AGU PUBLICATIONS

Earth's Future

RESEARCH ARTICLE

10.1002/2016EF000393

Water sustainability of large cities in the United States from the perspectives of population increase, anthropogenic activities, and climate change

Wondmagegn Yigzaw[1] and Faisal Hossain[2]

[1]Department of Civil and Environmental Engineering, Tennessee Technological University, Cookeville, Tennessee, USA,
[2]Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington, USA

Key Points:

- Central Valley of California, Los Angeles, Phoenix, and Tucson will face further challenges as Colorado River depletes
- The West, Southeastern Coast, and FL should consider desalination
- West and Central CONUS can use the Mississippi for inter-basin transfer

Corresponding author:
F. Hossain, fhossain@uw.edu

Citation:
Yigzaw, W., and F. Hossain (2016), Water sustainability of large cities in the United States from the perspectives of population increase, anthropogenic activities, and climate change, *Earth's Future*, *4*, doi:10.1002/2016EF000393.

Received 17 JUN 2016
Accepted 8 NOV 2016
Accepted article online 14 NOV 2016

Abstract Balancing water demand and supply with depleting sources and increasing demand needs a multi-dimensional approach given the pace at which the world is urbanizing. This study selected the contiguous United States (CONUS), 42 specific cities and their river basins to determine: *Which basins and cities are more susceptible to increased water shortage?* Population, water use, hydrologic model and climate model data from CMIP5 were used. Representative Concentration Pathways scenarios: RCP2.6, RCP4.5, RCP6, and RCP8.5 represented different climate change conditions. Period 1 (1950–2004) showed that more areas are affected by monthly runoff and streamflow than annual averages. In some cases, significant decreasing trends in water availability were observed during the summer (June–July–August) and spring (March–April–May) seasons. The second period (2005–2049) indicated an annual increasing trend (more water available) with higher intensity for the RCP6 scenario. Summer and spring showed areas of decreasing trend (less water available) for RCP4.5 and RCP6. Period 3 (2050–2099) exhibited a decreasing trend for the RCP2.6 (Western and Central CONUS, Great Lakes, and FL), RCP4.5 (Southwest CONUS), RCP6 (Western United States), and Central CONUS (RCP8.5). The Mississippi River has a mixed sensitivity to future climate change. The Central Valley of California, Los Angeles, Phoenix, and Tucson can face further challenges as the Colorado River becomes depleted. Seawater desalination and inter-basin water transfer can be considered in future and present policies and structural developments. The West, Southeastern Coast, and FL may consider desalination, while the West and Central CONUS can use the Mississippi for inter-basin transfer.

1. Introduction

There is an intertwined relationship between water resources sustainability, urbanization, and climate change. While one drives the other, all fall into one of two variables; "*supply*" and "*demand*." Supply is affected by actual and virtual availability of surface and ground water while demand is a cumulative result of population, urbanization, and socioeconomic factors. Virtual water availability can refer to imported agricultural (water) products [*Chapagain and Hoekstra*, 2008]. Population growth leads to lateral urbanization in cities if space allows it. Particular to large cities (megacities), an increase in population might lead to an increase in density without noticeable lateral land cover change. While lateral urbanization can be considered in its physical impact in the land-atmospheric interaction, population density increases result in a vertical expansion and can be quantified by an increase in water demand. There is a multi-dimensional increase in water demand associated with urbanization; direct demand for consumptive use, demand for food production, and demand for power.

Land use land cover change (LULCC), population, and overall climate change contributes to available water resources. However, the part any of these factors play in water availability has a spatial dependency. For example, in some areas, population trends might outweigh LULCC, and climate change could dominate all factors [*Sun et al.*, 2008]. Individual sectors have their own influence on water demand. Agricultural water demand is primarily responsible for future water stress; while power plant demand also has a considerable impact [*Averyt et al.*, 2013]. A U.S. Geological Survey statistics (USGS) on water use in United States during 2010 puts agricultural withdrawal to be about 32% and that of thermoelectric plants at 45% (USGS: http://water.usgs.gov/watuse/wuto.html). A study by *van Vliet et al.* [2012] identified the vulnerability of energy production in Europe and the United States as a result of climate change. In their study, they indicated that power production from thermoelectric plants can decrease as much as 16% during the summer as a result of water scarcity and increase in water temperature. According to the U.S. Census Bureau, the U.S. population will increase up to 30% by the year 2060. The balance between population increase and natural (water) resources is a crucial matter [*Falkenmark and Widstrand*, 1992].

Water scarcity can be divided into physical and economic scarcity depending on the respective water resource development. Economical scarcity represents a situation where water resources are physically available but price and technological constraints hinder extraction. Economical scarcity is most evident in developing countries [*Seckler et al.*, 1999]. Given the recurrent water shortage in the Southern and Western United States, an increase in water demand as a result of population growth is inevitable. The current water resource management in the United States has problems such as the recurrence of drought and floods along with aging water management infrastructures. At the federal level, there is an initiative to consider climate change and its impact in future water resources design and management. Available water resources in the contiguous United States (CONUS) are dependent on both surface and ground water with the major source of surface water being rivers, lakes, and reservoirs. These rivers can range from small streams to big rivers. One example is the Colorado River with most of the southwestern United States depending on this river system. According to the United States Bureau of Reclamation (USBR), nearly 40 million Americans and 5.5 million acres of land depend on the water supplied by the Colorado River system [*U.S. Bureau of Reclamation (USGS)*, 2012].

Given the probable increase in water demand, the prospect of water supply in this basin and around the CONUS is challenging. The Mississippi, Rio Grande, and Colombia Rivers also play a role in the socioeconomic development of the United States through navigation (for trade, commerce), irrigation (for agricultural production), and hydropower (for energy). Desalination contributes to water supplies. The contribution of desalination plants has increased over the past decades due to technological advances and higher water demand [*Mickley*, 2012; *Vedachalam and Riha*, 2012]. According to *Mickley* [2012], there are more than 300 desalination plants in the United States that can produce water at a rate of 95 m^3 per day. The Tampa Bay desalination plant is a good example of supplementing surface water sources to help meet municipal water demands.

A noticeable effort focusing on future water demand and supply in the Western United States is the USBR's WaterSMART Program (Sustain and Manage America's Resources for Tomorrow, http://www.usbr.gov/WaterSMART/). Multiple basin studies have been conducted under this program, which includes the basins of the Colorado River, Henrys Fork, Lower Rio Grande, Santa Ana Watershed, Milk-St Mary Rivers, and the Yakima River.

The major uncertainty in understanding future water demand and supply in these studies is the variability of both as a result of climate change and socioeconomic factors. Water-related problems in the future may not be straightforward but can be generally categorized as water shortage and lack of infrastructure; while the solutions include exploring alternative water sources, reducing water demand, and modifying operations [*USBR*, 2012]. Water management policy has a direct contribution toward tackling climate change impacts [*Huntjens et al.*, 2011; *Haasnoot et al.*, 2012; *USBR*, 2012]. For example, policy changes that implement climate change mitigation can cap the greenhouse gas concentration and hence future change in temperature and runoff [*USBR*, 2012]. Transformation and adaptation-based policy can also have a significant impact on alleviating climate change problems [*Viviroli et al.*, 2011; *Kates et al.*, 2012]. The impact of LULCC on water availability (rainfall, runoff, and groundwater) can be substantial and prompts counter measures to minimize the effects that include afforestation and similar land use management. Contribution of structural solutions and non-structural solutions (e.g., policies focusing on climate change path and water supply).

AQ3

There is a wide range of research on water resources management in the United States by government agencies [*National Research Council (NRC)*, 2004]. However, such research does not adequately address socioeconomic growth and its impact on water availability. Multidisciplinary research, advanced structural design, and climate change adaptation are the main areas that water resources management should focus to develop "*resilience*" toward a changing water supply–demand equation. The main objective of this study was to understand the prospect of water resources availability over the CONUS in the future using climate model data. This was achieved by understanding the *spatial and temporal variation of runoff over CONUS*, and *identifying basins and cities that are susceptible to increasing water shortages*. The findings from this study can be used to identify cities and regions of water shortage based on a projected climate change scenario. A solution for water shortage basically falls in either restricting demand (policy and conservation) or increasing supply (structural). These fall under the contribution of structural solutions and non-structural solutions (e.g., policies focusing on climate change path and water supply). A qualitative policy and structural-based solution to alleviate these shortages and their respective prioritization as a solution can also be drawn from the final results and discussion of the study.

2. Study Area

The CONUS and specific city and basin were selected as study areas. The CONUS was considered for an overall understanding future trend of water availability on a continental level. Selecting specific study areas was important to identify areas of concern (water supply/demand stress) so that water resources management measures can be appropriately implemented. The first criterion in selecting specific areas was total population and rate of population increase based on 2013 census data. This approach identified 268 cities with a positive increase rate and a total population exceeding 100,000 inhabitants. This selection was further refined based on urbanization and water demand rate. The urbanization rate was calculated by considering 1992 as a base year and then analyzing new urban areas for the years 2001 and 2011. Some cities have grown rapidly between 1992 and 2001 and then stabilized (e.g., Aurora, IL; Overland Park, KS; Henderson, NV); while others have continued expanding beyond 2001 (e.g., Austin, TX; Albuquerque, NM; Phoenix, AZ). The city of Frisco in Texas experienced the greatest increase in urbanization: an increase of 85% and 118% from 1992 to 2001 and 2011, respectively. These criteria resulted in a large number of cities (more than 100). The source of water supply was then evaluated for these locations. Interestingly, a large number of cites use groundwater wells (aquifers) as the main source of water supply. As the primary focus of this study was surface water, all cities that primarily use groundwater were excluded regardless of the rate of urbanization increase (e.g., Surprise, AZ, which has observed an urbanization increase of 197% from 1992 to 2011).

Water demand at the county-level was used to refine the number of cities selected using population and urbanization criteria. Less focus was given to water use data for two reasons; the data were not city based, and commercial, consumptive use, and hydroelectric power were missing for the years 2005–2010. A comparison of water demand change for cities of similar population change rate and size was made. Those cities that had higher water demand between 2005 and 2010 were selected as study areas. Using population, urbanization, and water use data, a total of 42 specific cities were selected. The selected cities fall in different Koeppen-Geiger climate classifications representing all possible classes in the CONUS. It can be also argued that most of the CONUS cities have been represented (with at least one city in a state, except those with groundwater sources). There were only eight cities out of the total selected, which draw their water supply from an upstream artificial reservoir. However, using a reservoir depends on water right, as for example, cities like Los Angles draw water from a distant reservoir (Lake Havasu) through conveyance system (The Colorado River Aqueduct). The specific river basins for surface water sources of the selected cities were also delineated (Figure 1) for further analysis of future water trends.

3. Data and Methodology

3.1. Data

Population census, land use land cover (LULC) (in the form of urbanization), water use, and climate model data were used. The U.S. Census Bureau (http://www.census.gov/) was a source for city-based population data. Census data of cities between 2010 and 2013 were used to identify population growth rate. This period represented a stable population change rate that accounts for the unusual in or out migration following the economic crisis in 2008 and 2009. Population data from metropolitan areas were excluded to avoid the confusion of multiple water supply sources. That is, a metropolitan area can have two different water supply sources (surface or ground water) but a large total population, which biases study area selection. There was no city-based water use data in the United States. The best available data was at the county-level from the USGS database (http://water.usgs.gov/watuse/data/) spanning 1985–2010. These water use data may have some uncertainty in depicting the real water use even at a county-level as some sectors were missing (commercial, consumptive, and hydroelectric power use) between 2005 and 2010. Three sets of LULC data from the USGS National Land Cover Database (NLCD) were used for urbanization change calculation: 1992, 2001, and 2006.

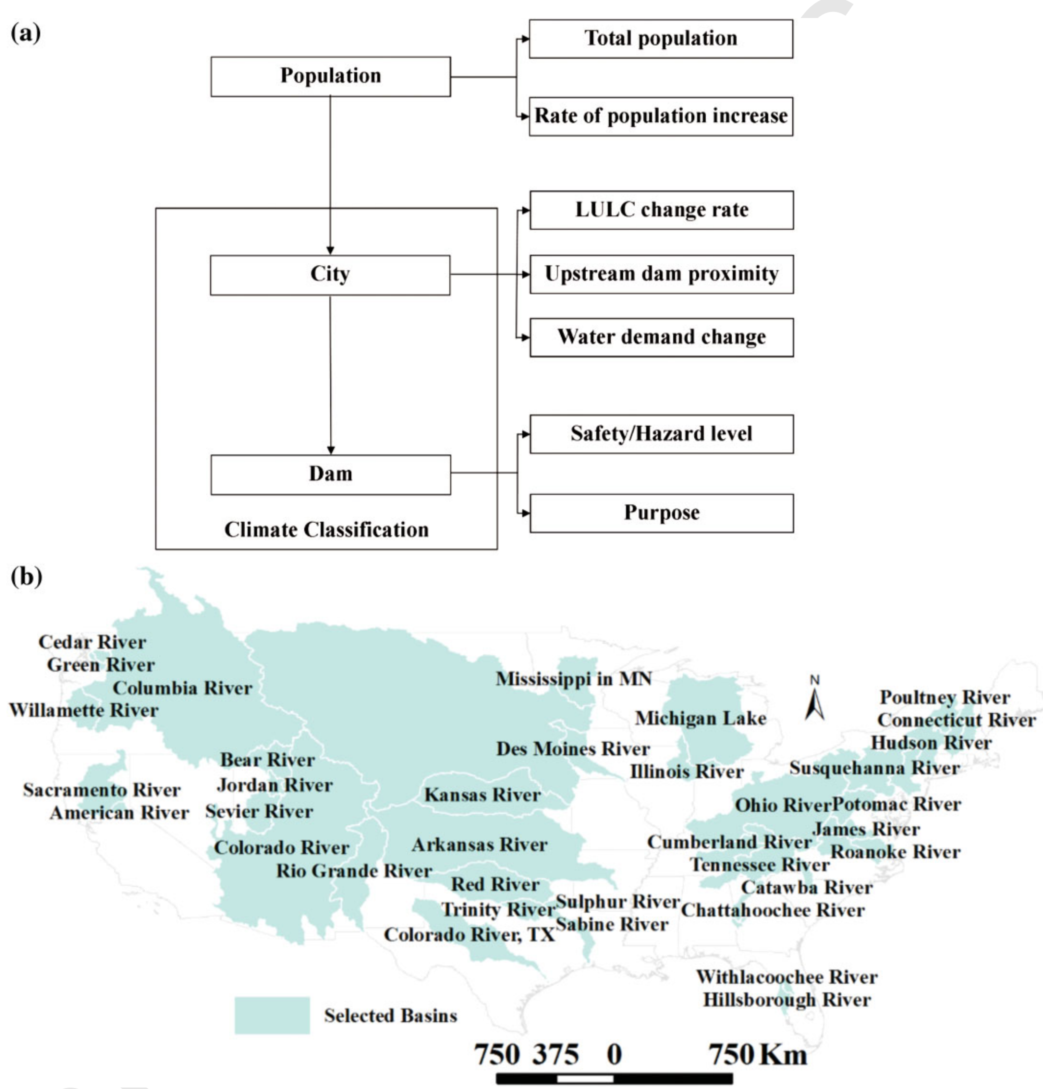


Figure 1. Study area selection flowchart (a) and selected river basins (b).

Hydrology data (runoff) on surface water availability that were simulated by the Variable Infiltration Capacity (VIC) hydrologic model [*Liang et al.*, 1994, 1996] using climate model projection data were used from the World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project phase 5 (CMIP5) multi-model dataset [*Maurer et al.*, 2007] (Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections archive at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/). The climate projections were downscaled using two statistical approaches, Bias-Correction Spatial Disaggregation (BCSD) and Bias-Correction Constructed Analogues (BCCA). The BCSD technique was used for the CMIP5 streamflow and runoff projections over the CONUS. Weather results from BCSD technique were forced through VIC to simulate grid-based runoff using water balance approach. Infiltration process for each grid is estimated using the Nanjing model. A detailed description of CMIP5-related results can be found in *Taylor et al.* [2012], *Meehl et al.* [2009], *Meehl and Hibbard* [2007], and *Brekke* [2014]. The temporal coverage for the climate (retrospective and projection) data was from 1950 to 2099 with a spatial resolution of 1/8 degree. These runoff data (mm/d) were available in streamflow form that had been routed on selected stations by the National Center for Atmospheric Research (NCAR) and West-Wide Climate Risk Assessments (WWCRA). The streamflow data available covered only those areas west of the Mississippi River.

The Representative Concentration Pathways (RCPs) are greenhouse gas (GHG) concentration representative trajectories in the form of radiative forcing were placed into five categories: RCPs, RCP2.6,

Table 1. Representative Concentration Pathways (RCPs) With Equivalent CO_2 Emission

	Equivalent CO_2 Emission, ppm (Estimate) Year			
RCP Scenarios	2000	2010	2050	2100
2.6	367	396	458	433
4.5	367	396	500	583
6	367	396	533	733
8.5	367	396	633	1233

RCP4.5, RCP6, and RCP8.5. Since these values are concentrations they can be represented equivalently using carbon concentration. Emissions will rise and decline on different time periods according to these GHG concentration assumptions. The RPC2.6, RPC4.5, and RPC6 assume a stable concentration in the years 2020, 2040, and 2080, respectively; while RCP8.5 increases beyond 2100 [*Meinshausen et al.*, 2011]. Equivalent CO_2 emission for these RPCs is provided in Table 1. Detailed RCP descriptions are available AQ4 from, e.g., *Fujino et al.*, 2006; *Rao and Riahi*, 2006; *Smith and Wigley*, 2006; *Riahi et al.*, 2007]. Out of the available climate model results, this study used only those models from the United States, specifically the CMIP5 multi-model ensemble from the NASA Goddard Institute for Space Studies (giss-e2-r-, ftp://gdo-dcp.ucllnl.org/pub/dcp/archive/cmip5/hydro/ascii/BCSD_daily_tgz/).

3.2. Methodology

In identifying population and urbanization increase rates, the annual percentage increase in population census and urban areas (change in developed area) from successive years were used. For population rates, only three successive years were used, 2010–2013. Urbanization data used rate changes from 1992 to 2011. Water demand data analyzed were on a 5-year interval from 1985 to 2010. Quantification of the exact future water demand was challenging due to uncertainties in the involved parameters. However, a simple forecast estimate of water demand was made based on direct proportionality with the population increase rate and keeping per-capital use constant. This approach excluded any impact by urban water use and any per-capita water use variation, which would require a further detailed study as comprehensive as the one reported here.

Past and forecasted streamflow/runoff was analyzed on three temporal scales, monthly, yearly, and seasonal. These variable scales allowed us to understand water availability at different time scales, which can help water resources management from design to general policy making. The seasonal periods used were, DJF (December–January–February), MAM (March–April–May), JJA (June–July–August), and SON (September–October–November). The selected climate model results were divided into three periods: 1950–2004, 2005–2049, and 2050–2099 representing past, near future, and distant future, respectively. The future trends were divided into two so that possible trends are not temporally lumped together. The streamflow data were available at station locations and runoff fluxes from VIC were on a grid-based format. Hence, the trend analyses for the three selected periods were performed accordingly at stations AQ5 and grid by grid over CONUS. The non-parametric Mann–Kendall [*Mann*, 1945; *Kendall*, 1975] trend test was implemented at the 95% significance level ($\alpha = 0.05$) to define trends for the selected periods. In this method the null hypothesis of no trend was tested using the selected significance level and probability threshold ($P < 0.05$).

4. Results

4.1. Population, Urbanization, and Water Demand Trend

LULC rapidly changed for cities in the Midwest, West, and Southwest CONUS as urbanization changed over the years. Urbanization here represented the change of land into developed areas according to NLCD between 1992 and 2011. Population and urbanization were presented separately to state the impact each has on climate change and/or water demand. It is argued here that when more land is developed, watershed hydrology (land–atmosphere interaction) is altered. Conversely, when population increases with less change in lateral developed area (high density), the impact will be more on water demand than

Table 2. Urban Area Expansion of Selected Cities Between 1992 and 2011

City	State	Urban Area Change % From 1992	
		To 2001	To 2011
Frisco	TX	85	118
McKinney	TX	51	63
El Paso	TX	9	30
Henderson	NV	39	23
Phoenix	AZ	13	23
Louisville	KY	1	3
Milwaukee	WI	0	3
New York	NY	0	3
Philadelphia	PA	1	3
Portland	OR	1	2

the physical watershed hydrology. Close to 50% of the selected cities showed more than a 10% increase in urbanization (developed area) between the years 1992 and 2011. The fastest growing cities were found in Texas, Arizona, Nevada, and New Mexico. Frisco, McKinney, and El Paso expanded by 118%, 63%, and 30%, respectively, between 1992 and 2011 (Table 2). Considering the CONUS, about 0.4% of land was developed into urban areas between 2001 and 2011. Meanwhile, population increases in these cities were rapid compared to urban development resulting in an increase in population density. For example, three cities—Frisco, McKinney, and Midland grew in population by about 15%, 12%, and 11%, respectively, between 2010 and 2013 (Figure 2). It is worth noting that from a water resources management aspect, total population has to be considered as well. The fastest growing cities identified in this study have a total population greater than 100,000 as of 2013 census.

Due to unavailability of city-based data, only county-based surface water use (withdrawal) data from the USGS was analyzed. By considering the counties where the selected cities were situated, an increase in water use as high as 75% and a decrease as low as 40% was observed between 2005 and 2010 (Table 3). Most of the counties with an increase in water use were found in the Southwestern States of Arizona and Texas. Some counties in the Western, Central, Northern, and Eastern States, California, Washington, and Missouri, exhibited a decreasing trend. However, it can be argued that the decrease found in the selected areas could be attributed to two options. The first could be the way water use data were collected which did not account for all water use (e.g., commercial and power withdrawals). The second and more important reason could be water management policies and physical water availability. That is the decrease in "supply" from surface water sources and policies imposed by state and local officials could have contributed to a decrease in water use. Recent events in Western and Southwestern States is a testament to these cases. California has imposed mandatory restrictions on water use for the fourth consecutive year since 2011 to tackle its water shortage (https://www.gov.ca.gov/docs/4.1.15_Executive_Order.pdf).

Quantification of future water demand (use) is difficult given uncertainties in the parameters involved, socioeconomic (population and urbanization), climate, and policy changes. However, quantification can be estimated using the rate at which a population is changing. Here, the rate of population increase was used to estimate future water requirements for selected cities. Results of population census analyses showed an increase in population as high as 15% in 3 years. The USGS estimates the per-capita water use in the United States to be between 303 and 379 L per day. Average water use results estimated an annual increase in water use rates as high as 2513×10^6 L/d and as low as 4×10^6 L/d for New York City, NY and Evansville, IN, respectively (Table 4). A high increase in daily demand was evident for cities in Western and Southwestern States. These future estimates indicated the combined impact of total population and annual population growth rates on future water use.

4.2. Streamflow Trend

The non-parametric Mann–Kendall test was performed on three temporal windows (periods): 1950–2004 (past), 2005–2049 (near future), and 2050–2099 (distant future) for streamflow results. The period

10.1002/2016EF000393

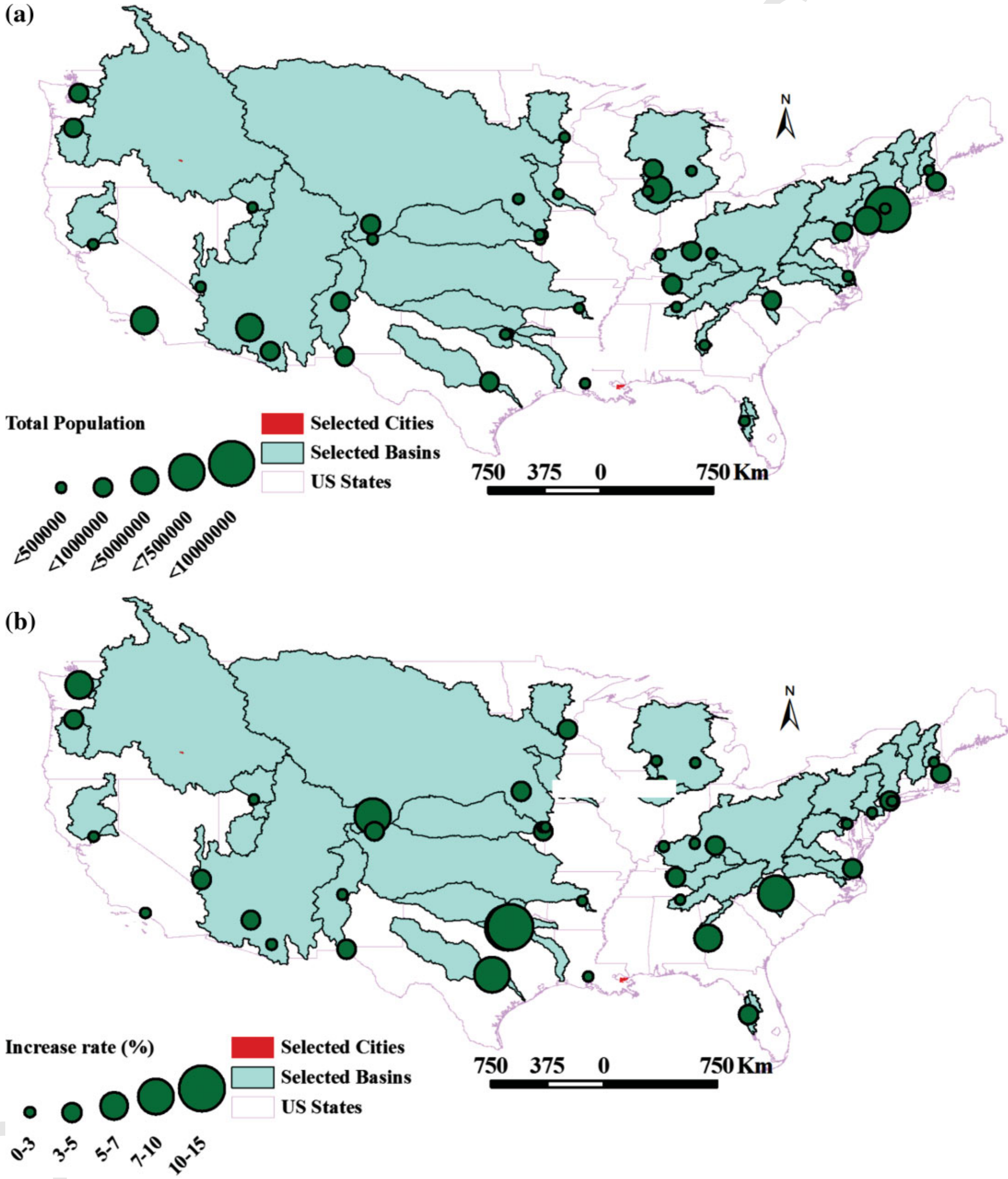


Figure 2. Total population of selected cities (a) and population growth rate between 2010 and 2013 (b).

1950–2004 represented base years for the climate models. Showing the results here would only present model performance, which is not the objective of this manuscript. Input data preparation, model set-up, and calibration can be found at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5 HydrologyMemo.pdf.

These three periods were further divided into annual trend (trend of annual daily runoff), monthly trend (trend of monthly daily runoff), and seasonal trend. The seasonal trends were divided into DJF, MAM, JJA, and SON. Further, the analyses used all four scenario projections (RCP2.6, RCP4.5, RCP6, and RCP8.5). Analyzing four of the climate scenarios can provide guidance to engineers and policymakers on the range of adaptation strategies to explore for their feasibility. Considering annual average streamflow values, Period 1 showed no streamflow change at most of the stations considered for all four climate scenarios. However, stations in the upstream Missouri River and downstream Arkansas River exhibited a decreasing trend. Significant trends were observed for RCP6 when considering Period 2 (Figure 3a). The increasing trend for RCP6

Table 3. Water Use Change in Selected Counties Between 2005 and 2010

State	County	Water Use ($L \times 10^6$/d) 2005	2010	% Increase (2005–2010)	Absolute Fresh Water Availability Index [After *Padowski and Jawitz*, 2012]
CO	Denver	893	564	−37	0.39
CA	Los Angeles	12,579	8229	−35	0.05
CO	El Paso	492	348	−29	0.07
MD	Baltimore	3131	2483	−21	0.26
UT	Salt Lake	901	1147	27	0.05
WI	Milwaukee	4614	6624	44	0.52

USGS, U.S. Geological Survey statistics.
Data from the USGS.

Table 4. Estimated Annual Water Use Increase Over Selected Cities Using a 341 L/Person/d Usage

City	Population % Change 2010–2013	Average Annual Water Use Increase ($L \times 10^6$/d)
New York, NY	2.63	2513
Los Angeles, CA	2.33	1029
Austin, TX	8.60	867
Phoenix, AZ	4.42	761
Charlotte, NC	7.33	659
Denver, CO	7.64	564
Seattle, WA	6.90	511
Kansas City, KS	1.68	26
Aurora, IL	0.91	19
Baltimore, MD	0.14	11
Manchester, NH	0.70	8
Evansville, IN	0.20	4

was more evident for the West (Sacramento River), Pacific Northwest (Colombia River), and The Great Plains (Missouri River, Colorado River). Most stations exhibited an increasing trend for the case of RCP6 with no change in most areas for the cases of RCP2.6, RCP4.5, and RCP8.5. An increasing trend is observed for the case of RCP8.5 at few stations found in Arkansas River. For Period 3, the trends in RCP2.6 remained the same as Period 2 except for an increasing trend at a few stations downstream of the Arkansas River. Upstream sections of the Columbia River showed an increase for the case of RCP4.5 and RCP8.5. However, the RCP6 scenario nearly reversed its trend from Period 2 as shown in Figure 3b. Sacramento, Colorado, Columbia rivers, and upstream of the Missouri and Platte River experienced a decreasing trend in streamflow. A comparison of streamflow and runoff trends was made for west of The Mississippi. This comparison showed that the trends followed by runoff and streamflow were similar which is assumed to be reasonably representative of the rest of Mississippi.

A finer temporal scale shows a better response of streamflow to climate change scenarios over the selected periods. Similarly, the monthly average streamflow for Period 1 demonstrated a decreasing trend in upper portions of the Missouri, Snake, and Platte Rivers, downstream of the Kansas and Arkansas Rivers regardless of the climate change scenario. However, some stations in the Colorado River showed an increasing trend. Most stations demonstrated no trend in this period. Given the lumped temporal approach which considers 55 years of data in one period, this result is consistent with actual observations in the past which showed a decrease in the Western and Central parts of the CONUS. In contrast to Period 1, the results of monthly streamflow values for Period 2 showed no trend for most parts and an increase in the Missouri, Kansas, and Arkansas Rivers for the RCP2.6 scenario. In the case of RCP4.5, upstream sections of the Missouri, Snake, and

10.1002/2016EF000393

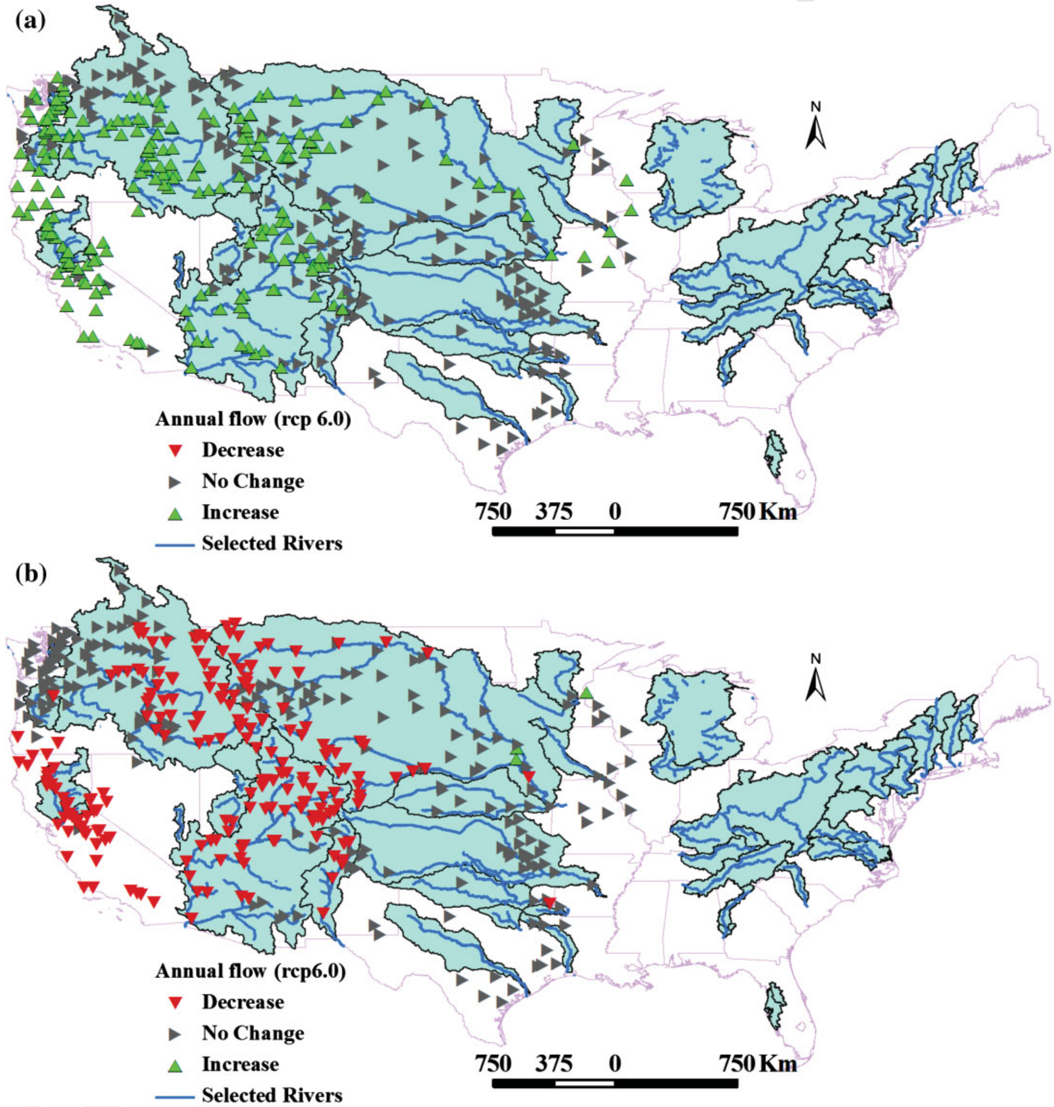


Figure 3. Trend of annual streamflow on selected stations for the RCP6 scenario for period 2 (2005–2049, a) and period 3 (2050–2099, b).

Mississippi Rivers demonstrated an increasing trend while upstream of the Colorado and Rio Grande Rivers experienced a decrease. Results from RCP6 showed an increase in most stations except those stations downstream of the Red and Sabine Rivers. The Rio Grande, Sabine, Arkansas, Kansas, and Red Rivers showed an increasing trend while most parts remain unchanged for the RCP8.5 scenario. Period 3 revealed a no trend result for most stations for RCP2.6, RCP4.5, and RCP8.5. However, a considerable number of stations in California (Sacramento and San Joaquin Rivers) and the upstream Colorado and Platte Rivers experienced a decreasing trend. According to the RCP6 scenario, all stations showed a decreasing trend in monthly streamflow.

The next temporal scale to consider after annual and monthly averages was seasonal trend for Periods 2 and 3 for different climate change scenarios. The winter season (DJF) showed no change in streamflow trends for most stations except for an increase over the entire Missouri River for RCP2.6 and RCP6, downstream of the Arkansas River for RCP8.5, and most parts of the Snake, Sacramento, Colorado, and Rio Grande Rivers for the RCP6 scenario. During the spring period (MAM), the Missouri River saw an increase for RCP2.6 and RCP4.5. The Snake, upstream Colorado, and Rio Grande Rivers as well as western portions of California and Oregon experienced an increase for the RCP6 scenario. The Columbia, Snake, Colorado, Platte, Kansas, and Yellowstone Rivers pointed to an increase in streamflow in the case of RCP8.5. Summer season (JJA) streamflow trends remained unchanged for all scenarios except for an increase in the Snake, Columbia, and upstream Missouri Rivers for RCP6 and a decrease in downstream Columbia and other rivers in Washington (Chehalis, Green, Nisqually Rivers) for the RCP8.5 scenario. Streamflow showed no trend for the majority of the fall season (SON) except for an increase in the RCP4.5 and RCP6 cases for western Oregon, Washington (including the Columbia and Snake Rivers) and northwestern California. The Arkansas and Sabine River exhibited an increase for the RCP8.5 scenario.

Seasonal changes in Period 3 demonstrated a consistency in decreasing trend for RCP6 only with spatial variations. During the winter in this period, most stations indicated no change in trend except for an increase in upstream Columbia and Snake Rivers for RCP4.5 and the Missouri River for that of RCP8.5. The Snake, Columbia, Missouri, and upstream Colorado Rivers experienced a decreasing trend for RCP6. The spring season (MAM) exhibited an increase for the Spokane River for both RCP2.6 and RCP8.5 and the upstream Yellowstone, Kansas, and Colorado Rivers for RCP8.5. The Central Valley in California, the entire Colorado, and Rio Grande Rivers showed a decreasing trend for the case of RCP6 and RCP8.5 (only the Central Valley). The trend during summer season showed no change for the cases of RCP2.6 (except the increase in the Missouri and Sabine Rivers) and RCP4.5. The entire Central Valley, Snake, and Colorado Rivers experienced a decrease in this period for RCP6 and RCP8.5 (including rivers west of the Cascade Range in Washington and Oregon). During the fall season (SON), most stations indicated unchanged trends for the RCP2.6, RCP4.5, and RCP8.5 cases. The Colombia, Snake, Colorado, upstream Missouri, Yellowstone, and Kansas Rivers showed a decreasing trend for the RCP6 case.

4.3. Runoff Trend

The same methodology used in analyzing streamflow trends was applied for runoff fluxes from the VIC model. The *P*-values from the trend test, indicating significance level, are summarized in Table 5. Past trends (Period 1) for annual average runoff demonstrated no trend in most areas and decreasing annual average

Table 5. Summary of *P*-Values From the Mann–Kendall Test

			P Value							
			RCP2.6		RCP4.5		RCP6		RCP8.5	
Period	Scale		Min	Max	Min	Max	Min	Max	Min	Max
1 (1950–2004)	Monthly		0.000	0.050	0.000	0.050	0.000	0.050	0.000	0.050
	Annual		0.006	0.049	0.004	0.049	0.005	0.049	0.007	0.049
	Seasonal	DJF	0.000	0.049	0.027	0.049	0.002	0.049	0.002	0.049
		MAM	0.011	0.049	0.005	0.049	0.009	0.049	0.010	0.049
		JJA	0.000	0.049	0.000	0.049	0.000	0.049	0.000	0.049
		SON	0.001	0.049	0.000	0.049	0.001	0.049	0.001	0.049
2 (2005–2049)	Monthly		0.000	0.050	0.000	0.050	0.000	0.050	0.000	0.050
	Annual		0.000	0.049	0.001	0.049	0.000	0.049	0.000	0.049
	Seasonal	DJF	0.002	0.049	0.003	0.049	0.000	0.049	0.001	0.049
		MAM	0.005	0.049	0.000	0.049	0.002	0.049	0.008	0.049
		JJA	0.004	0.049	0.000	0.049	0.005	0.049	0.001	0.049
		SON	0.001	0.049	0.002	0.049	0.000	0.049	0.000	0.049
3 (2050–2099)	Monthly		0.000	0.049	0.000	0.049	0.000	0.049	0.000	0.049
	Annual		0.000	0.049	0.003	0.049	0.001	0.049	0.000	0.049
	Seasonal	DJF	0.009	0.049	0.008	0.049	0.001	0.049	0.007	0.049
		MAM	0.000	0.049	0.001	0.049	0.000	0.049	0.001	0.049
		JJA	0.000	0.049	0.008	0.049	0.010	0.049	0.004	0.049
		SON	0.007	0.049	0.001	0.049	0.009	0.049	0.000	0.049

DJF, December–January–February; JJA, June–July–August; MAM, March–April–May; RCP, Representative Concentration Pathways; SON, September–October–November.

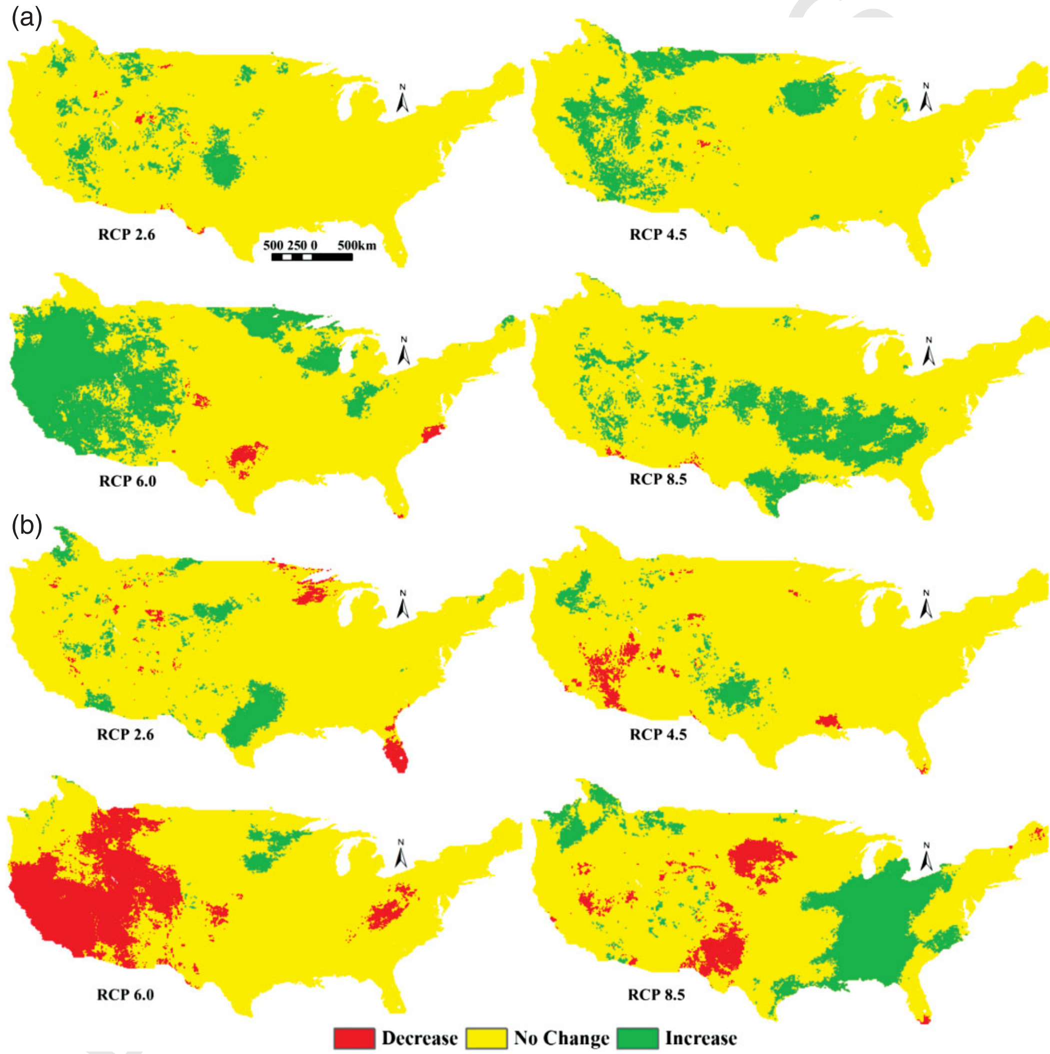


Figure 4. Trend of annual average runoff (mm/d) for period 2 (2005–2049, a) and period 3 (2050–2099, b).

runoff in areas west of Sierra Nevada (Nevada, Arizona, and Utah) and the central United States. There was no significant spatial variation in this decreasing trend over CONUS regardless of the scenarios considered. Northern parts of Arizona, central Utah, and Texas had an increase in runoff over this period. This result was similar to streamflow trend considering the same temporal window and scale.

In the case of Period 2 (Figure 4a), runoff fluxes increased over significant parts of the CONUS especially for RCP4.5 and RCP6. While most parts showed no trend in this period, some portions of Texas and Colorado showed a decreasing trend for the RCP6 scenario. During Period 3, runoff is affected by the climate model scenario (Figure 4b). For the case of RCP2.6, most areas remain unchanged while Wisconsin and FL experienced a decreasing trend and an increase was observed in areas of Texas, Wyoming, and Montana (Missouri Basin). Nevada and some areas of Louisiana (part of the Mississippi River Basin) showed a decreasing trend for the case of RCP4.5 while at the same time, northwest Texas and West Oregon (Columbia River Basin) displayed an increasing trend. A considerable area in the Western and Central parts of CONUS and a few areas along the west Appalachian (Kentucky and West Virginia) experienced a decrease in runoff for the case of RCP6. East tributaries of the Mississippi River (Ohio, Tennessee, and Cumberland Rivers) showed an increase in runoff for the case of RCP8.5 during Period 3.

Monthly runoff response displayed the signature of the annual trend, but with more spatial variability. During Period 1, the runoff in most parts of CONUS remained unchanged while a decreasing trend was noted for Western (east of the Cascade Range and Sierra Nevada) and Midwestern areas (contributing to

10.1002/2016EF000393

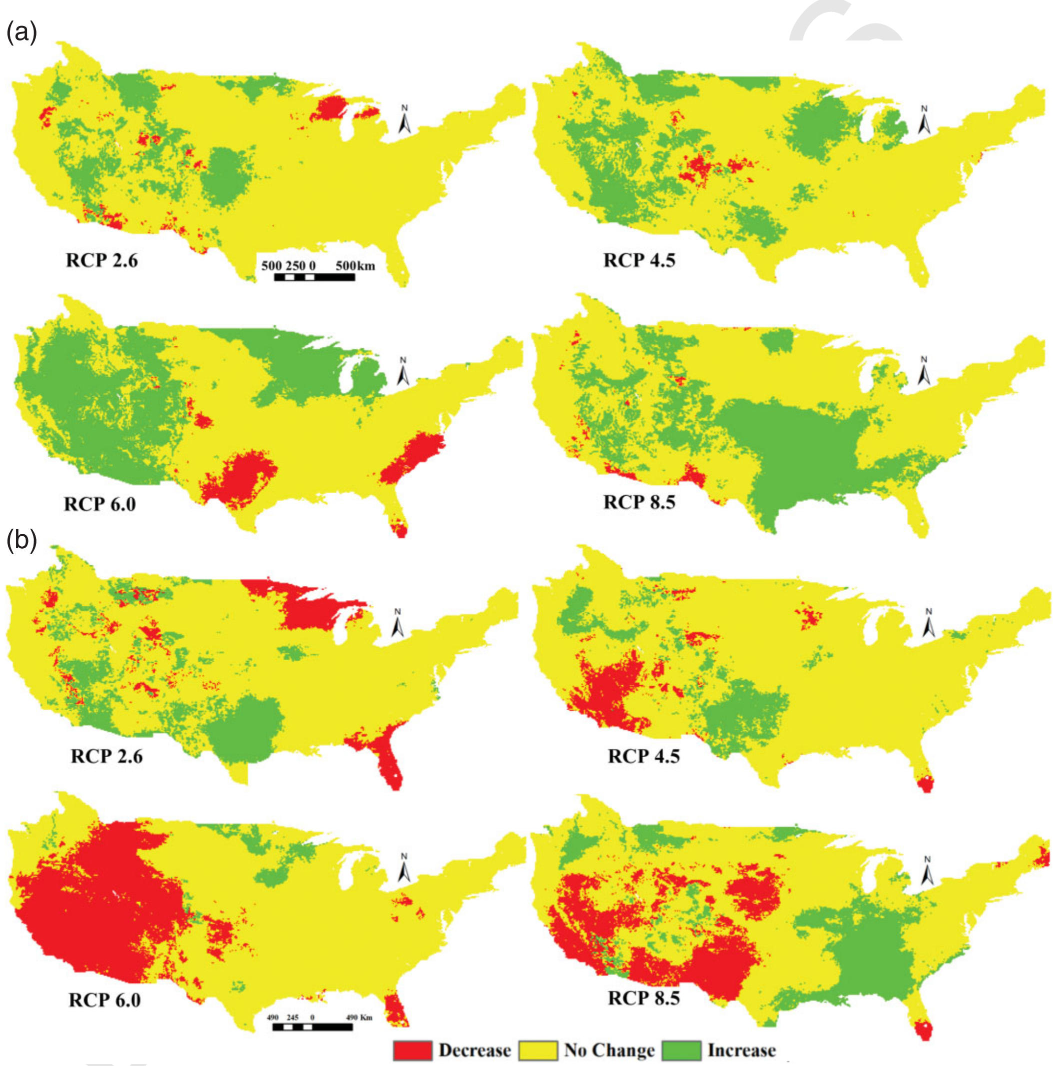
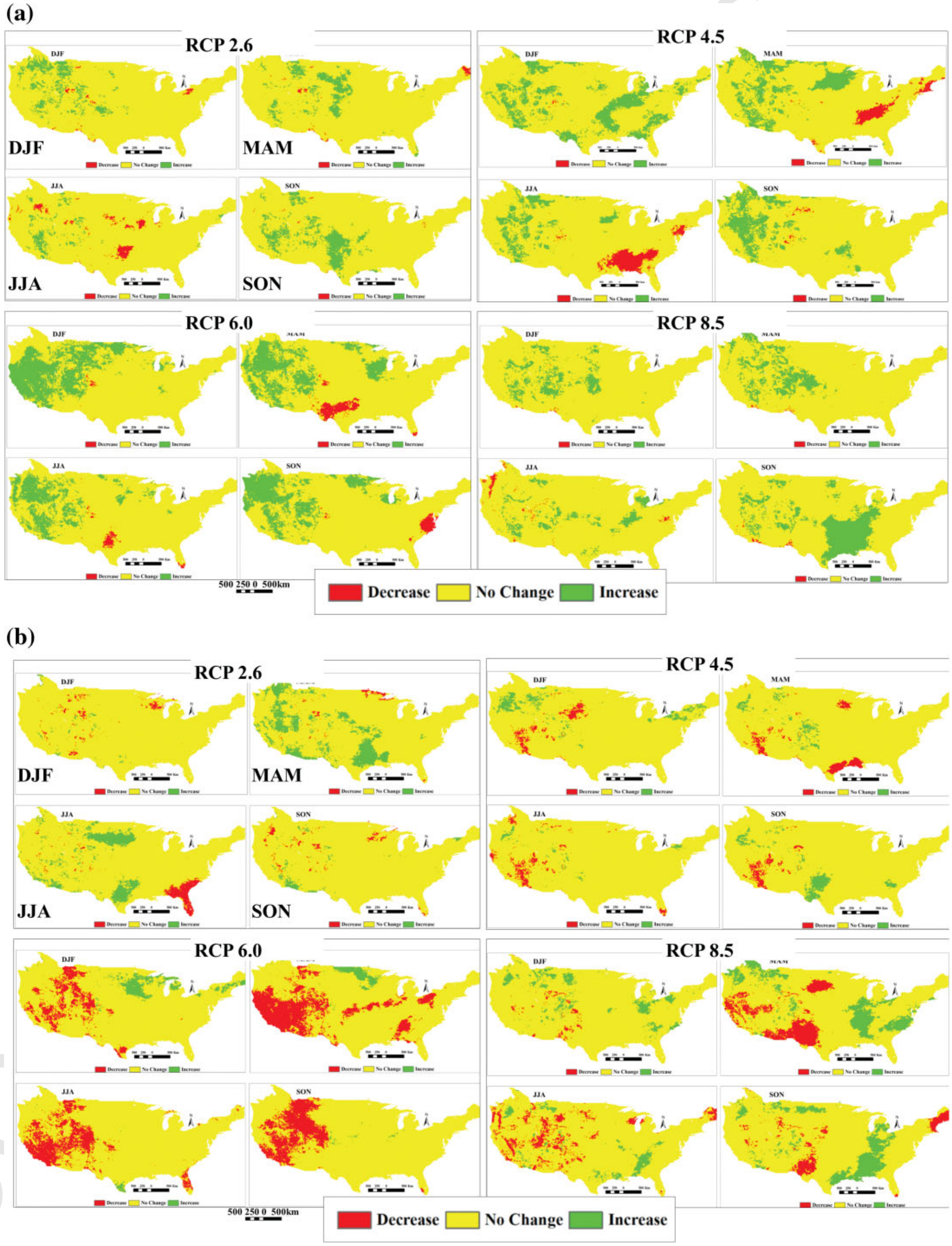


Figure 5. Trend of monthly average runoff (mm/d) for period 2 (2005–2049, a) and period 3 (2050–2099, b).

the Missouri, Arkansas, and Kansas Rivers). Areas in eastern Texas and the Appalachians (Tennessee, The Carolinas) showed an increasing trend as did areas in Arizona and Utah (contributing to Colorado River Basin). Period 2 showed promise for increases in runoff for most part of CONUS except areas in Texas, The Carolinas, Georgia, and FL during case RCP6 (Figure 5a). The RCP8.5 scenario resulted in a spatial shift in increasing runoff from the West to South and Southcentral CONUS. Results from Period 3 showed diverse spatial trends for the four scenarios (Figure 5b). For RCP2.6, West, Central, and South CONUS experienced an increase and part of the Upper Mississippi (Minnesota and Wisconsin) and FL showed a decreasing trend. Most parts of the Colorado River displayed a decrease in runoff for the RCP4.5 scenario; areas contributing to the Snake (and Columbia) Rivers, west Texas (Red and Colorado Rivers) pointed distinctly to an increasing trend. West CONUS and FL were highly affected by a decreasing runoff trend considering the RCP6 scenario. Similar to the annual runoff case, areas contributing to the Mississippi from the east (Ohio, Tennessee, and Cumberland Rivers) exhibited an increase in runoff during the RCP8.5 scenario.

Seasonal variations of runoff for Period 1 (1950–2004) depicted a decreasing trend for some parts of West and Central CONUS. The areas affected in the decreasing trend extended further east during the summer season (JJA) regardless of the different scenarios considered. Period 2 (2005–2049) of the seasonal analysis indicated increasing runoff over sporadic areas of the West and Central CONUS (Figure 6a). However, spring and summer seasons presented a noticeable decrease in runoff for locations in Eastern and Southern CONUS especially for the case of RCP4.5. A decreasing runoff trend dominated West CONUS for RCP6 and

10.1002/2016EF000393



AQ6

Figure 6. Trend of seasonal average runoff (mm/d) for period 2 (2005–2049) (a) and trend of seasonal average runoff (mm/d) for period 3 (2050–2099) (b).

RCP8.5 scenarios during Period 3 (2050–2099, Figure 6b). Some areas in West and Central CONUS showed an increasing trend during the spring and summer season of the RCP2.6 scenario; the RCP8.5 scenario extended these areas to Central and East CONUS (areas contributing Mississippi River).

4.4. Summary

Population and urbanization are increasing at a considerable rate for most western (California, Oregon, and Washington) and southwestern (Arizona, Texas) states. This increase has contributed to a direct increase in water demand stressing the importance of considering total population and its growth rate. Comparing temporal scales, it can be seen that more areas are affected by monthly runoff and streamflow than annual averages. On the seasonal scale for some cases, the greatest decrease observed was during the summer (JJA) and spring (MAM) seasons . The trend intensity was higher (regardless of trend direction) for the RCP6 scenario, which assumes a stable GHG concentration by 2080. Decreasing and increasing trends seemed to follow geographical signatures like a specific state or feature (Sierra Nevada and Cascade Range; Great Plains; Appalachians). Influence of a geographical feature was also evident from the results as the Great Plains and the leeward side of Sierra Nevada and the Cascade Range showed a decreasing water trend pattern. Rapidly growing cities identified in this study were found in states that border an ocean, which would point to an evitable water supply solution that can be supplemented by desalination. However, the cost effectiveness of desalination should be analyzed against the option of virtual water transfer, especially in considering water supply for agricultural purposes (green virtual water transfer).

5. Conclusion

Urbanization comes with an increasing population, which drives water demand. Every data analyzed in this study emphasized the challenge of water resources availability at a scale ranging from a city to a basin as large as the Mississippi River. Temporally, water availability varied from monthly to annually and seasonally. The challenge for the United States is the physical scarcity given the extensive network of hydraulic structures and overall water resources management practice. However, this does not mean that further structural development that includes construction of dams, canals, and other water transfer systems should be restricted.

Climate change impacts (increase or decrease in water availability) were more apparent over the western and central parts of CONUS. This observation was made worse by the fact that accelerated urbanization and population increases dominated these regions compared to other parts of the United States. The per-capita water demand increased with a higher annual rate. Water supply sources in these areas were a combination of surface and groundwater. A discontinuity (imbalance) in the hydrologic cycle can drive some areas to an irreversible water availability pattern. One of the main reasons for imbalance is a decrease in surface water availability that led to a depleted groundwater reserve (due to less recharge and excessive withdrawals). Based on the above three scenarios (RCP4.5, RCP6, and RCP8.5), the Columbia and Colorado Rivers should be given special attention to identify structural and policy-based solutions to a decreasing trend in water availability.

Climate model results have uncertainties across all model types. Even results from a specific model are based on different assumptions assuming an anticipated climate change direction. However, the best argument would be to integrate model results cautiously with present water use practice and future water resource management policy. Both structural and policy (non-structural) based solutions are recommended for future water shortages over the CONUS. The Central Arizona Project, Colorado River, and Los Angeles Aqueducts are good examples that this study addresses for sustainable water resource management. Solutions for specific cities will depend on technical and economic feasibility. The scenario-based results used in this study (RCP2.6, RCP4.5, RCP6, and RCP8.5) can be represented using "policy" (policies that affect the direction of climate change and water consumption) as proxy. That is, the direction of climate change is dependent on which path (scenario) is followed.

Generally, cities (regions) that are in the Arid and Warm Temperature Koeppen-Geiger climate classification face a greater water shortage than other areas in CONUS. A constant water demand was assumed in this study, however, there is encouraging steps from cities around the country to reduce per-capital consumption. The Mississippi River has a mixed response to future anticipated water requirements with most of its tributaries showing an increase, especially in the Arkansas and Red, and Ohio Rivers. A recent study released by the USGS indicated that water demand by the year 2062 will surpass current supply if urbanization continues at current rates [*Wilson et al.*, 2016]. The Central Valley of California will also experience a decrease in water availability. Cities in California and Arizona (e.g., City of Los Angeles and surrounding areas, Phoenix, and Tucson) are at greater risk because their surface water is imported from the distant Colorado River. Coincidentally, the population in these areas is increasing which means the problem of water scarcity is more serious than water availability results show. For example, New York City has hydrological steady water availability, however, annual water demand increases as a result of population growth and that is not evident in the climate models. Cities on the West Coast, Southeastern CONUS, and FL are beginning to supplement surface and groundwater with a desalination-based water supply system. To supplement this physical water supply, policy toward water usage and conservation has to be augmented so that water demand and losses are minimized. These cities in the Central and Northeastern CONUS have to adopt the policy of multi-dimensional water conservation, which would minimize demand (domestic, agricultural, power). Unless a country adopts a specific policy toward resilient and sustainable water resource management, abundant climate model results will have little impact on improving water sustainability of United States cities. These policies can range from local to regional, and to national.

Acknowledgments

The first author was supported by a grant from the NASA Earth System Science (NESS) Fellowship Program (NNX13AN73H). The data used are listed in the references, tables, and supplements can also be requested from the first author via email. We acknowledge the World Climate Research Program Working Group on Coupled Modeling, which is responsible for CMIP. We thank NASA Goddard Institute for Space Studies (GISS) for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Inter-comparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

References

Arnell, N. W., D. P. van Vuuren, and I. Morna (2011), The implications of climate policy for the impacts of climate change on global water resources, *Glob. Environ. Change*, *21*(2), 592–603, doi:10.1016/j.gloenvcha.2011.01.015.

Averyt, K., J. Meldrum, P. Caldwell, G. Sun, S. McNulty, A. Huber-Lee, and N. Madden (2013), Sectoral contributions to surface water stress in the coterminous United States, *Environ. Res. Lett.*, *8*(3), 035046, doi:10.1088/1748-9326/8/3/035046.

Brekke, L. (2014), Errata for "Downscaled CMIP3 and CMIP5 climate and hydrology projections: Release of hydrology projections, comparison with preceding information, and summary of user needs".

Chapagain, A. K., and A. Y. Hoekstra (2008), The global component of freshwater demand and supply: An assessment of virtual water flows between nations as a result of trade in agricultural and industrial products, *Water Int.*, *33*(1), 19–32, doi:10.1080/02508060801927812.

Falkenmark, M., and C. Widstrand (1992), Population and water resources: A delicate balance, *Popul. Bull.*, *47*(3), 1–36.

Fujino, J., R. Nair, M. Kainuma, T. Masui, and Y. Matsuoka (2006), Multi-gas mitigation analysis on stabilization scenarios using AIM global model. Multigas mitigation and climate policy, *Energy J.*, *3*(Special Issue).

Haasnoot, M., H. Middelkoop, A. Offermans, E. Van Beek, and W. P. A. van Deursen (2012), Exploring pathways for sustainable water management in river deltas in a changing environment, *Clim. Change*, *115*(3–4), 795–819, doi:10.1007/s10584-012-0444-2.

Huntjens, P., et al. (2011), Adaptive water management and policy learning in a changing climate: A formal comparative analysis of eight water management regimes in Europe, Africa and Asia, *Environ. Policy Gov.*, *21*(3), 145–163, doi:10.1002/eet.571.

Kates, R. W., W. R. Travis, and T. J. Wilbanks (2012), Transformational adaptation when incremental adaptations to climate change are insufficient, *Proc. Natl. Acad. Sci. U. S. A.*, *109*(19), 7156–7161, doi:10.1073/pnas.1115521109.

Kendall, M. G. (1975), *Rank Correlation Methods*, Griffin, London.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges (1994), A simple hydrologically based model of land surface water and energy fluxes for GSMs, *J. Geophys. Res.*, *99*(D7), 14415–14428, doi:10.1029/94JD00483.

Liang, X., E. F. Wood, and D. P. Lettenmaier (1996), Surface soil moisture parameterization of the VIC-2L model: Evaluation and modifications, *Global Planet. Change*, *13*, 195–206, doi:10.1016/0921-8181(95)00046-1.

Mann, H. B. (1945), Nonparametric tests against trend, *Econometrica*, *13*, 245–259, doi:10.2307/1907187.

Maurer, E. P., L. Brekke, T. Pruitt, and P. B. Duffy (2007), Fine-resolution climate projections enhance regional climate change impact studies, *Eos Trans. AGU*, *88*(47), 504, doi:10.1029/2007EO470006.

Meehl, G. A., and K. A. Hibbard (2007), A strategy for climate change stabilization experiments with AOGCMs and ESMs, *WCRP Informal Rep. No. 3/2007, ICPO Publ. No. 112, IGBP Rep. No. 57*, 35 pp., World Clim. Res. Programme, Geneva, Switzerland.

Meehl, G. A., et al. (2009), Decadal prediction. *Bull. Am. Meteorol. Soc.*, *90*, 1467–1485, (doi:10.1175/2009bams2778.1).

Meinshausen, M., et al. (2011), The RCP greenhouse gas concentrations and their extensions from 1765 to 2300, *Clim. Change*, *109*(1–2), 213–241, doi:10.1007/s10584-011-0156-z.

Mickley, M. (2012), US municipal desalination plants: Number, types, locations, sizes, and concentrate management practices, *IDA J. Desalination Water Reuse*, *4*(1), 44–51, doi:10.1179/ida.2012.4.1.44.

National Research Council (NRC) (2004), *Committee on Assessment of Water Resources Research. Confronting the Nation's Water Problems: The Role of Research*, Natl. Acad. Press, XXX.

Padowski, J. C., and J. W. Jawitz (2012), Water availability and vulnerability of 225 large cities in the United States, *Water Resour. Res.*, *48*, W12529, doi:10.1029/2012WR012335.

Rao, S., and K. Riahi (2006), The role of non-CO_2 greenhouse gases in climate change mitigation: Long-term scenarios for the 21st century. Multigas mitigation and climate policy, *Energy J.*, *3*(Special Issue), 177–200.

Riahi, K., A. Gruebler, and N. Nakicenovic (2007), Scenarios of long-term socio-economic and environmental development under climate stabilization, *Technol. Forecast. Soc. Change*, *74*(7), 887–935, doi:10.1016/j.techfore.2006.05.026.

Seckler, D., R. Barker, and U. Amarasinghe (1999), Water scarcity in the twenty-first century, *Int. J. Water Resour. Dev.*, *15*(1–2), 29–42, doi:10.1080/07900629948916.

Smith, S. J., and T. M. L. Wigley (2006), Multi-gas forcing stabilization with the MiniCAM, *Energy J.*, (Special Issue #3), 373–391.

Sun, G., S. G. McNulty, J. A. M. Myers, and E. C. Cohen (2008), Impacts of multiple stresses on water demand and supply across the Southeastern United States, *J. Am. Water Resour. Assoc.*, *44*(6), 1441–1457, doi:10.1111/j.1752-1688.2008.00250.x.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl (2012), An overview of CMIP5 and the experiment design, *Bull. Am. Meteorol. Soc.*, *93*, 485–498, doi:10.1175/bams-d-11-00094.1.

U.S. Bureau of Reclamation (USGS) (2012), *Colorado River Basin Water Supply and Demand Study: Executive Summary*, USGS, Denver, Colo.

Vedachalam, S., and S. J. Riha (2012), Desalination in northeastern US: Lessons from four case studies, *Desalination*, *297*, 104–110, doi:10.1016/j.desal.2012.04.008.

Viviroli, D., et al. (2011), Climate change and mountain water resources: Overview and recommendations for research, management and policy, *Hydrol. Earth Syst. Sci.*, *15*(2), 471–504, doi:10.5194/hess-15-471-2011.

van Vliet, M. T., J. R. Yearsley, F. Ludwig, S. Vögele, D. P. Lettenmaier, and P. Kabat (2012), Vulnerability of US and European electricity supply to climate change, *Nat. Clim. Change*, *2*(9), 676–681, doi:10.1038/nclimate1546.

Wilson, T. S., B. M. Sleeter, and D. R. Cameron (2016), Future land-use related water demand in California, *Environ. Res. Lett.*, *11*(5), doi:10.1088/1748-9326/11/5/054018.