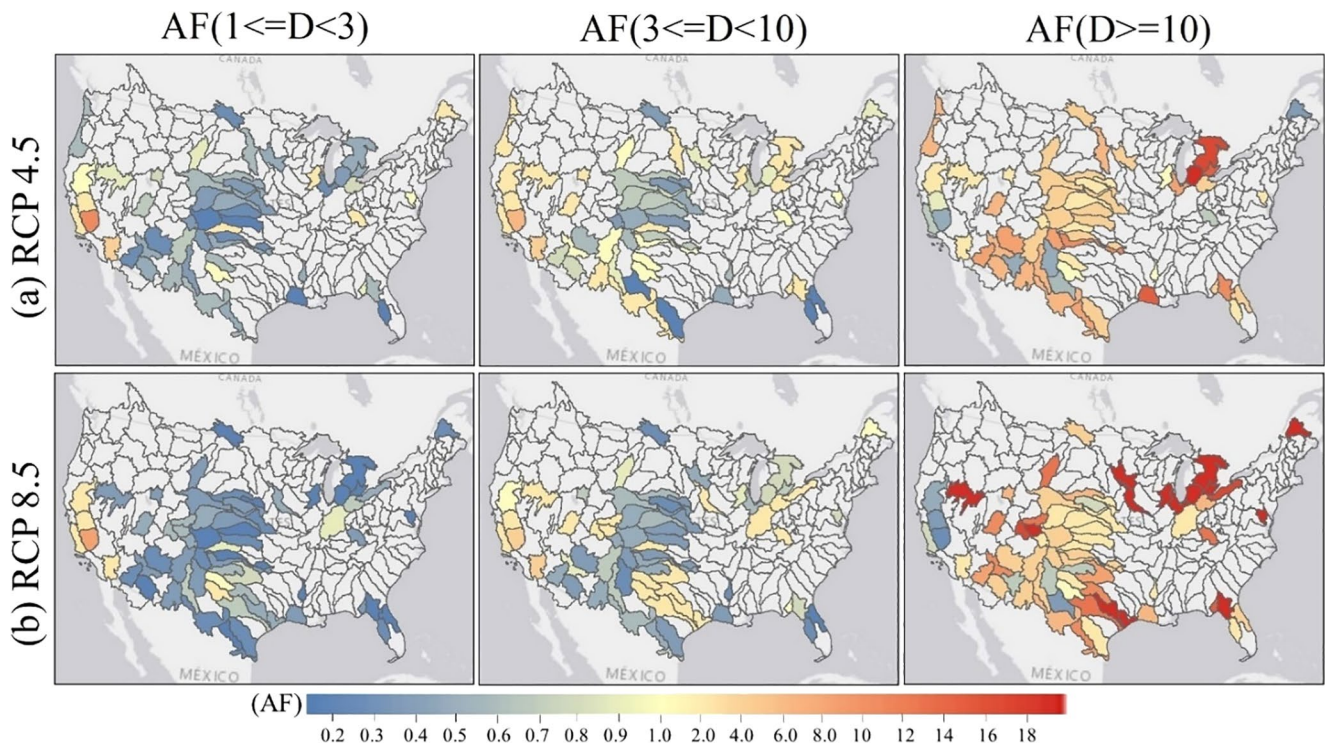


Figure 6. The frequency amplification factor (AF) under (a) radiative concentration pathway (RCP) 4.5 and (b) RCP 8.5.

rate ($AF \sim 0.5$) compared to events with $1 \leq D < 3$ years. However, the frequency was estimated to increase in the West Coast river basins with a lower rate compared to the events with $1 \leq D < 3$ years.

For events with $D > 10$ years, unlike the events with $1 \leq D < 3$ years and $3 \leq D < 10$ years, the frequency is more likely to increase in most river basins located in the Southwest, Southern, and middle Great Plain regions. Additionally, the decadal events were projected to decrease in the West Coast region. Note that the highest increase in the frequency of decadal events was projected to occur in Great Lakes regions.

Overall, the result indicates that the frequency of decadal events ($D > 10$ years) is likely to increase in the future while annual and multi-year events are likely to be less frequent. Conversely, the West Coast river basins are more likely to experience less frequent decadal ($D > 10$ years) events and more frequent annual and multi-year events in the future.

Additionally, the assessment of water shortage at the annual scale indicates that the Southwest and the middle Great Plain river basin are more likely to experience more intense multi-year and decadal water shortage events with more frequent decadal events ($D > 10$ years) and less frequent annual and multi-year events. Conversely, the West Coast river basins are likely to experience a decrease in the intensity of multi-year and decadal water shortage events in the future with less frequent decadal ($D > 10$ years) events and more frequent annual and multi-year events.

3.4. Relationship Between Water Shortage Characteristics and Changes in Water Supply and Demand Condition

In this section, we separately evaluated the effects of changes in water supply and water demand conditions on the water shortage properties to characterize change as to which of them is more effective on shifts in water shortage IDF relationships for each HUC4 river basin. For this purpose, we considered two different scenarios: first, we assumed that demand would remain constant from current to future conditions, and second, we assumed that water yield will not change from current to future conditions. Then, HUC4 river basins with higher changes in water shortage characteristics under the first scenario were considered demand-based basins (more vulnerable to changes in the demand), and HUC4 river basins with higher

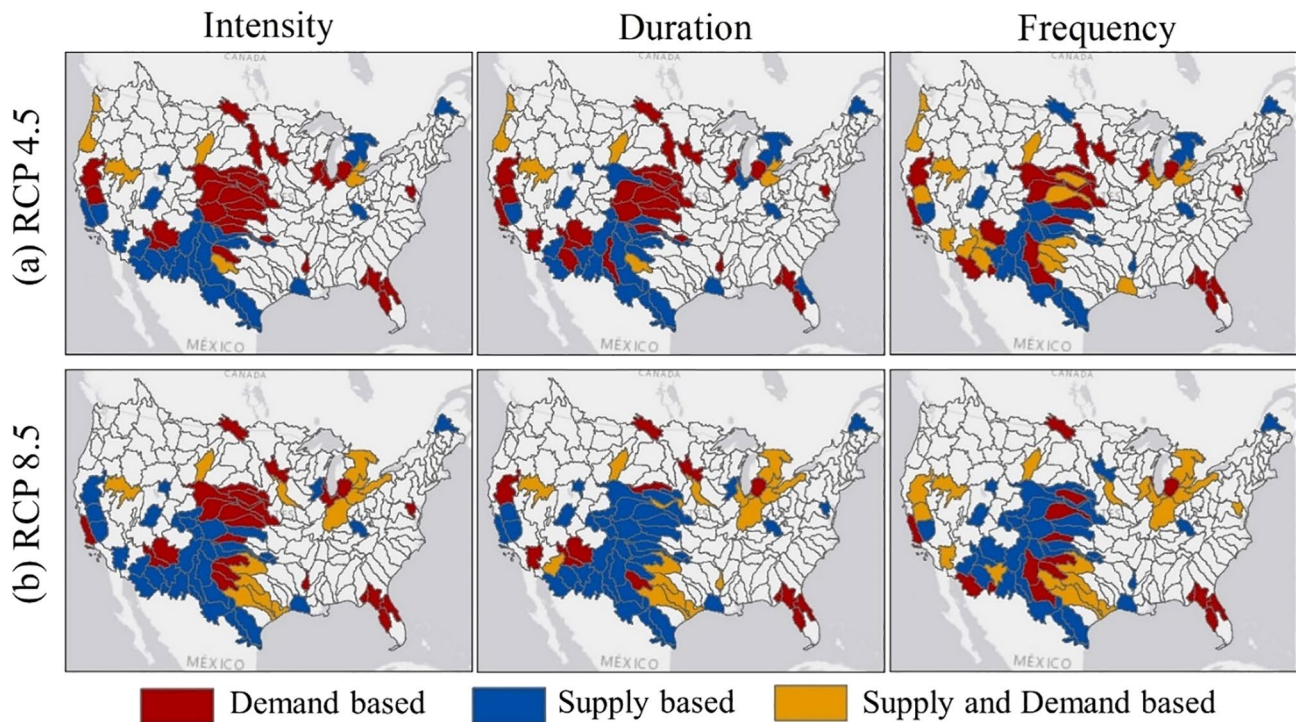


Figure 7. The characterization of river basins that are more vulnerable to changes in demand (demand-based), supply (supply-based), or both water demand and water supply (supply/demand-based) under (a) radiative concentration pathway (RCP) 4.5 and (b) RCP 8.5.

changes under the second scenario were considered supply-based basins (more vulnerable to changes in the supply).

Figure 7 shows demand-based, supply-based, and supply/demand-based river basins according to higher changes in intensity, duration, and frequency of water shortage conditions. According to changes in the intensity of water shortage events, the river basin within the middle Great Plain region is demand-based under both RCPs 4.5 and 8.5 meaning that keeping the water demand constant in this region leads to a higher decrease in the intensity of water shortage conditions in the future. Thus, implementation of demand-based adaptation and mitigation strategies can be recommended in this region. Conversely, most river basins located in the Southwest region are supply-based under both RCPs 4.5 and 8.5, indicating that keeping the water yield conditions constant in this region leads to more reduction in the intensity of water shortage events in the future. Therefore, the application of supply-based strategies can be more effective to attenuate the effects of climate change.

Besides, according to changes in the duration of water shortage events, the river basin within the middle Great Plain region is demand-based under RCP 4.5 and supply-based under RCP 8.5 meaning that the implementation of adaptation and mitigation strategies for decreasing the duration of water shortage events in this region can be sensitive to the future concentration pathway scenario. However, the Southwest river basins are supply-based under both RCPs 4.5 and 8.5. This means that keeping the water yield conditions constant in this region leads to more reduction in both intensity and duration of water shortage events compared to keeping the water demand constant. Therefore, the application of supply-based strategies can be recommended to reduce both the intensity and duration of water shortage events in this region.

Finally, we compared the two aforementioned scenarios in terms of decreases in the frequency of water shortage events in the future. Under this assumption, there are more river basins (e.g., Great Lakes region) that both supply-based and demand-based strategies can be recommended meaning that keeping water supply and water demand constant have similar effects on decreases in the frequency of water shortage events.

Additionally, we statistically assessed the relationships between the intensity, duration, and frequency of water shortage events and aridity index (the ratio of the potential evapotranspiration to the precipitation) in

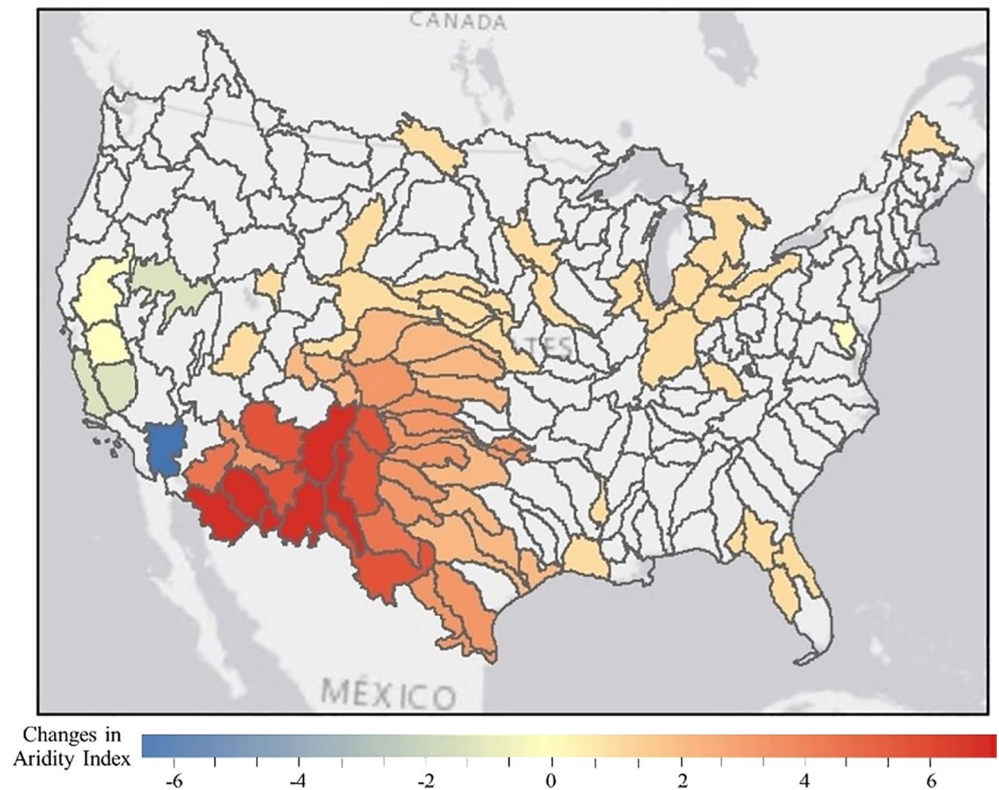


Figure 8. Changes in the aridity index from current to future conditions under the driest Multivariate Adaptive Constructed Analog climate model with radiative concentration pathway 8.5.

the supply-based regions. Figure 8 shows changes in the aridity index of river basins from current to future conditions. We aimed to figure out how the long-term anomalies such as changes in aridity index can affect the short-term anomalies such as sub-annual water shortage events. Table 1 provides the coefficient and the P-value of correlation between aridity index with the frequency amplification factor (AF) and intensity of sub-annual water shortage events.

The p-value under all correlations is less than 0.05 indicating that there is a significant correlation between the aridity index with all sub-annual water shortage characteristics. Although the frequency amplification factor of events with $D > 12$ months is directly correlated with the aridity index, the frequency amplification factor of events with $1 \leq D < 12$ months is inversely correlated with the aridity index. This indicates that the increase in the aridity index is likely to increase the frequency of over-year ($D > 12$ months) water shortage events while decrease the frequency of interannual ($D < 12$ months) events.

Overall, the South, Southwest, middle Great Plain, and Great Lakes regions are likely to experience aridification under long-term changes in climate and freshwater availability. This situation may also lead to water shortage events with more frequency, higher intensity, and longer duration. The findings highlight that long-term increases in the aridity index of river basins can lead to the initiation of prolonged events, particularly in more arid regions where natural, water, and economic resources even during normal years may be inadequate to meet water needs. Besides, the intensity of water shortage events is significantly correlated to the aridity index, meaning that an increase in aridity index can lead to an increase in the intensity of sub-annual water shortage events.

Conversely, the West Coast region is likely to experience wetter hydroclimatic conditions. Although this condition can lead to higher freshwater availability, this region is likely to experience more frequent water shortage events within the year due to an increase in extreme weather

Table 1
Statistical Correlation Between Changes in the Aridity Index and Water Shortage Events

Aridity index correlation with	Coefficient	P-value
AF ($D > 12$)	0.40	0.0059
AF ($1 \leq D < 12$)	-0.54	0.0002
Intensity ($T = 100$ years)	0.66	0.0000

anomalies over the basin. The findings highlight that while the long-term hydroclimatology of a river basin can tend to wetter conditions, the frequency of interannual events may increase very rapidly if extreme weather anomalies rise over the basin. Interannual water shortage events are likely to occur during the growing seasons that may exacerbate the negative consequences on agriculture and crop productions.

4. Uncertainties and Limitations

The main goal of this study is to provide a new approach to improve vulnerability assessment of water supply systems to shortage in response to climate change and rapid population growth. We projected changes in the water shortage IDF relationships of the United States river basins at different timescales from monthly to decadal events and assessed their relationships with changes in long-term anomalies such as aridification.

To demonstrate the importance of our proposed approach, we used the driest climate projection from the MACA climate data set, the A1B population growth scenario, the baseline water demand projection without implementing adaptation strategies, the water yield projection from the VIC hydrological model, and the mixture Gamma-GPD model to characterize IDF of water shortage events. However, it should be noted that the global assessment of water shortage propagation under various anthropogenic water demand scenarios, climate change projections, and water supply infrastructure designed is out of the scope of this study. Thus, the results of the demonstration study were subject to several sources of uncertainty in the climate model and population growth projections, water demand, water yield and water allocation simulations, and characterization of water shortage IDF relationships.

From the climate side, we only used the IPSL-CM5A-MR (driest) climate model under RCPs 4.5 and 8.5 as the worst-case projection on average for the CONUS to compare the various responses of HUC4 river basins to shifts in water shortage properties under the considerable shifts in water supply and demand conditions. First, applying only one model can add to the uncertainties of the results. Although, the MACA climate models have on average a common spatial pattern at the conterminous scale (Heidari, Arabi, Warziniack, & Kao, 2020; Joyce & Coulson, 2020), the driest model can lead to water shortage conditions with higher frequency, severity, and greater spatial extent. Therefore, using ensemble climate simulation or more different climate models can be a prospect for this study to assess the vulnerability of the U.S. water supply to water shortage under a wider range of future climate possibilities. However, it does not ensure that actual future conditions will fall within the range that can be captured by the selected climate models. Besides, the ensemble climate simulation also depends on individual models while it can lead to a more reliable result than that of any one model. Second, note that the IPSL-CM5A-MR climate model is not always the driest in all river basins across the CONUS. The driest climate model indicates the model that is on average the driest MACA models at the conterminous scale.

From the demand side, using multiple socioeconomic scenarios is needed to examine the drivers of water demand more clearly across multiple sectors. In addition to the uncertainties in the climate projections and population growth, some uncertainties remain associated with the VIC model, and WEAP model. The VIC model may not capture all physical basin characteristics, water management regulations, and land cover changes (Naz et al., 2016). Besides, some uncertainties can be added associated with the model parameters and structural deficiencies of the model simulation (Gharari et al., 2020; Melsen et al., 2016). To decrease the uncertainty in the hydrological simulation, the design of hydrological multimodal runs with different parameters is needed. Besides, applying different hydrologic and network analysis models at a finer resolution with accurate legal arrangements can also be another prospect for this study to assess the uncertainty in future water shortage IDF characterization and evaluate the modeling uncertainty associated with the role of hydrological models (Oubeidillah et al., 2014).

Additionally, this study is not considered implementation of technological, management, and policy solutions that can highly affect the projections of future water shortage conditions. This is also one of the most important prospects for this study that can help decision makers and water planners to appropriately optimize and select the best adaptation and mitigation strategies such as water reduction strategies.

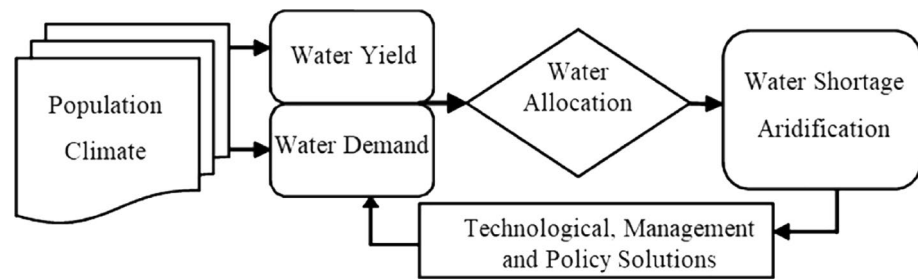


Figure 9. The proposed framework of water shortage analysis.

Note that future projections are inherently uncertain and become more uncertain when socioeconomic factors are included. The goal of this study is to propose a new approach and demonstrate the important role of water shortage IDF characterization from the interannual to decadal scales that can be implemented in the future regional water resource planning and management. A comprehensive assessment of future water supply and demand conditions of the United States river basins in response to climate change is beyond the scope of this study. Comprehensive planning regulation and strategies for sustainable development in the future needs an interdisciplinary collaborative work between hydrologist, geologist, policymakers, economist, and social scientist.

Despite these limitations and uncertainties in our methods, comparisons of differences in IDF characteristics of water shortage events from the current period (1986–2015) to the future period (2070–2099) are more likely to be accurately estimated than are the absolute amounts from which the differences are computed. Therefore, the findings of this study can be applied to update water shortage IDF properties under the worst-case conditions at the conterminous scale that can be used to assess water storage, to plan water supply systems under nonstationary conditions, and to optimize water institutions and management including water rights.

5. Summary and Conclusions

The main finding of this study is consistent with the results of previous studies (Brown et al., 2019; Foti et al., 2012; Gober & Kirkwood, 2010; Jaeger et al., 2017; Warziniack & Brown, 2019; Yigzaw & Hossain, 2016) that predicted water shortage conditions are likely to increase because of the rapid population growth and climate change in the United States. This situation may exacerbate the increase in water demand and the decrease in freshwater availability and lead to an increase in the vulnerability of water supply systems to water shortage at various spatial and temporal scales.

The improved understanding of evolution, propagation, and spread of water shortage conditions at various timescales from interannual to multi-year to decadal scales and their relationships with long-term shifts in hydroclimatic factors such as aridification are crucial considerations to be appropriately characterized across the United States over the 21st century. The characterization of water shortage events at various timescales allows determining short-term dry periods during a long-term wet period.

The main goal of this study is to propose an approach to improve vulnerability assessment of the United States water supply systems by addressing the aforementioned considerations and highlight the importance of shifts in water shortage IDF relationships at both sub-annual and annual scales. Figure 9 illustrates the roadmap of the developed approach and where it is located in the future water resource planning and management and how it can inform decision makers and planners to accordingly implement appropriate adaptation and mitigation strategies in the future.

As it is suggested in Figure 9, the technological, management, and policy solutions are recommended to assess in a loop with water demand and supply and future water shortage conditions to appropriately optimize and select the best adaptation and mitigation strategies. It can help decision makers and water planners to optimize implementation of water conservation methods and water reduction strategies such as rationings and increasing water supply sources in response to future water shortage conditions at various scales. The

developed steps can help decision makers to assess the efficiency of various adaptation and mitigation strategies at a regional and national scale to attenuate the negative consequences of water shortage conditions.

We demonstrated the proposed approach under the driest climate change scenarios to evaluate its importance and significance on characterization of future minor and major changes in water shortage IDF relationships and improving vulnerability assessment of water supply systems to water shortage that can highly affect water supply systems in the future. The monthly water demand and water supply at the HUC4 watershed level were projected under the A1B population growth scenario and the driest climate model with RCPs 4.5 and 8.5 for current (1986–2015) and future (2070–2099) conditions. The water demand data was also obtained from the product of a water use driver and a water withdrawal rate for six water use sectors including domestic and public, agricultural irrigation, thermoelectric, industrial, commercial, and mining, livestock, and aquaculture. The WEAP model was used to project the water supply allocated to each HUC4 river basin. Changes in intensity, duration, and frequency of water shortage conditions at monthly and annual scales were assessed using the Mixture Gamma-GPD model.

The results of the demonstration study show the characterization of water shortage conditions across the United States river basins under the driest climate change scenario at various timescales from interannual to decadal events. A consistent spatial pattern of changes in the IDF relationships of water shortage events was found across the RCPs 4.5 and 8.5. However, RCP 8.5 also leads to a higher increase in the intensity of events. Besides, the water shortage events will become more frequent under the RCP 8.5. The projected shifts in water shortage characteristics of river basins across the CONUS vary from one region to another. The current patterns of water yield and water demand indicate that higher water demand occurs in basins with lower water yield.

Overall, the findings under the worst-case scenario at the conterminous scale indicate that the river basins located in the Southwest, Southern, and the middle Great Plain regions may experience more intense water shortage conditions at the end of the century. Besides, the Southwest, Southern, and the middle Great Plain river basins are likely to experience less frequent interannual ($D < 12$ months), annual ($D > 1$ year), and multi-year ($D > 3$ years) events in the future. However, the frequency of over-year ($D > 12$ months) events at the sub-annual scale and decadal ($D > 10$ years) events at the annual scale were projected to increase in the future in these regions. Conversely, the river basins located in the West Coast region are likely to experience a decrease in the intensity of water shortage conditions. Although the frequency of over-year ($D > 12$ months), and decadal ($D > 10$ years) events were estimated to decrease in the West Coast regions under the on average the driest climate change scenario for the CONUS, the interannual ($D < 12$ months) events at the monthly scale and annual ($D > 1$ year) and multi-year ($D > 3$ years) events at the annual scale were projected to increase in the future in the West Coast regions. The intensity of water shortage events with longer duration and higher return periods is likely to be more affected in the future in response to climate changes and population growth.

Then, we characterized the statistical relationships between the aridity index as the long-term anomalies and sub-annual water shortage events as the short-term anomalies to understand the mechanism behind that. The results from the demonstration study indicate an increase in aridity index from current to future conditions and has a correlation with the intensity of water shortage events meaning that river basins with increasing aridification are more prone to experience intense water shortage conditions in the future. Besides, we found that increase in the aridity index of river basins in the future is also positively correlated with the frequency of over-year ($D > 12$ months) events and negatively correlated with the frequency of interannual ($D < 12$ months) events indicating that the aridification tends to increase the frequency of over-year events and decrease the frequency of interannual events. Subsequently, we figured out that river basins with the projected decrease in aridity index are likely to experience more frequent interannual ($D < 12$ months) water shortage conditions due to the increase in extreme weather anomalies under future climate conditions.

Rising CO₂ concentrations, increasing temperatures, rapid population growth, and precipitation changes will combine to cause shifts in IDF relationships of water shortage events at various spatial and temporal scales leading to prolonged events in drier regions and interannual events in wetter regions. The results recommend that more attention should be gained to prolong water shortage conditions in drier regions and

interannual events in wetter regions of the United States at the end of the 21st century. Besides, we illustrated that under the driest climate change scenario, most river basins located in the Southwest, middle Great Plain, and Great Lakes regions are, respectively, supply-based, demand-based, and supply/demand-based.

Findings are the crucial considerations to be characterized sufficiently on a national scale in the United States for enhanced water resource managements in the future in response to climate change and population growth. Enhanced assessments of water shortage characteristics under climate, population growth, and socioeconomic changes can be applied to improve the design of water supply systems, and optimize water institutions and management, particularly in the American West. The findings of this study can be used as an input into a comprehensive plan to determine the most appropriate preparedness actions that can be implemented for water shortage related disasters.

Although, the comprehensive vulnerability assessment of the United States water supply systems under various climate change projections, anthropogenic water demand scenarios, water supply infrastructures, and implementation of different adaptation and mitigation strategies is not the purpose of this study, it can be suggested as one of the most important prospects. The adequacy of adaptation and mitigation strategies such as the reduced irrigation, instream flow reductions, groundwater mining, municipal water demand management strategies, and additional reservoir storage capacity can be examined to accommodate the projected increase in intensity, duration, and frequency of water shortage conditions across the U.S. river basins.

Furthermore, the primary impacts of future changes in hydroclimatology, decadal, and interannual water shortage events in agricultural regions and crop yield projections can be investigated as another prospect for this study. Agriculture is by far one of the largest water users in many regions of the United States. Long-term hydroclimatic changes may force farmers to change their crops based on the new regional climate conditions.

Improvements in the characterization of water shortage conditions from interannual to decadal events by incorporating shifts in long-term hydroclimatic conditions across the CONUS over the 21st century can result in enhanced infrastructure operation and water allocation, particularly during increasingly severe future events. Although the results of the study are directly beneficial to water planners and policymakers in the United States, the developed approach can be applied to any other regions of the world.

Data Availability Statement

The baseline forcing data from 1980 to 2015 are provided by Naz et al. (2016). The projected MACA climate data from 1950 to 2099 are provided by Abatzoglou and Brown (2012). The historic monthly runoff is obtained from the USGS WaterWatch runoff data set (Brakebill et al., 2011). The A1B scenario was obtained from the IPCC Fourth Assessment set of global socioeconomic scenarios. The consumptive water uses factors computed based on the USGS water use circulars.

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