

Earth's Future

RESEARCH ARTICLE

10.1029/2020EF001657

Key Points:

- Hydroclimatic variables were projected over the 21st century using VIC hydrological model driven by downscaled MACA climate data set
- Hydroclimatic shifts of U.S. river basins in response to climate change were evaluated by movements in the Budyko space
- The U.S. river basins were clustered to seven unique hydroclimatic groups associated with the regional climate, landform, and ecosystem

Supporting Information:

- Supporting Information S1

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Citation:

Heidari, H., Arabi, M., Warziniack, T., & Kao, S.-C. (2020). Assessing shifts in regional hydroclimatic conditions of U.S. river basins in response to climate change over the 21st century. *Earth's Future*, 8, e2020EF001657. <https://doi.org/10.1029/2020EF001657>

Received 8 JUN 2020

Accepted 27 AUG 2020

Accepted article online 29 AUG 2020

Assessing Shifts in Regional Hydroclimatic Conditions of U.S. River Basins in Response to Climate Change over the 21st Century

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Abstract Characterization of shifts in regional hydroclimatic conditions helps reduce negative consequences on agriculture, environment, economy, society, and ecosystem. This study assesses shifts in regional hydroclimatic conditions across the conterminous United States in response to climate change over the 21st century. The hydrological responses of five downscaled climate models from the Multivariate Adaptive Constructed Analogs data set ranging from the driest to wettest and least warm to hottest were simulated using the variable infiltration capacity (VIC) model. Shifts in regional hydroclimatic conditions at 8-digit hydrologic unit scale (HUC8) were evaluated by the magnitude and direction of movements in the Budyko space. HUC8 river basins were then clustered into seven unique hydroclimatic behavior groups using the K-means method. A tree classification method was proposed to illustrate the relationships between hydroclimatic behavior groups and regional characteristics. The results indicate that hydroclimatic responses may vary from a river basin to another, but basins in the same neighborhood follow a similar movement in the Budyko space. The systematic hydroclimatic behavior of river basins is highly associated with their regional landform, climate, and ecosystem characteristics. Most HUC8s with mountain, plateau, and basin landform types will likely experience less arid conditions. However, most HUC8s with Plain landform type behave differently according to the regional ecosystem and climate. This study provides a potential roadmap of shifts in regional hydroclimatic conditions of U.S. river basins, which can be used to improve regional preparedness and ability of various sectors to mitigate or adapt to the impacts of future hydroclimate change.

Plain Language Summary Long-term changes in climate and water availability may lead to aridification or desertification of river basins. This study characterizes regional changes in the relationship between climate and water budgets of river basins across the continental United States over the 21st century. Results provide insights for decision-makers and water planners to prepare for changes in factors that influence the vulnerability to water shortage.

1. Introduction

Climate change may significantly beget shifts in long-term hydroclimatic conditions of river basins (Jaramillo et al., 2018; Piemontese et al., 2019; Xing et al., 2018; Zaninelli et al., 2019) and cause serious impacts on the environment, agriculture, economies, and ecosystems (Ashfaq et al., 2013; Greve et al., 2014; Hemmati et al., 2020; Ponce Campos et al., 2013). Characterization of shifts in regional hydroclimatic conditions can help water managers and decision-makers to mitigate potential consequences of climate change on various sectors (Destouni et al., 2013). This study investigates future shifts in regional hydroclimatic conditions of river basins across the conterminous United States (CONUS) in response to climate change over the 21st century.

In the CONUS, hydroclimatic parameters such as precipitation, temperature, evaporation, water yield (or total runoff), and potential evapotranspiration have been projected to change over the 21st century (Hay et al., 2011; Mahat et al., 2017; Sanford & Selnick, 2013; Sankarasubramanian & Vogel, 2003). The CONUS covers broad physiographic, ecological, and climatic conditions. Thus, regional hydroclimatic shifts in response to climate change can be quite different from one region to another (Abatzoglou & Ficklin, 2017).

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Regional characterization of hydroclimatic changes is vital to improve implementation of region-specific adaptation and mitigation strategies (Piemontese et al., 2019; Zaninelli et al., 2019).

Most previous studies that discussed changes in hydroclimatology of river basins within the CONUS focused on particular basins or individual parameters (e.g., streamflow, precipitation, and evaporation) (Ashfaq et al., 2013; Naz et al., 2016; Renner et al., 2012; Wang & Hejazi, 2011; Weiskel et al., 2014). A few studies have assessed the integrated shifts in hydroclimatic conditions of river basins as the combination of changes in aridity and evaporative indices across the CONUS to understand how different river basins with varying climatic, ecological, and physiographical characteristics respond to climate change (Abatzoglou & Ficklin, 2017; Piemontese et al., 2019).

One effective way to evaluate the combined hydroclimatic changes is through the Budyko framework (Van derPiemontese et al., 2019; Van Der Velde et al., 2014; Zaninelli et al., 2019). The Budyko framework describes a relationship between evaporative and aridity indices (Budyko, 1974, 1982). A number of previous studies have used the Budyko framework to estimate actual evaporation and streamflow from long-term water and energy balances (Deng et al., 2018; Li et al., 2019; Reis et al., 2013; Rouholahnejad Freund & Kirchner, 2017; Thomas et al., 1993; Xing et al., 2018; Yang et al., 2006; Zhang et al., 2017). A river basin can move over time in the Budyko space due to a combination of shifts in aridity and evaporative indices (Van Der Velde et al., 2014; Piemontese et al., 2019; Zaninelli et al., 2019). Additionally, movement in the Budyko space can be characterized by a magnitude and direction (Jaramillo et al., 2018; Piemontese et al., 2019; Zaninelli et al., 2019). Direction can determine regional differentiation and magnitude can characterize the most sensitive regions under climate change (Van Der Velde et al., 2014).

This study assesses regional hydroclimatic changes induced by shifts in the Budyko space across the CONUS over the 21st century at an 8-digit hydrologic unit code (HUC8) basin scale under a range of possible climate change models. Specifically, the objectives are to (1) evaluate changes in combined hydroclimatic variables in response to climate change using Budyko space; (2) identify regions with unique hydroclimatic behavior in response to climate change using the K-means clustering method; (3) assess the most important factors which differentiates the hydroclimatic responses using the tree classification method; and (4) determine hotspot regions of hydroclimatic changes across the CONUS over 21st century. This study provides a potential roadmap of changes in regional hydroclimatic conditions across the CONUS, which can help decision-makers and water managers to implement region-specific adaptation and mitigation strategies for regional water resource management.

2. Materials and Methods

Future changes in climatic variables were obtained from the downscaled Multivariate Adaptive Constructed Analogs (MACA) data sets. The projected climatic variables were then used as inputs to the variable infiltration capacity (VIC version 4.1) model to evaluate the hydrologic responses of future climate projections. The Budyko space was applied to estimate changes in hydroclimatic conditions of the CONUS at HUC8 river basin scales. HUC8 river basins across the CONUS were clustered into groups with unique hydroclimatic behavior in response to climate change using the K-means method. Then, the association between hydroclimatic behavior groups and basin characteristics such as regional climate, landform, and ecosystem was assessed using the tree classification method. The 1986–2015 period was used as the baseline to represent current conditions while the 2070–2099 period represented the future conditions.

2.1. Hydroclimatic Projections

Raw global climate model (GCM) outputs cannot be used for regional hydroclimatic assessments due to the coarse resolution of grid cells, approximately on the order of 150–200 km (Naz et al., 2016). Thus, the downscaled MACA data sets were used to provide possible future climate change models in this study (Abatzoglou & Brown, 2012). The MACA climate data set includes 20 models that were downscaled for the entire CONUS at the grid size of ~4 km (1/24 degree) under the RCP 4.5 and RCP 8.5 emission scenarios. 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 (Table 1) (Joyce & Coulson, 2020). In this study, we used these five selected MACA models to study the shifts of combined hydroclimate conditions. It should be

Table 1
Projected MACA Climate Models (Joyce & Coulson, 2020)

	HOT	WARM	WET	DRY	MIDDLE
Name	HadGEM2-ES365	MRI-CGCM3	CNRM-CM5	IPSL-CM5A-MR	NorESM1-M
Model agency	Met Office Hadley Center, UK	Meteorological Research Institute, Japan	National Centre of Meteorological Research, France	Institute Pierre Simon Laplace, France	Norwegian Climate Center, Norway

noted that HOT, WARM, WET, and DRY, respectively, indicate the MACA climate models that are on average the hottest, warmest, wettest, and driest MACA models at the conterminous scale. For example, the DRY climate model is not always the driest in all river basins across the CONUS.

The MACA climate data set includes forcing data such as the maximum daily temperature near surface (tasmax), the minimum daily temperature near surface (tasmin), the average daily precipitation amount at surface (pr), the average daily eastward component of wind near surface (uas), and the average daily northward component of wind near surface (vas). The total wind speed was calculated in this study as the combination of the eastward and northward winds ($\sqrt{uas^2 + vas^2}$).

We used the term baseline to denote a historical period from 1986 to 2015 as a basis for comparison with future climate. The historical climate data were obtained from a combination of Daymet (Thornton et al., 1997) and the Parameter-elevation Regressions on Independent Slopes Model (PRISM, Daly et al., 2008) data sets. Precipitation and daily maximum and minimum temperature were calculated by Daymet and biased corrected with PRISM at the monthly scale. Additionally, wind speed was 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 the details about this historic forcing data set. In addition to the selected MACA models, we also conducted VIC simulation using this forcing data set to estimate the baseline hydrologic conditions.

The VIC version 4.1 hydrologic model (Liang et al., 1994) was set up at the grid size of ~4 km (1/24 degree) to simulate the hydrologic responses driven by different forcing data sets. The VIC model is a semidistributed macroscale model that solves full water and energy balances using the VIC curves (Cherkauer & Lettenmaier, 2003). The VIC model has been widely used to simulate streamflow over a number of large river basins in North America (Andreadis & Lettenmaier, 2006). Topography, soil characteristics, vegetation, land surface classification, and meteorological forcing are key hydrological inputs to the VIC model. Required meteorological forcing includes daily minimum and maximum temperature, precipitation, and wind speed. The VIC model uses the Penman-Monteith equation to estimate potential evapotranspiration.

We obtained the VIC model parameters also from Oubeidillah et al. (2014) and Naz et al. (2016), which were calibrated using the historic monthly runoff from the USGS WaterWatch runoff data set (Brakebill et al., 2011) at each HUC8 unit. 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 HUC8 basin. The naturalized streamflow routed to gauge locations has been traditionally used to calibrate hydrological models. However, calibrating the VIC model using the WaterWatch monthly runoff data leads to the homogenous application of the VIC model for all grid cells with the same resolution, and the parameter transfer to ungauged basins is not required. 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. It should be considered that the historical human impairments might result in a biased estimation of HUC8s runoff. The VIC model was run in full energy mode. Readers are referred to Oubeidillah et al. (2014) and Naz et al. (2016) for the detailed description of the VIC model set up, calibration, and evaluation. The daily hydroclimatic outputs were then aggregated to annual values at each HUC8 unit for evaluation.

2.2. Movements in the Budyko Space

Changes in hydroclimatology of each HUC8 river basin across the CONUS were characterized as a function of shift in the Budyko space (Budyko, 1974, 1982). The Budyko framework describes an empirical relationship between the evaporative index and aridity index. The evaporative index is defined as

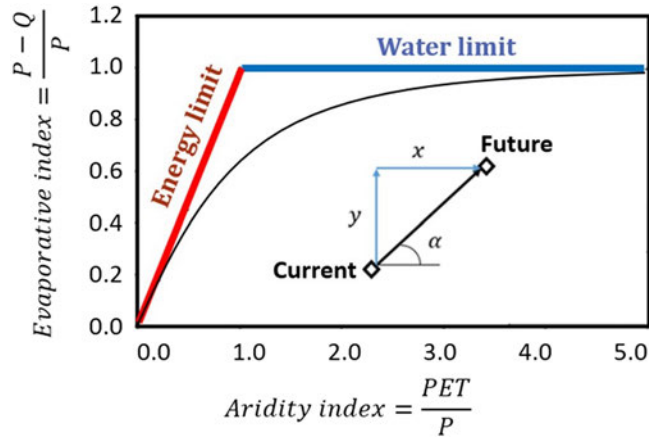


Figure 1. Characterization of magnitude and direction of movements in the Budyko space.

$$\text{Evaporative index} = \frac{P - Q}{P} \quad (1)$$

where P is precipitation and Q is water yield (or total runoff) in the river basin. Water yield is the average of freshwater that runs off in a basin (Foti et al., 2012; Kumar et al., 2018). $P - Q$ can be simplified to actual evapotranspiration. The aridity (or dryness) index is defined as

$$\text{Aridity index} = \frac{PET}{P} \quad (2)$$

where PET is potential evapotranspiration. The aridity index is a ratio of long-term average potential water demand (i.e., PET) to long-term average water supply (i.e., P) (Yang et al., 2006; Zhang et al., 2017). The interaction between aridity and evaporative indices can be defined as the Budyko space (Figure 1) (Jaramillo et al., 2018).

Aridity and evaporative indices have been commonly used to combine these hydroclimatic variables to assess changes in long-term hydroclimatic conditions of river basins.

Characterization of changes in long-term anomalies such as aridity and evaporative indices is a different way of approaching the extreme events assessment rather than characterization of temporary anomalies such as floods (Ghanbari et al., 2019; Ghanbari et al., 2020) and droughts (Heidari et al., 2020; Maliva & Missimer, 2013).

A river basin may move in the Budyko space over time due to a combination of changes in the aridity and evaporative indices (Van Der Velde et al., 2014). The combination of shifts in the Budyko space can be identified by the direction and magnitude of movements (Jaramillo et al., 2018; Piemontese et al., 2019; Zaninelli et al., 2019). The direction of movement can be defined by

$$\text{Direction } (D) = \arctan\left(\frac{\Delta y}{\Delta x}\right) \quad (3)$$

where Δy is change in the evaporative index and Δx is change in the aridity index (Figure 1). Subsequently, the magnitude of change in the Budyko space can be obtained as follows:

$$\text{Magnitude } (M) = \sqrt{x^2 + y^2} \quad (4)$$

The direction represents regional differentiation, and the magnitude of change identifies the most sensitive regions (Van Der Velde et al., 2014).

Movements in the Budyko space are constrained by physical limits on energy demand when the aridity index is equal to the evaporative index (red line in Figure 1), and water demand when the evaporative index is equal to one (blue line in Figure 1). Moving to the right means warmer and drier climatic conditions and moving to the left means less arid conditions. Besides, moving downward indicates higher rates of river discharge or wetter conditions, while moving upward indicates less water yield or streamflow for a given HUC8 river basin.

2.3. Hydroclimatic Behavior Groups

River basins in close vicinity may follow systematic and similar movements in the Budyko space. Systematic movements are meaningful and represent a common water and energy balance adaptation to regional climate change (Jaramillo et al., 2018; Piemontese et al., 2019; Zaninelli et al., 2019). We used cluster analysis with the K-means method to identify unique hydroclimate behavior groups in response to climate change across the CONUS based on the direction and magnitude of movements in the Budyko space. The CONUS was subdivided into seven hydroclimatic behavior groups with similar direction and magnitude.

The United States landform (supporting information Figure S1), ecoregion (Figure S2), and climate classifications (Figure S3) were applied to explain the differentiations in hydroclimatic behavior groups in response

to climate change. Figure S1 represents five major types of landforms within the CONUS including basin, lake, mountain, plain and plateau (Esri, 2014). Figure S2 illustrates the spatial map of U.S. ecoregions provided by the Environmental Protection Agency (EPA) and the Commission for Environmental Cooperation (CEC) (Omernik & Griffith, 2014). Each ecoregion group specifies a unique ecosystem across the United States, which specifies type, quality, and quantity of environmental resources. The ecoregion classification uses four levels. Level I is shown in Figure S2. Figure S3 shows the main groups of the U.S. Koppen climate classifications including dry, temperate, continental, and tropical (Chen & Chen, 2013). This classification is based on the seasonal precipitation and temperature patterns. In addition, these main climate groups are based on vegetation types in a given climate classification region (Chen & Chen, 2013).

Pearson's chi-square test was used to assess the statistical significance of the association between the aforementioned regional basin characteristics and the assigned hydroclimatic behavior groups as two categorical variables. Classifications with *p*-values less than 0.05 would suggest significant association. In addition, the statistical Goodman and Kruskal tau measure (Goodman & Kruskal, 1954) was also applied to determine the strength of associations. Classifications with higher values from the Goodman and Kruskal tau measure have higher strength of association to the seven hydroclimatic behavior groups. Finally, a tree classification method was applied to test for relationships between each hydroclimatic behavior group and the regional landform, ecosystem, and climate types.

3. Results and Discussion

The study reveals that shifts in U.S. regional hydroclimatic conditions in response to climate change vary from a region to another. However, HUC8 river basins in the same neighborhood can generally follow a similar and systematic movement in the Budyko space. The CONUS can be subdivided into seven groups with similar changes in direction and magnitude in the Budyko space. These hydroclimatic behavior groups are highly associated with the regional types of climate, ecosystem and landform. This study suggests a potential roadmap of shifts in regional hydroclimatic conditions to improve the preparedness and ability of river basins across the United States to mitigate or adapt to the impacts of hydroclimate change over the 21st century. We further used the nine U.S. climate regions defined by the National Climatic Data Center (National Oceanic and Atmospheric Administration, 2014) to explain regional shifts in hydroclimatic conditions across the United States through this section. This U.S. climate regions are regularly used in climate summaries.

3.1. Changes in Hydroclimatic Variables

Changes in five hydroclimatic variables including precipitation, temperature, evaporation, water yield, and potential evapotranspiration were first evaluated. Figure S4 provides the 30-year baseline climatology maps of these five variables. Besides, Figure S5 shows the temporal evolution of the five selected MACA models under RCP 4.5 and 8.5 emission scenarios. Figures S6, S7, and S8 represent the spatial patterns of the five selected MACA models under RCP 8.5 emission scenario for precipitation, potential evapotranspiration, and water yield, respectively. It should be noted that the estimated potential evapotranspiration highly depends on calculation method. The Penman–Monteith equation was used in the VIC model to estimate potential evapotranspiration. The projections under all five climate models are highly variable. The DRY model with RCP 8.5 has the highest decreases in precipitation and evaporation and the highest increases in potential evapotranspiration and temperature. Conversely, the WET model with RCP 8.5 has the highest increases in precipitation, water yield, and evaporation and the highest decrease in potential evapotranspiration. Note that temperature increases across all climate projections though the magnitude of temperature increases varies.

The West United States has the highest increase in precipitation and water yield and the highest decrease in potential evapotranspiration. However, the South United States has the highest decrease in precipitation and water yield and the highest increase in potential evapotranspiration from current conditions to future conditions.

Water yield, precipitation, and potential evapotranspiration have the primary control on water and energy balance (Yang et al., 2006; Zhang et al., 2017). Figure 2a shows the 30-year average of annual aridity index during the baseline period (1986–2015). The majority of river basins in the Northeast, Central, Northwest,

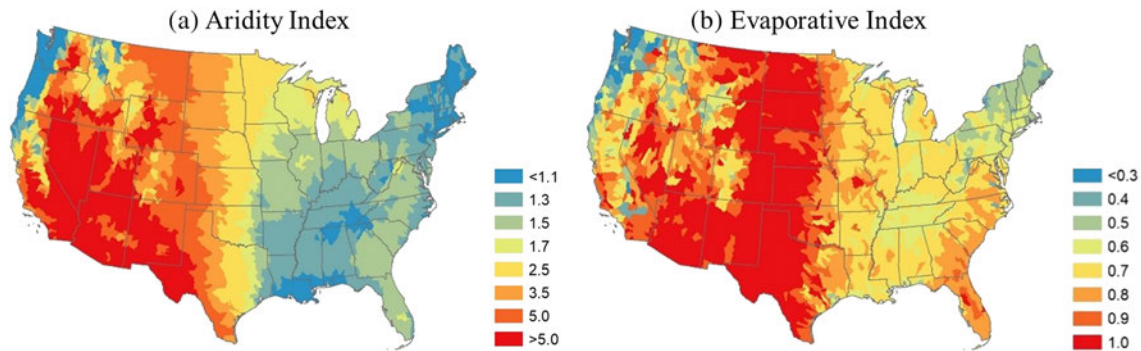


Figure 2. Maps of current (a) aridity index and (b) evaporative index for the baseline period (1986–2015).

and Southeast United States with lower aridity indices have been limited by available energy, while most river basins located in the West and Southwest United States with higher aridity indices have been limited by water availability. In addition, Figure 2b illustrates the 30-year average of evaporative index during the baseline period. River basins in the West North Central, South, and Southwest United States with higher evaporative index have comparatively less water yield.

Figure 3 provides the 30-year normal annual aridity and evaporative indices across all HUC8 river basins from 1980 to 2099 under RCPs 4.5 and 8.5 scenarios for the historic baseline and five selected MACA models. The historical period obtained from the combination of Daymet and PRISM from 1986 to 2015 was shown as a baseline in black. Under RCP 4.5, DRY, and WET climate models are approximately representative of upper and lower bounds of future aridity and evaporative indices, respectively. However, there is not a substantial and consistent trend. Under RCP 8.5, the DRY climate projection foresees a substantial increase in aridity and evaporative indices over the 21st century. However, the WET and WARM models consistently project decreases in aridity and evaporative indices over the 21st century. Under the MIDDLE and HOT models, aridity and evaporative indices show slight changes compared to the baseline period.

For a detailed assessment of hydroclimatic changes across the CONUS, we further used DRY, WET, and MIDDLE climate models under RCP 8.5 to capture a wide range of potential future climate change across the entire CONUS. Figure 4 shows spatial changes in the aridity and evaporative indices of these three

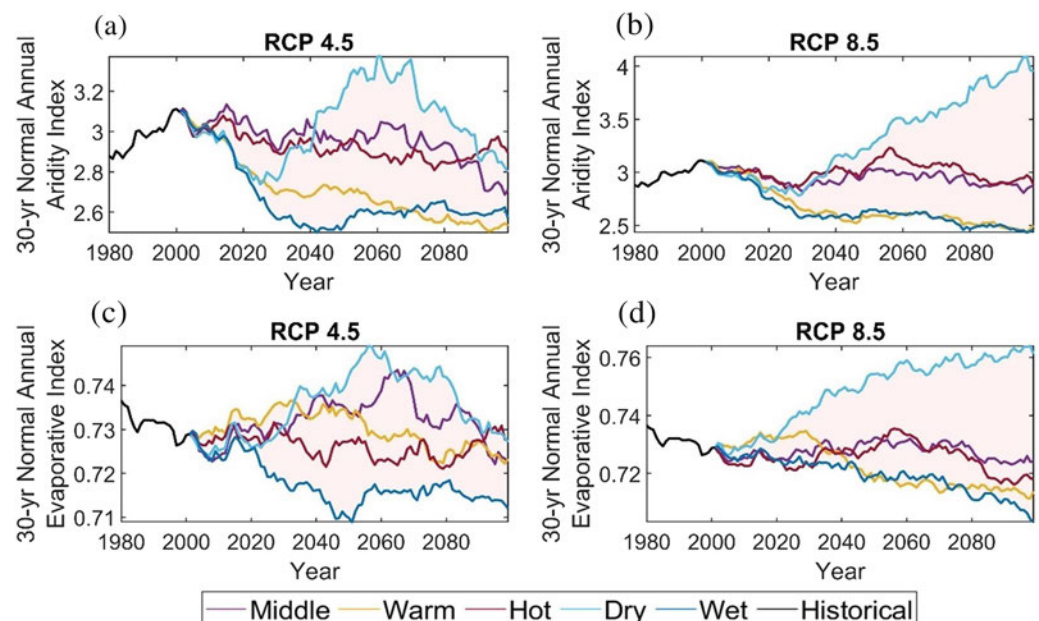


Figure 3. Timeseries of annual aridity index and evaporative index under RCPs 4.5 and 8.5 emission scenarios.

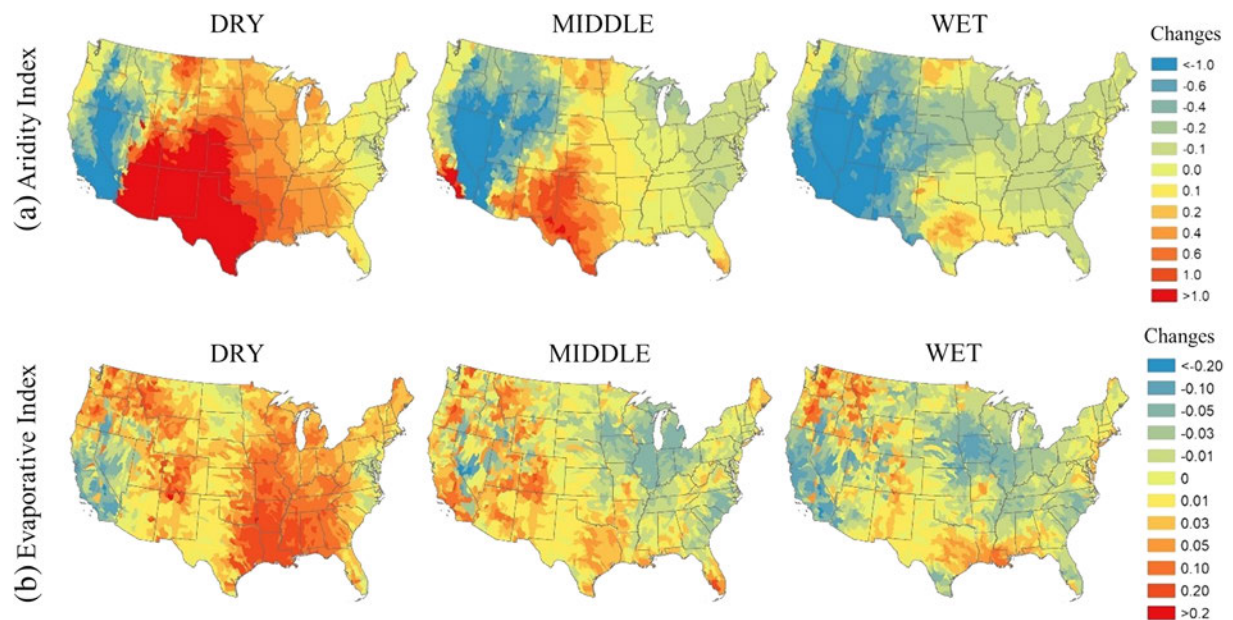


Figure 4. Spatial changes in (a) aridity and (b) evaporative indices from baseline (1986–2015) to future (2070–2099) periods (RCP 8.5).

climate projections from baseline (1986–2015) to future (2070–2099) periods. Changes indicates the value of future indices minus the value of current indices.

Under DRY, MIDDLE, and WET climate projections, the majority of HUC8 river basins located in the West United States show decreases in evaporative and aridity indices. Decreases in evaporative and aridity indices suggest increases in the chances of higher river discharges in these regions (Piemontese et al., 2019). Most river basins located in the South United States will have higher aridity and evaporative indices under all three climate projections indicating the likelihood of prolonged droughts in these regions (Piemontese et al., 2019). These findings are in line with the projections for precipitation, potential evapotranspiration, and water yield (Figures S6 to S8).

3.2. Movements in the Budyko Space

Direction of movement in the Budyko space characterizes regional differentiation, while the magnitude of movement reveals the most sensitive regions (Van Der Velde et al., 2014). Here, we projected shifts of each

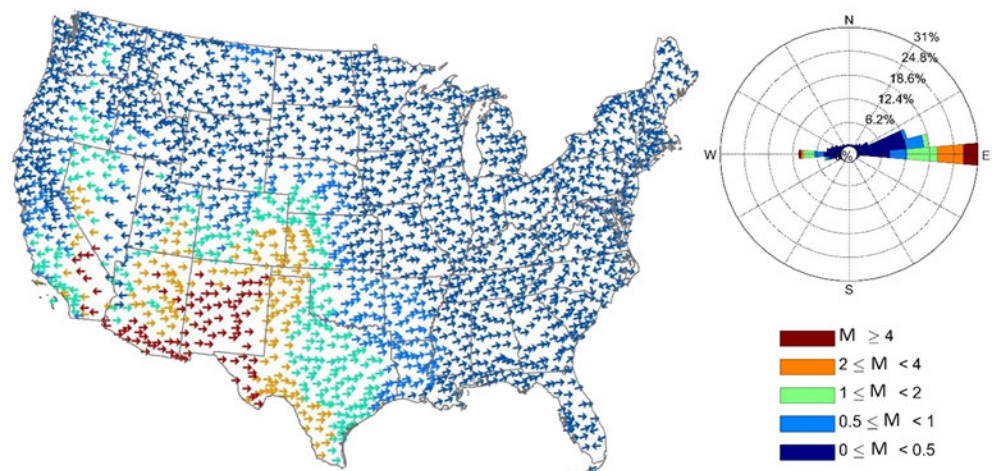


Figure 5. Movements in the Budyko space under the DRY climate model with RCP 8.5.

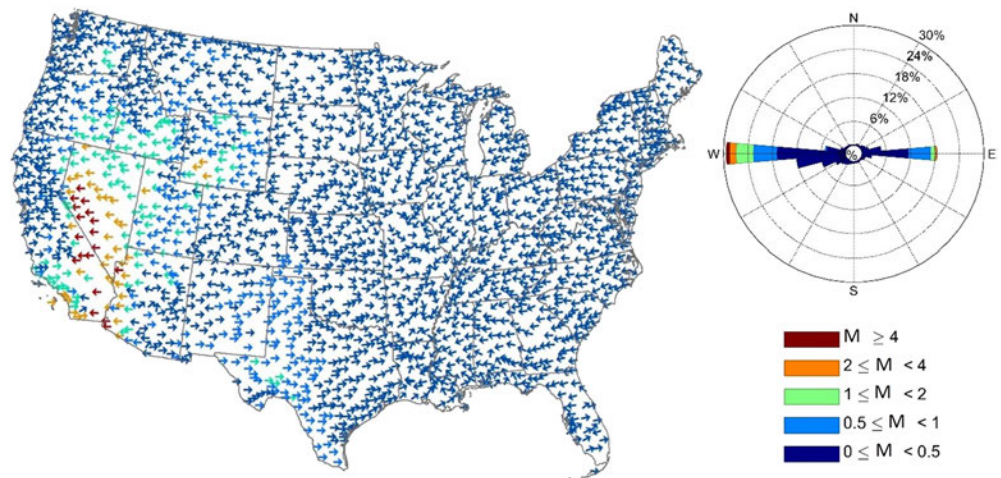


Figure 6. Movements in the Budyko space under the MIDDLE climate model with RCP 8.5.

HUC8 in the Budyko space from baseline (1986–2015) to future (2070–2099) periods across the CONUS under DRY, MIDDLE, and WET climate projections with RCP 8.5 emission scenario.

Under the DRY climate projection (Figure 5), most river basins deviate from the energy limit line (red line in Figure 1) meaning that the ratio of potential evapotranspiration to precipitation (i.e., aridity index) is increasing. In other words, most river basins are becoming more water limited. However, some HUC8 river basins in the West and Northwest United States move closer to the energy limit line. Additionally, most river basins in the Central and East North Central United States move to the upper-right meaning that the evaporative index is also increasing in these regions. Wind rose diagram in Figure 5 visualizes the summary of movements in the Budyko space including direction, magnitude, and frequency for all HUC8 river basins. This type of diagrams has been used in global hydroclimatic change assessments (Destouni et al., 2013). Based on the wind rose diagram in Figure 5, river basin movements are more likely to occur in the directions represented by the right, right-upper, and left quadrants of the rose diagram, respectively. The results indicate that most river basins in the West and Southwest United States have high magnitude of changes meaning that the hydroclimatology of these regions is more sensitive to climate change.

Under the MIDDLE climate projection (Figure 6), river basins in the West, Northwest, Northeast, and Southeast United States move closer to the energy limit line meaning that the aridity index is decreasing. However, most HUC8 river basins in the South United States deviate from the energy limit line meaning that

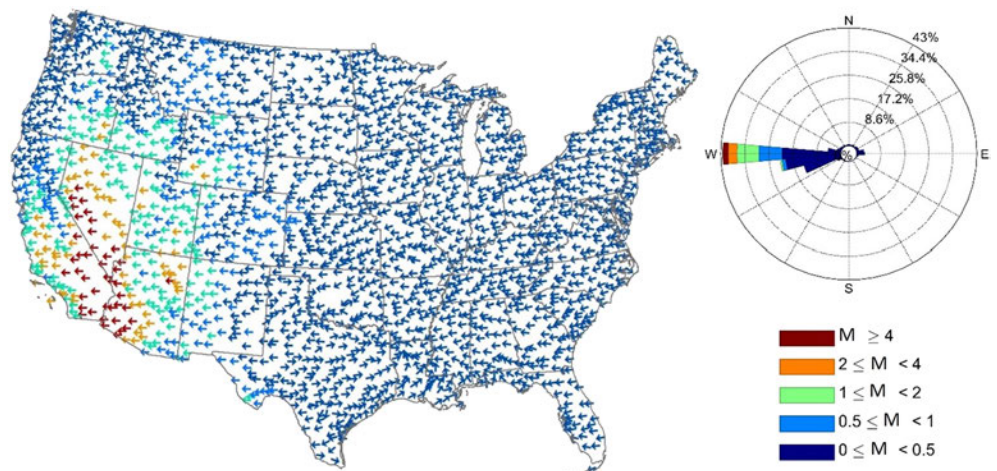


Figure 7. Movements in the Budyko space under the WET climate model with RCP 8.5.

Table 2
Hydroclimatic Behavior Group

Behavior group	Direction (D) and Magnitude (M)
1	D (135-190) with M (<0.095)
2	D (135-190) with M (>3.4)
3	D (135-190) with M (0.95-3.4)
4	D (220-360)
5	D (190-220)
6	D (0-45) with M (>0.5)
7	D (0-45) with M (<0.5)

the climate is getting warmer and drier in this region. The majority of river basins do not show an increase or decrease in the evaporative index. There is only a slight decrease in evaporative indices of river basins located in the Central United States. According to the wind rose diagram in Figure 6, river basin movements are more likely to occur in the directions represented by the left, right, and left-lower quadrants of the rose diagram, respectively.

Under the WET climate projection (Figure 7), a significant number of river basins moved toward left meaning that the aridity of river basins is decreasing. The HUC8 river basins in the WEST and Southwest

United States have higher magnitude of changes meaning that the hydroclimatology of these regions is more sensitive to climate change compared to other regions. In addition, the majority of river basins in the Central and East North Central United States deviate from the water limit line (blue line in Figure 1) meaning that the evaporative index is decreasing in this region. In other words, the ratio of streamflow to precipitation is increasing, which resulted in higher river discharges. According to the wind rose diagram in Figure 7, river basin movements in the Budyko space are more likely to occur in the directions represented by the left and left-lower quadrants of the rose diagram, respectively.

Under all three climate projections, the systematic movements of HUC8 river basins in the Budyko space indicate that the CONUS will experience nonstationary changes in water and energy cycling over time. Figure S9 compares changes in direction and magnitude across the three climate projections. As a common pattern across the all three climate projections, climate change will cause a wetting trend over the western and eastern CONUS but a drying trend over the central and southern CONUS. A consistent pattern of changes in direction and magnitude was found across the three climate changes projections for the South and West United States, respectively. These river basins are likely to experience a similar hydroclimatic change regardless of the future climate projections. The magnitude of the change is particularly large along the West and Southwest United States under all three climate projections. The magnitude of change characterizes the most sensitive areas. Thus, hydroclimatic conditions of the West and Southwest United States are the most sensitive to climate changes over the 21st century. Direction determines regional differentiation. Most river basins in the South United States will likely get drier and warmer under all three climate projections.

3.3. Hydroclimatic Behavior Groups

HUC8 river basins with systematic and similar magnitude and direction of movements in the Budyko space can be clustered to a hydroclimatic behavior group in response to climate change. To better understand the pattern of shifts across the CONUS, we clustered movement in the Budyko space under the MIDDLE model which can have potential implications for regional adaptation and mitigation strategies. The K-means method was used to cluster HUC8 river basins to the seven regions with unique hydroclimatic behavior. Table 2 and Figure 8 provide the ranges of direction and magnitude of each hydroclimatic behavior group that are in line with the wind rose diagram in Figure 6.

Groups 1, 2, and 3 have the same direction (moving to the left). However, they have different magnitude of changes. Groups 2 and 3 have higher magnitude than group 1. In addition, Groups 6 and 7 have the same direction (moving to the right-upper). However, Group 6 has higher magnitude of changes than Group 7. Groups 6 and 7 are more likely to experience prolonged drought, while Group 5 with movement to the left-lower is likely to experience higher river discharge under wetter conditions. Group 4 includes a wide range of direction from 220 to 360 degree with more frequent movements to lower and lower-right.

Regional landform, climate, physiology, ecology, and landcover play important roles in the hydroclimatic behavior of a river basin in response to climate change. In this regard, Koppen climate classifications, ecoregions, and landform (Figures S1 to S3) were used to relate systematic movements in the Budyko space to the regional river basin characteristics. Based on the Pearson's chi-square test, all regional classifications have *p*-values close to zero meaning that they are associated to the hydroclimatic behavior groups. Table 3 shows the *p*-value and chi-square values of each classification. In addition, the Goodman and Kruskal tau measure was used to determine strength of association between each classification with hydroclimatic behavior

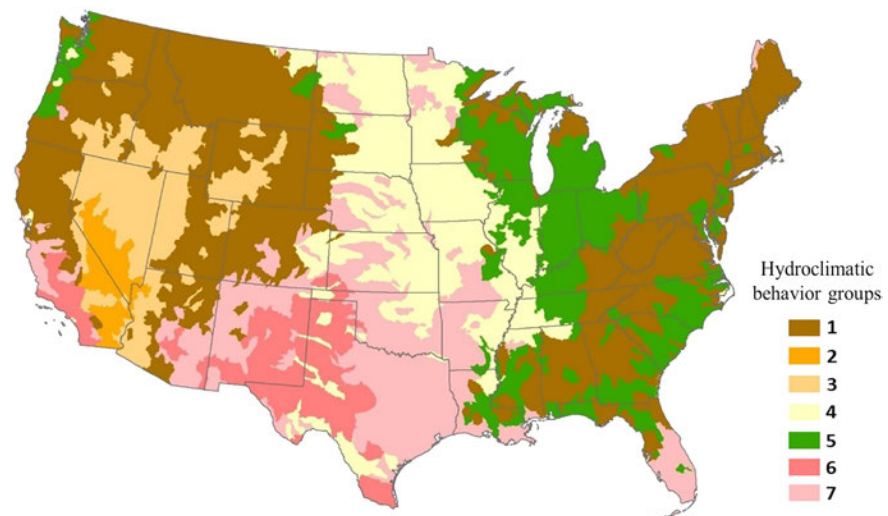


Figure 8. Regional hydroclimatic behavior groups of the United States under the MIDDLE climate model with RCP 8.5.

groups. Landform zones, ecoregion zones, and climate zones have respectively higher associations. A tree classification method was then used to find a relationship between hydroclimatic behavior groups and hydroclimatic factors based on the combination of these basin characteristics. Figure 9 illustrates the relationship between each hydroclimatic behavior group and its regional landform, ecosystem, and climate.

Figure 10 shows projected hydroclimatic behavior groups based on the tree classification method. It shows an acceptable accuracy for the spatial pattern of hydroclimatic behavior groups in comparison with Figure 8, which is useful to make a prediction for regional characteristics of each hydroclimatic behavior group. The tree classification method has the lowest accuracy for Group 6, though it has captured its spatial trend.

The majority of Group 1 is within the mountain and plateau types of landform. Group 2 includes basin regions with a dry climate, and Group 3 is related to basin regions with a semi-arid climate. Group 4 includes some parts of great plain with continental climate type. Group 5 comprises most plains which are located in the eastern forest type of ecosystem with both continental and temperate climates. Group 6 comprises plains with dry climate located in the south central semi-arid prairies type of ecosystem, and majority of Group 7 is related to plains with temperate climate within the great plains.

Overall, the aridity in the mountain, plateau, and basin types of landforms is decreasing over the 21st century. Aridity will decrease more in the basin region compared to mountain and plateau types of landform, meaning that the hydroclimatology of the basin region is more sensitive to climate change than that of the mountain region. In addition, within the basin regions, basin regions with dry climate have larger declines in aridity than basin regions with semi-arid climates.

However, river basins with the plain landform type behave differently in response to climate change according to their ecosystem and climate. Some river basins in the plains with dry climates inside the west central semi-arid prairie ecosystem behave like mountains and will have wetter climate conditions. Plains with

Table 3

Statistical Test for Association Between Hydroclimatic Behavior Groups and Regional Climate, Ecoregion, and Landform Classification of the United States

Classification	Pearson's <i>p</i> -value	Pearson's chi-square	Goodman and Kruskal tau measure
Climate zones-Level 1	<i>p</i> -value < 2.2e-16	707.83	0.157
Climate zones-Level 2	<i>p</i> -value < 2.2e-16	1,160.4	0.13
Climate zones-Level 3	<i>p</i> -value < 2.2e-16	1,580.3	0.118
Ecoregion zones-Level 1	<i>p</i> -value < 2.2e-16	1,944.2	0.238
Ecoregion zones-Level 2	<i>p</i> -value < 2.2e-16	3,173.3	0.128
Ecoregion zones-Level 3	<i>p</i> -value < 2.2e-16	5,213.2	0.045
Landform zones	<i>p</i> -value < 2.2e-16	1,410.5	0.245

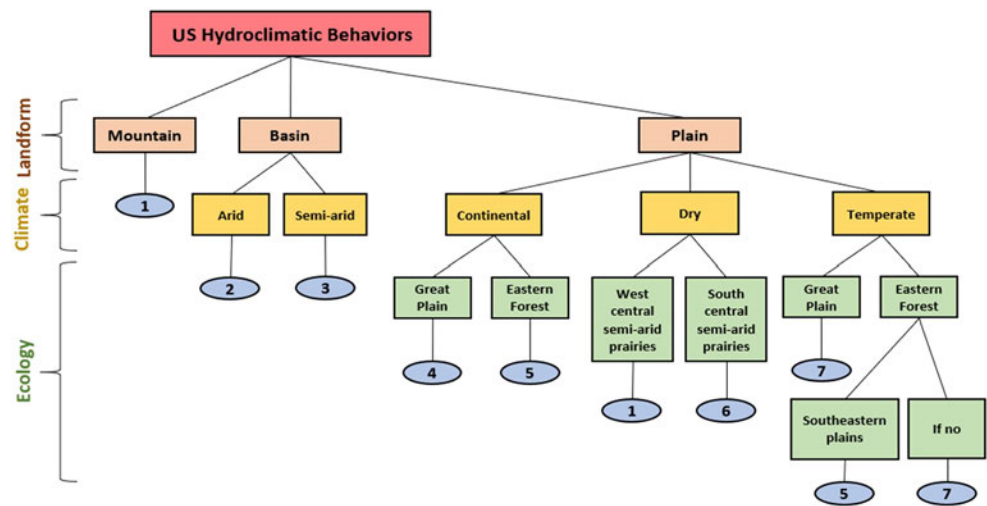


Figure 9. A tree classification to explain relationship between U.S. hydroclimatic behavior groups and regional basin characteristics (landform, climate, and ecosystem) under the MIDDLE climate model with RCP 8.5.

eastern forest ecosystems are more likely to experience wetter climate conditions over the 21st century. The evaporative indices of these regions will also decrease significantly compared to mountain and basin types of landforms, meaning that the rate of discharge will be higher in the future.

Both aridity and evaporative indices will increase in Plains regions with dry climate in the south central semi-arid prairies ecosystems, and in plains regions with temperate climates in the great plains. These regions will experience less streamflow under drier climate conditions. However, some parts of the great plains with continental climates experience decrease in their evaporative index with increase in aridity index, meaning that this region will experience higher streamflow even under drier climate conditions.

It can be concluded that river basins inside the great plains are getting warmer and drier in terms of climate conditions. However, some parts of the great plains which are located in the continental climate will have higher rates of streamflow in the future while other parts of the great plains with temperate climates and dry climates (located in south central semi-arid prairies) will experience lower rates of streamflow.

These findings highlight the need for regional differentiation in adaptation and mitigation strategies according to regional climate, landform, and ecosystem of river basins in the United States to protect vulnerable

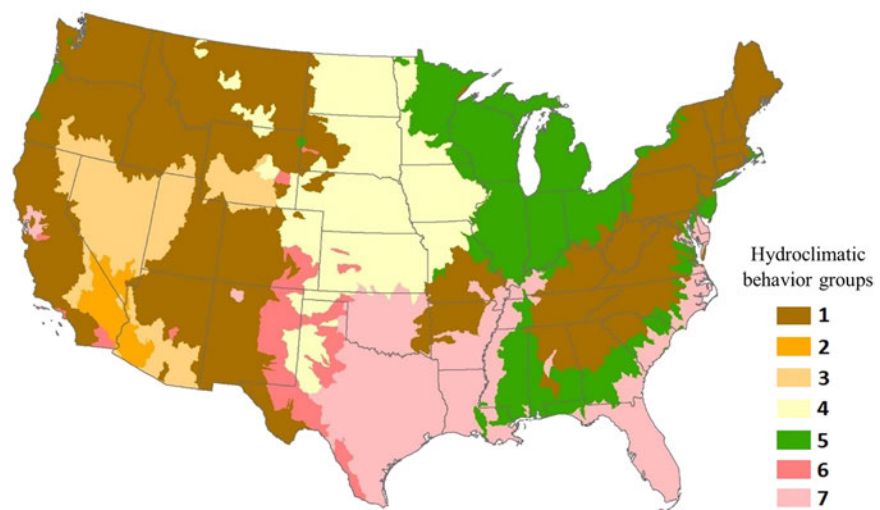


Figure 10. Estimation of U.S. hydroclimatic behavior groups based on the tree classification under the MIDDLE climate model with RCP 8.5.

resources and reduce potential consequences on agriculture, environment, economy, society, and ecosystem.

Given the high uncertainty in the MACA climate projections, VIC hydrological modeling, K-means clustering, and tree classification methods, this study is aimed to provide a general overview of future shifts in the regional hydroclimatic conditions of U.S. river basins in response to possible range of changes in climate variables. The findings can be used as a roadmap for decision-makers to implement adaptation and mitigation strategies at an improved and modified regional scale.

4. Summary and Conclusions

Climate change can alter hydroclimatology of river basins at various spatial and temporal scales. This study evaluates the potential impact of climate change on hydroclimatic conditions of U.S. river basins over the 21st century. Five sets of hydroclimatic projections were conducted using the VIC hydrologic model driven by the downscaled MACA data sets. Shifts in the long-term hydroclimatic conditions at the HUC8 river basin scale were expressed by magnitude and direction of movements in the Budyko space. Hydroclimatic responses vary from one river basin to another. However, a consistent pattern of changes in direction and magnitude was found across the climate change projections. Overall, six important conclusions can be made here:

1. HUC8 river basins can be clustered into seven hydroclimatic behavior groups with a similar, unique, and systematic movement in the Budyko space indicating that there should be common regional water and energy balance adaptations to climate change.
2. This finding challenges the stationary assumption of long-term water and energy cycles meaning that climate change may lead to shifts in long-term water and energy balances and changes in hydroclimatic conditions.
3. The hydroclimatic behavior of U.S. river basins in response to climate change are highly associated with basin characteristics such as regional landform, climate, and ecosystems. These findings highlight the need for regional differentiation in adaptation and mitigation strategies to protect vulnerable resources and reduce negative consequences of hydroclimatic shifts on various sectors.
4. The aridity index in the mountain, plateau, and basin types of landforms will decrease over the 21st century with higher rates in basin compared to mountain and plateau regions. Additionally, both aridity and evaporative indices will decrease in the plains with eastern forest ecosystems.
5. The aridity will increase over 21st century in plains with dry climates in the south central semi-arid prairies, plain with temperate climates in the great plains, and some parts of the great plains with continental climates. The evaporative index also decreases in river basins inside the great plains with continental climates, meaning that the rate of river discharge increases even though the climate gets warmer and drier.
6. The South and Southwest United States are the hotspots for shifts in long-term hydroclimatic conditions. The majority of river basins in the South United States move to the right-upper with high magnitude indicating that this region is likely to experience warmer and drier conditions with higher chances of prolonged droughts. Most river basins in the West United States move to the left-lower with high magnitude indicating that this region is likely to experience wetter conditions and increased river discharges.

These findings have potential implications for human and agricultural activities. Adaptation and mitigation strategies are best designed at a modified and improved regional scale to protect vulnerable ecosystems and freshwater resources. This study can help decision-makers to assess and improve the ability and preparedness of various resources to mitigate or adapt to the impacts of climate changes across the United States over 21st century.

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).

Acknowledgments

This work was funded by NSF Sustainability Research Network (SRN) Cooperative Agreement 1444758 as part of the Urban Water Innovation Network (UWIN) and a cooperative agreement with US Forest Service Research and Development, Rocky Mountain Research Station.

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