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Projecting Water Withdrawal and Supply for Future Decades in the U.S. under Climate Change Scenarios

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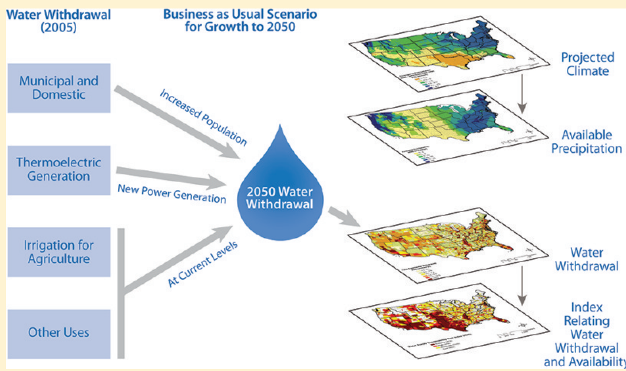
Supporting Information

ABSTRACT: The sustainability of water resources in future decades is likely to be affected by increases in water demand due to population growth, increases in power generation, and climate change. This study presents water withdrawal projections in the United States (U.S.) in 2050 as a result of projected population increases and power generation at the county level as well as the availability of local renewable water supplies. The growth scenario assumes the per capita water use rate for municipal withdrawals to remain at 2005 levels and the water use rates for new thermoelectric plants at levels in modern closed-loop cooling systems. In projecting renewable water supply in future years, median projected monthly precipitation and temperature by sixteen climate models were used to derive available precipitation in 2050 (averaged over 2040–2059). Withdrawals and available precipitation were compared to identify regions that use a large fraction of their renewable local water supply. A water supply sustainability risk index that takes into account additional attributes such as susceptibility to drought, growth in water withdrawal, increased need for storage, and groundwater use was developed to evaluate areas at greater risk. Based on the ranking by the index, high risk areas can be assessed in more mechanistic detail in future work.



INTRODUCTION

Human needs for water continue to grow with increasing population, primarily for direct consumption, but also secondarily for energy production, and agricultural and industrial activities. The sustainability of water resources, broadly defined as the maintenance of natural water resources in adequate quantity and with suitable quality for human use and for aquatic ecosystems, is adversely affected by these increasing demands. Over the coming decades, climate change, caused by the buildup of heat-trapping greenhouse gases in the atmosphere, is expected to be another stressor on water resources.[1−5] Using recent climate projections,[6] synthesis reports for the U.S. provide an overview of the hydrologic changes that might be expected due to climate change, which include continuing increases in extreme precipitation, intensification of droughts, acceleration of snowmelt, increased evaporation, and other effects, resulting in impacts to infrastructure, water availability, and aquatic ecosystems.[7−9] More geographically focused studies, using 21st century projected climate from one or more atmosphere-ocean general circulation models (AOGCMs or GCMs, also known as "global climate models") as input to hydrologic models, have been reported and are generally focused on changes in runoff in watersheds of different spatial extents.[10−13]

The assessment reported here adds to the general body of knowledge by providing region-specific information on the potential impacts of climate change on water resources across the U.S. using an index-based approach where water withdrawals for different human uses are compared to water availability. The analysis estimates local renewable water availability, under scenarios that consider potential changes in precipitation and temperature over a 20-year period centered around 2050 as projected by GCMs. The extent of climate change over this time frame is less severe than for projections of the end of the 21st century (or beyond), but was chosen because it is within the time horizon of most major infrastructure planning activities, especially related to water resources and energy production.

For the purpose of this analysis, we project future water withdrawals under scenarios of continued population growth

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and associated municipal/domestic water, electricity and cooling water demands, focusing on freshwater withdrawals from groundwater and surface water sources. Withdrawals refer to the quantity of water removed from a source for a given human use, a portion of which may be returned to the environment in aqueous form. Consumptive use refers to the fraction of water that is lost to the atmosphere. In this work we focus on withdrawal volumes, because this is the quantity of water that must be present in a water source to meet a current or future need, not just the consumptive use fraction. Water withdrawal projections are based on a water use survey reported by the U.S. Geological Survey (USGS) for 2005, which has been conducted every five years since the 1950s.[14] Population projections are based on Census Bureau estimates,[15] and electricity production estimates are from the Department of Energy.[16]

Using the 2005 withdrawal values, and making assumptions on water use per capita and water use per unit of electricity generated, we estimate future water demand growth as a result of additional domestic supply and electricity generation. This projection is a business-as-usual (BAU) scenario, representing current rates of water use for new growth. It does not specifically represent future enhancements in water use efficiency in these sectors and does not consider changes in the rates of use that might be related to climate change. This is a somewhat artificial scenario, in that water use efficiency is not static and has continued to improve over the last 30 years. However, despite improved efficiency, there are regions in the U.S. where withdrawals have risen over 1985−2005.[17] By highlighting discrepancies between potential future demand and future supply using the BAU scenario, we focus attention on areas where there are likely to be the greatest pressures to improve management of surface water and groundwater resources. This could occur by management of demand growth, realignment in water use among competing uses, greater water recycling, and creation of new supplies through treatment of impaired or nontraditional water sources.[18] The past paradigm where new demands could be simply met by greater withdrawals from natural systems, with no consideration of impacts to sustainability, is unlikely to be considered as plausible in water resources development in most regions.[19]

Projected future withdrawals are related to a simple measure of renewable water production, or available precipitation,[20] which is calculated under current and future temperature and precipitation scenarios. GCMs project future climate changes based on assumptions of different economic growth pathways and emissions of greenhouse gases, with A1b (medium), A2 (higher), and B1 (lower) being the most common scenarios in the terminology of Nakicenovic et al.[21] In this study, climate projections under a medium emission scenario (A1b) from 16 models were used. For this analysis, we consider that precipitation that is not lost to evapotranspiration (termed available precipitation) can be used for other purposes and is an approximate measure of local renewable water in a region. Available precipitation can exist in many forms, including runoff, infiltration, snowpack, and soil moisture. This work does not track water in these individual compartments but treats the sum of these as being indicative of water that is potentially available for various uses. A metric that represents the extent of water resources development in a region is the ratio of withdrawals to available precipitation.

The larger goal of this work was to develop an index to represent the relative risks of climate change to water resources across the U.S. Toward this end, a water supply sustainability risk index that takes into account multiple attributes of water use, in addition to the extent of development, susceptibility to drought, growth in water withdrawal, increased need for storage, and groundwater use, was developed to identify areas of greater relative risk. Although the maps produced in this work display significant local-scale complexity, the underlying analysis is intended to be relatively simple and provide a basis for more focused regional studies where appropriate and to be updated for different growth and climate change scenarios as these become available. Importantly, the index-based approach presented here is not a mechanistic water balance but rather a means to identify areas where, under climate change scenarios, water resources are at greater risk than under historical climate conditions. Available precipitation, as defined and used here, is a measure of local renewable water supply, and in some regions current water use is sustained by additional sources such as riverine transport, access to large water bodies, groundwater overdraft, or interbasin transfers that are protected by legal and institutional arrangements. Consideration of these factors was beyond the scope of the present study, but in the future may be addressed at more local scales in high-risk regions highlighted in this work.

■ METHODS

The objectives for this study required current data on water withdrawals and the estimation of future withdrawals for different uses. In addition, changing climate will drive changes in both precipitation and temperature, which will cause modifications in the net available precipitation. Details on the estimation of these quantities and the development and application of a water supply sustainability risk index, relating changes in supply and demand, are outlined below.

2005 Water Use Data. The most comprehensive data on water use in the U.S. are collected every five years by the USGS as part of the National Water Use Information Program and the most recent survey that is available is for 2005.[14] Although the classification of water use by sector has changed over the survey periods, in the most recent survey, surface and groundwater withdrawals as well as fresh and saline water withdrawal were reported for seven categories: municipal public and domestic water supply, industrial, mining, livestock, aquaculture, irrigation for agriculture, and thermoelectric cooling for electric generation. Municipal supply includes water that is supplied by public or private agencies and is used in homes and for commercial and industrial uses. Industrial uses where the water is withdrawn directly (not through a municipal supplier) are counted separately. Irrigation refers to water that is applied on the ground to sustain plant growth in all agricultural and horticultural practices.[14] Electricity generation, specifically thermoelectric cooling water withdrawal, and irrigation withdrawals for agriculture are the dominant components of the total freshwater withdrawal nationwide (40% and 36%, respectively), followed by municipal public and domestic water supply (14%).

Total freshwater withdrawal associated with thermoelectric cooling and irrigation from agriculture is shown in Figure 1. There are clear geographic variations in the major sectors associated with freshwater withdrawal: irrigation withdrawals from agriculture occur largely in the western states, whereas large thermoelectric withdrawals for cooling are in the eastern states and are clustered near the major rivers, such as the Ohio and Mississippi River basins, and the Great Lakes. These data

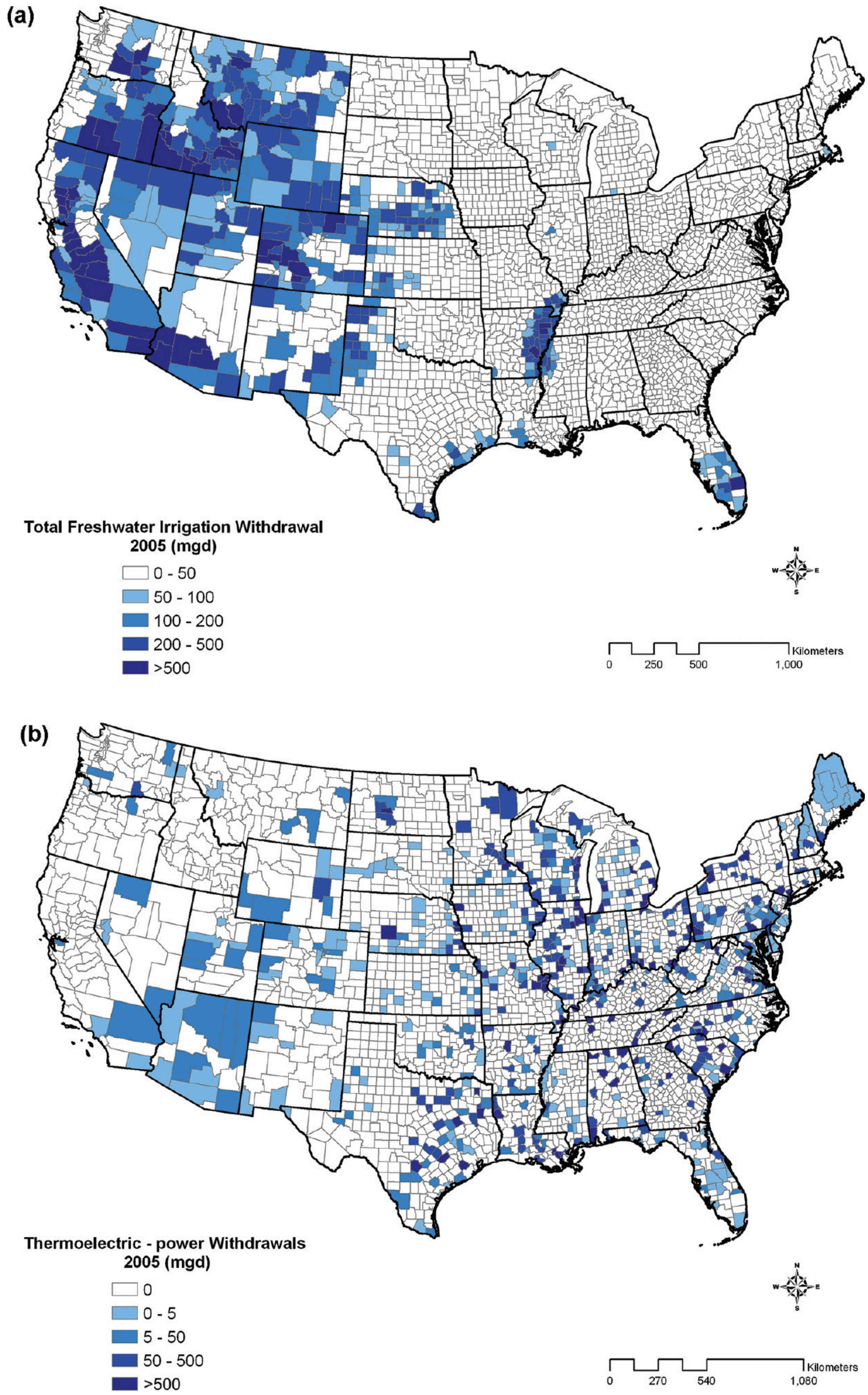

Figure 1. Withdrawals associated with (a) irrigation and (b) thermoelectric cooling, reported in units of mgd by the USGS (Data from Kenny et al., 2009).[14]

are shown in the units reported by USGS, i.e., in million gallons per day, or mgd, for each county.

Projecting Water Demand in 2050. Projection of future use is based on assumptions of the growth or decrease in demand in each major sector of water use, which depends on uncertain demographic and economic forces. For the purpose of this analysis, a business-as-usual projection of future water demand was made. It was further assumed that growth occurs only for domestic supply and for thermoelectric cooling. Water use for irrigation, livestock, aquaculture, and mining was assumed to remain at the same levels as in 2005.

Irrigation water use was held constant for the following two reasons: (i) Water use for irrigation has remained within a narrow range or has declined marginally over the period 1970–2005. (ii) In the USGS data set,[14] the irrigation intensity, i.e., water use per unit area, did not show a clear correlation with climatic drivers (such as average precipitation and potential evapotranspiration) and may well be affected by other factors not known at the national scale, such as total water availability and water rights, the crop types being irrigated, and the irrigation practices being used. In the absence of such information, the irrigation withdrawals values were maintained at 2005 levels.

Municipal water demand was projected based on estimated future population and with current levels of per capita water use.[20,22] Thermoelectric water use was based on new power generation projected by the Energy Information Administration (EIA) and water withdrawal per unit generation at levels typical in modern power plants. New electricity generation demand estimates up to 2030 for Electricity Market Module (EMM) regions were obtained from the EIA and extrapolated linearly to 2050. EMM regions are energy accounting units used by EIA in developing projections. There are a total of 13 EMM regions in the U.S., with each region comprising of one to several states. For the purpose of this analysis, we assumed that future addition of new power generation will use cooling technologies that are similar to those in modern plants with closed-loop evaporative cooling. This is a conservative estimate of water needs from future power generation and does not assume a broad shift toward cooling with very low water use, such as dry or hybrid wet–dry cooling. Water demand for irrigation, livestock, aquaculture, and mining was assumed to remain at the same levels as in 2005. Total water withdrawal in 2050 is the sum of projected municipal and thermoelectric water withdrawal and water use from these other categories.

Municipal Water Demand Projection. Municipal water demand projections were computed by multiplying the per capita water use in 2005 at the county level by the population projected for 2050. The per capita water use is derived as the total fresh water withdrawal from public supply and domestic water use, divided by total population served.

Population in the U.S. in 2050 is projected to increase by 48.8% from 282.1 million in 2000 to 419.9 million in 2050.[15] The increase is anticipated to be relatively linear through this period. Population projections have also been made at the state level for 2010–2030. County level projections are not published for the entire U.S. for this period. To make county level population projections, county level data from the Census Bureau for the period of 2000–2008 were used to estimate an annual population growth rate for each county (percent per year). Population in each county in 2050 was based on the annual percent growth rate computed for 2000–2008. The projected population at the county level was aggregated to the state level and compared to projections from Census Bureau for the period of 2010–2030. Generally good agreement was found (R^2 > 0.99) (Supporting Information (SI), Figure S1). Projected total population in the U.S. using the county-by-county method for 2050 is 419.0 million, which compares well to the Census Bureau national projection of 419.9 million.

Thermoelectric Water Withdrawal Projection. To estimate the total power generation over 2006–2050, electric generation projected by the EIA for the period of 2006–2030 at the EMM Regions was used.[16] The EIA estimates are based on a model of the energy-economic system of the U.S. and also include projections of fuel types used for electricity generation.[16] Until 2030, EIA projections show the continued dominance of fossil and nuclear fuel sources in the electricity supply mix. To extend the projections by EIA to 2050, the growth estimated for the period of 2010–2030 was extrapolated forward.

The projected changes in thermoelectric generation in 2050 at the EMM region were first converted to the state level by applying same percent changes for the period of 2005 to 2050 for all states within each EMM region. The percent changes were then applied to counties with existing thermoelectric generation in proportion to the level of current generation, i.e., the new generation was allocated to counties only with existing generation. This approach assumes that new thermoelectric generation, by virtue of proximity to existing transmission infrastructure or population centers, will be largely focused on areas with existing generation. Over a medium-term horizon, two to four decades, this is a reasonable starting assumption, although over a longer term, it may not hold, as the mix of generation, the population distribution, and transmission infrastructure may change.

In projecting water withdrawal due to increases in power generation, water withdrawal per unit of electricity generation was assumed to be 500 gallons/Megawatt-hour, based on a recent analysis of water use in modern closed-loop cooling power plants where values ranged from 226 to 1,100 gallons/Megawatt-hour.[22,23] The upper and lower bounds of this range are not typical, and 500 gallons/Megawatt-hour is considered a reasonable midrange value. The amount of thermoelectric water use in 2050 was calculated as the total thermoelectric freshwater withdrawal in 2005 (i.e., the current withdrawals continue as at present) plus the amount of water withdrawal due to new power generation.

Available Precipitation in 2050. *Climate Projections.* GCMs are relied upon to provide plausible, physically based estimates of the climate response to changes in composition of boundary conditions and increasing atmospheric greenhouse gas concentrations. Many GCMs are in current use, developed by different modeling groups throughout the world, and have been included in assessments in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report.[6] There is abundant support in the literature to use an ensemble of multiple models to represent a range of plausible future conditions, rather than to use the results of a single model.[24–28] For this study, we used an ensemble of sixteen GCMs (SI, Table S1).

The GCM output for these models, for both the 20th and 21st century simulations, was obtained from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel data set.[29] The data used were statistically downscaled data from the 16 models spanning a 150-year period from 1950 to 2099[26] downscaled to a 1/8° resolution (resulting in cells of approximately 12 by 12 km). For each GCM, outputs using different multiple emission scenarios are available, three of which have been used for the standardized model comparison as part of the CMIP3 work. These are labeled Scenarios A1b, A2, and B1.[21] Each scenario embodies a different storyline for growth, technology diffusion, and interconnectivity among different regions. The three emission scenarios represent a higher (A2), medium (A1B), and lower (B1) rate of emission growth through the 21st century. The A1B projections for temperature and precipitation were used in this work because it corresponds to a midrange

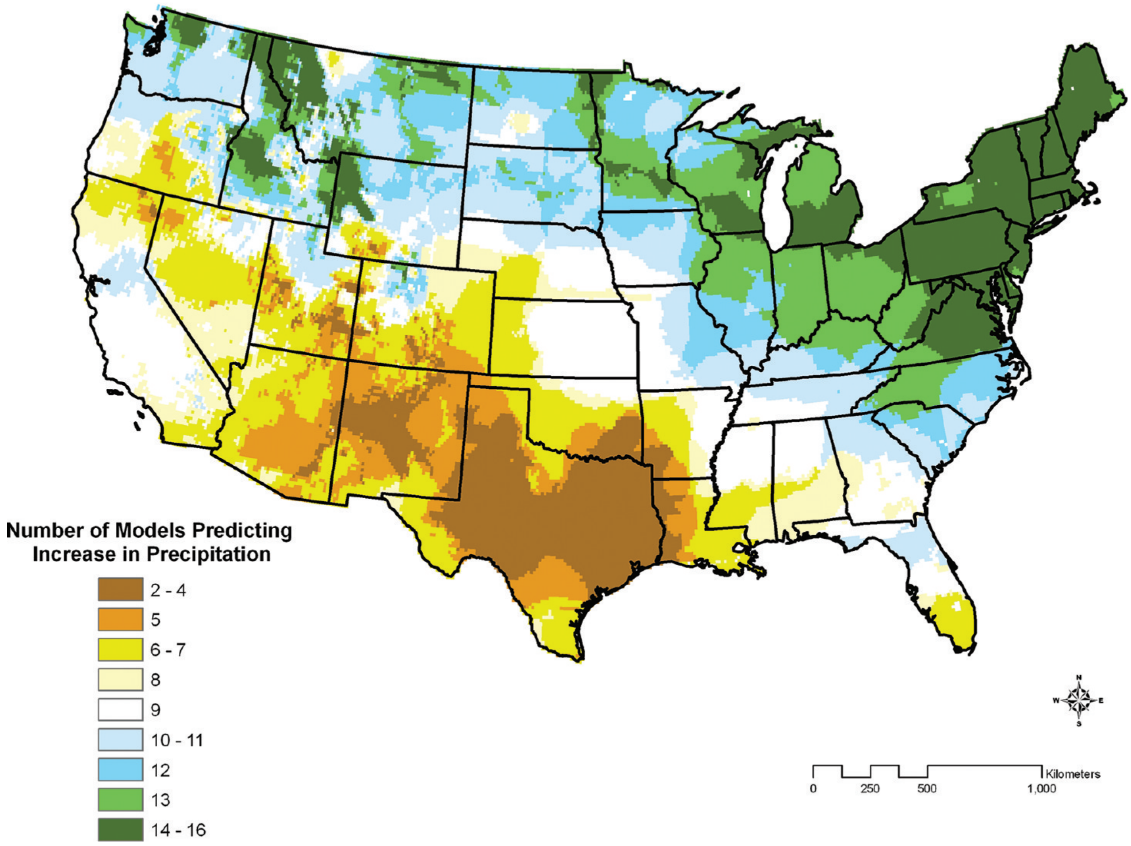

Figure 2. Number of models (out of an ensemble of 16 GCMs) projecting an increase in precipitation by 2050.

scenario. However, over the mid-21st century time frame, atmospheric concentrations of greenhouse gases are not very different across these three scenarios, the distinction becoming more apparent by end-century. Impacts under the different emissions pathways are even less likely to be distinguishable by midcentury, due to the long residence time of CO_2 in the atmosphere and the thermal inertia of the coupled ocean-atmosphere system.[30]

To account for year-to-year and decadal variations in temperature and precipitation projected by different GCMs, reflecting longer-term cycles in the underlying oceanic and atmospheric processes, projections for 2050 were represented using a twenty-year averaging period around the midpoint (2040–2059). Monthly values for a historical period (1961–1990) were also available in the GCM output. The GCM outputs are aggregated to compute annual total precipitation and annual mean precipitation for comparison of the two time periods. For analysis that required monthly data, the average monthly values across the 20-yr period were used for each GCM, thus a value for January is represented by the average of all 20 January values over the period of averaging. Sixteen such average values are possible for each month (one for each model). The median across the 16 GCMs was used for this analysis. A map of projected precipitation changes between 1961 and 1990 and 2040–2059 (SI, Figure S2) indicates decreases in precipitation in the west and parts of the Gulf States and increases in the northeast and parts of the Midwest. There are decreases in the Gulf states (Texas) of more than 1 in./yr (25 mm/yr) and increases in the northeast by 2–4 in./yr (51–102 mm/yr). Of the 16 models evaluated in this work, most indicate decreases in precipitation in the Southwestern and Southern U.S. (Figure 2). Projected increases in temperature for 2040–2059 range from 1.5 to 3 °C. The highest temperature increases are in the Midwest and Mountain regions of the West (SI, Figure S3).

Available Precipitation: Historical Values. Available precipitation, defined as the difference between precipitation and potential evapotranspiration (PET) for each month of the year,[20] was computed based on averages of historical data at 344 climate divisions over the period of 1934–2005. Monthly temperature and precipitation data at the climate division level was obtained from the National Oceanic and Atmospheric Administration.[31,32]

Projecting Evapotranspiration and Available Precipitation in Future Years. The monthly potential evapotranspiration (PET) for 2050 was estimated based on projected monthly temperature, using a commonly used formulation, the Hamon equation[33]

$$E = \frac{2.1 H_t^2 e_s}{(T_t + 273.2)} \tag{1}$$

where E = evaporation, day t (mm/day), H_t = average number of daylight hours per day during the month in which day t falls, e_s = saturated vapor pressure at temperature T_t (kPa), T_t = temperature, day t (°C), and H_t was calculated by using the maximum number of daylight hours on day t.

Saturated vapor pressure e_s was estimated as

$$e_s = 0.6108 \exp\left(\frac{17.27 T_t}{237.3 + T_t}\right) \tag{2}$$

The Hamon equation is one of several approaches used to estimate potential evapotranspiration and was used because of its simplicity and relatively modest data requirements. Other commonly used PET estimation approaches[34−37] were also evaluated across stations representing a range of climates (SI, Figure S4a and b) and were comparable for current conditions. For an increase of 2 °C applied for each month, the Hamon equation-predicted increase in PET was at the higher end, though not always the highest of the approaches considered (SI, Figure S4c). Besides these estimation approaches, more mechanistic representations can also be applied, but these usually have greater input data requirements, such as for solar radiation, wind speed, and relative humidity. Using GCM-level output (not downscaled) for these variables, the Hamon equation has also been found to be more temperature sensitive than other approaches.[38] All variables needed for these calculations are not currently available as statistically downscaled GCM outputs although some dynamically downscaled data are becoming available[39] and may be applied in the future or in more region-specific studies. Also, the relationship between atmospheric carbon dioxide concentrations and decreased plant evapotranspiration has been reported[40] and could be factored in future work. For the purpose of this study, given current data availability, the Hamon equation was considered suitable for use in estimating PET.

The difference between monthly precipitation and potential evapotranspiration (P−PET) over the course of a year was summed to estimate the annual available precipitation. When precipitation is less than potential evapotranspiration for a particular month, the available precipitation for that month was counted as 0. Available precipitation was estimated at each point across a 1/8° grid (latitude by longitude, approximately 12 km square) over the U.S.

Ratio of Future Water Withdrawal and Available Precipitation. The larger the fraction of available precipitation that is used to meet human needs, the greater the risk to supply when available precipitation decreases. As a metric representing the intensity of water development in a region, the ratio between water withdrawal and available precipitation can be computed. The projected available precipitation at 1/8° scale was aggregated to the county level. The projected water withdrawal in mgd as reported by the USGS was normalized to the county area and is represented in inches for direct comparison to available precipitation. High values of this ratio are indicative of the withdrawal of a large fraction of the available local precipitation and are representative of water resources development in a region.

Besides ratios of future water withdrawal and available precipitation, another metric computed was the summer deficit, defined as the available precipitation minus withdrawal in June, July, and August, typically the three warmest months of the year that correspond to increased municipal, thermoelectric cooling, and irrigation withdrawal. The summer deficit is a water requirement that needs to be met through stored surface water, groundwater withdrawals, or transfers from other basins. In estimating irrigation withdrawal in June, July, and August, it was assumed that irrigation needs are proportional to the monthly deficit in available precipitation (P−PET). The summer deficit is an indicator of water shortage on a seasonal basis that must be met through stored sources or groundwater.

Development of a Water Supply Sustainability Risk Index. The water resources literature presents several examples of indices that are used to integrate different measures of water availability and access to human populations.[41,42] Several of the published indices were developed to meet different purposes, ranging from human access to clean water and ecosystem health. In this study, where access to water for basic human needs is not a major concern, and where detailed data on water use are readily available through the USGS water use surveys, a more targeted index is developed that is focused on water supply concerns in coming decades. For this reason, building on past work,[20,22] a water supply sustainability risk index was developed to evaluate multiple water constraints.

Metrics considered in the index include use of local available precipitation or the extent of water development already in place, the region's susceptibility to drought, projected increases in water use, and the difference between peak summer withdrawal and available precipitation, a measure of storage requirements, and dependence on groundwater. Five criteria were used in compositing the index:

1 Extent of development of local renewable water supply: Greater than 25% of available precipitation is used. The larger the fraction of available precipitation that is used to meet human needs, the greater the risk to supply when available precipitation decreases. High percentages of withdrawals are also indicative of impacts not related to water quantity, specifically water quality and ecological impacts.
2 Susceptibility to drought: Summer deficit, as defined above, is greater than 10 in., and this water requirement must be met through stored surface water, groundwater withdrawals, or transfers from other basins. If the precipitation is lower than average, as is typical under drought conditions, the water requirements will increase, or some demands will not be met.
3 Growth in water withdrawal: The increase of total freshwater withdrawal between 2005 and 2050 is more than 20%. Growth in water demand is driven largely by population growth and the need for new thermoelectric generation.
4 Increased need for storage: summer deficit increases more than 1 in. from 2005 to 2050. As noted in item 2 above, the summer deficit is met through stored surface water, groundwater, or transfers from other basins. An increase in the summer deficit means that additional supply must be generated in the dry months through new storage or other means.
5 Groundwater use: The ratio of groundwater withdrawal to total withdrawal is greater than 25% (based on current groundwater withdrawal). Withdrawals below this percentage are indicative of regions in proximity to large surface water resources and less likely to be influenced by changes in local precipitation.

Given 2050 withdrawal estimates, the index can be computed for recent historical (1934−2005) or projected future precipitation. Each constituent of the index is scored as 1 if the value in question is exceeded and 0 otherwise. The total value of the index can range from 0 to 5. Example calculations for a county are shown in the SI, Appendix 1. The risk to water sustainability for counties meeting or exceeding two of the criteria are classified as "moderate," those meeting or exceeding three of the criteria are classified as "high," and those meeting or exceeding four or more are classified as "extreme". Counties meeting fewer than two criteria are considered to have low risk to water sustainability. To ensure that the constituent metrics

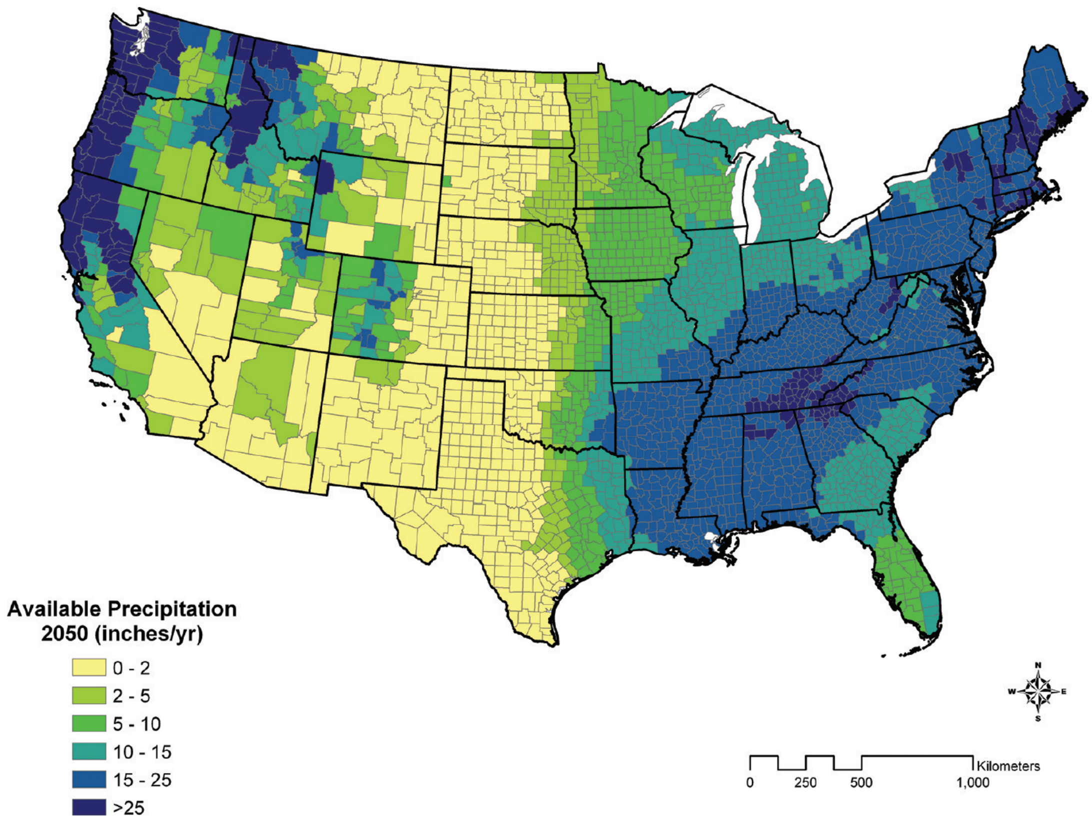

Figure 3. Projected available precipitation in 2050 aggregated to the county level, based on the 50th percentile of projected precipitation by climate models (ensemble of 16 GCMs).

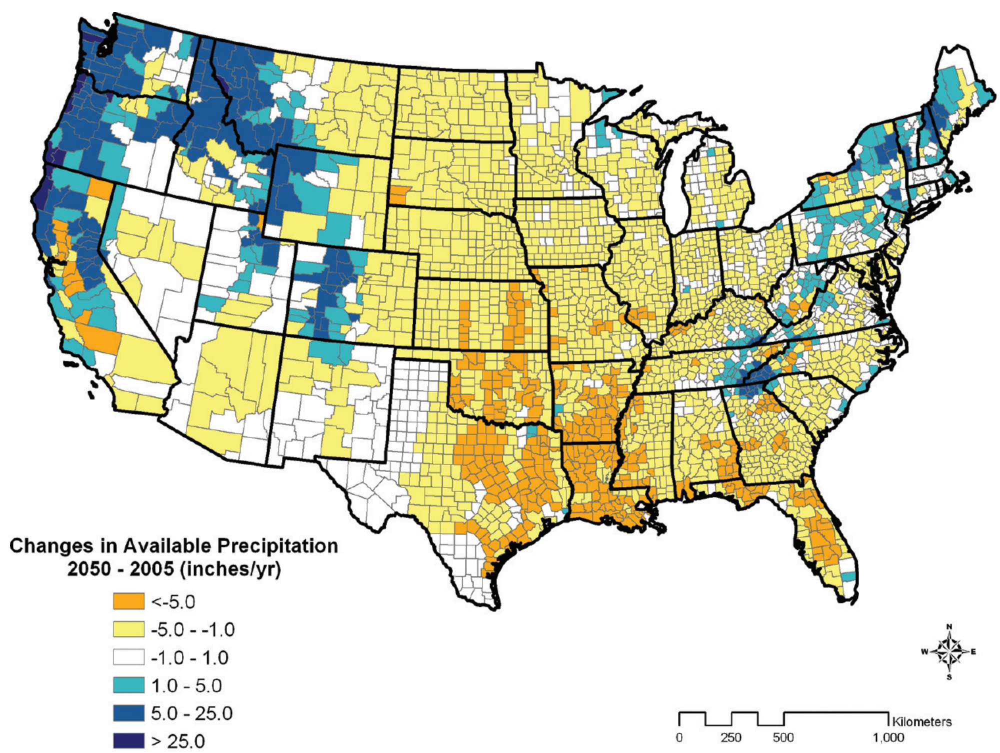

Figure 4. Changes in available precipitation from 2005 to 2050 in inches/yr. 2050 values are based on 50th percentile an ensemble of 16 GCMs and represent conditions between 2040 and 2059.

are not correlated with one another, and therefore redundant, the relationship between individual metrics was compared for each county in a pairwise manner. The comparison was performed using historical precipitation as well as projected 2050 precipitation (16-GCM median) (SI, Figure S5 and S6).

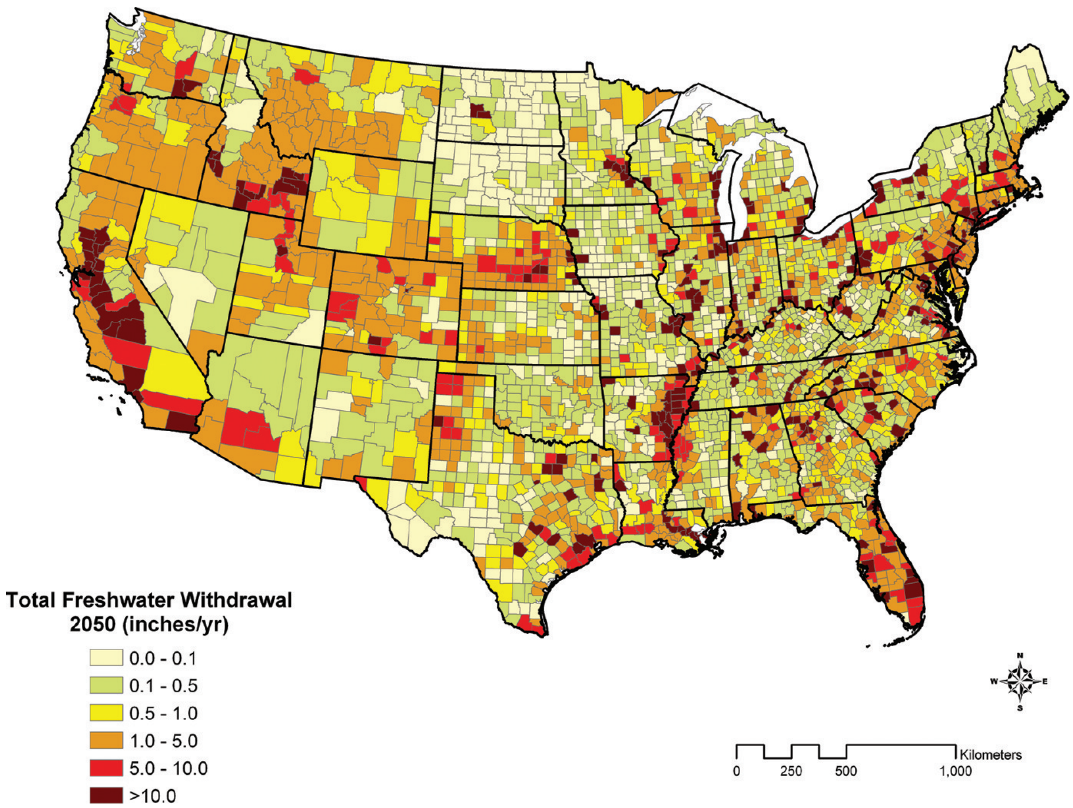

Figure 5. Projected total freshwater withdrawal in 2050 (inches/yr). The 2050 values are based on population growth and increased electric generation capacity, and assuming water use rates for domestic use at 2005 levels, albeit varying by county, and new cooling water use at 500 gallons/Megawatt-hour. Withdrawals for other sectors are assumed to remain at their 2005 levels.

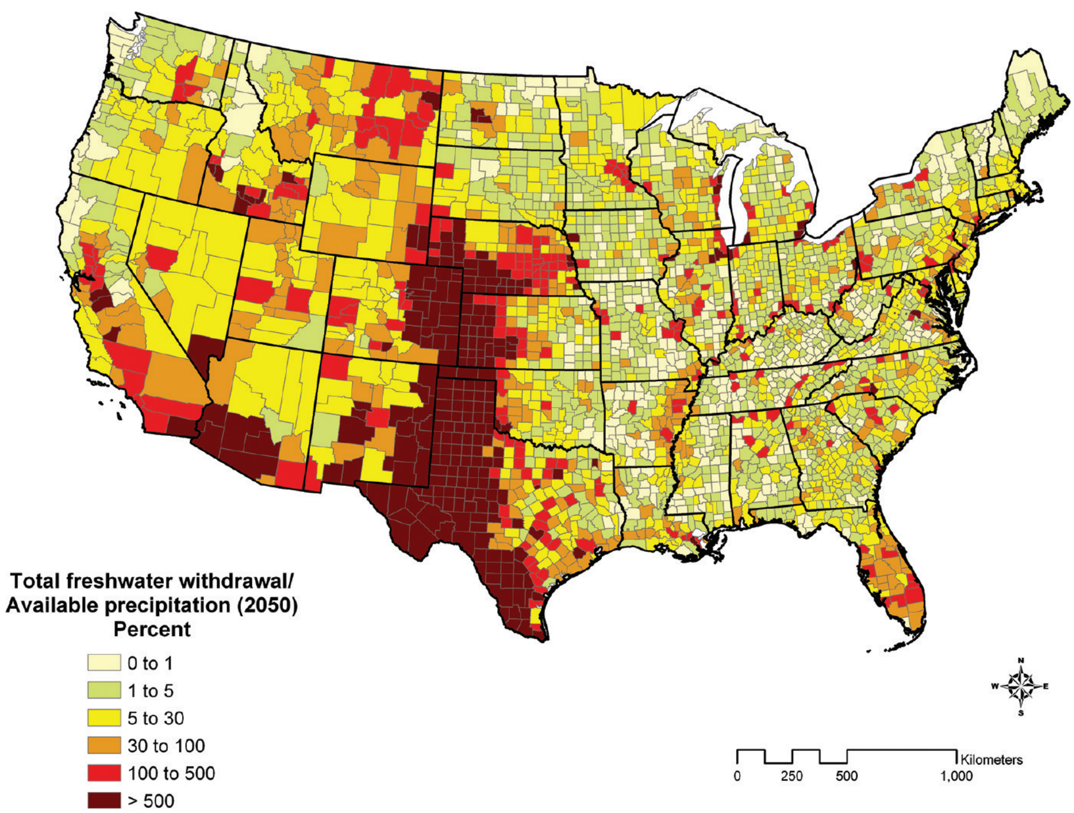

Figure 6. Projected total water withdrawal as percent of available precipitation in 2050. 2050 values are based on 50th percentile an ensemble of 16 GCMs and represent conditions between 2040 and 2059.

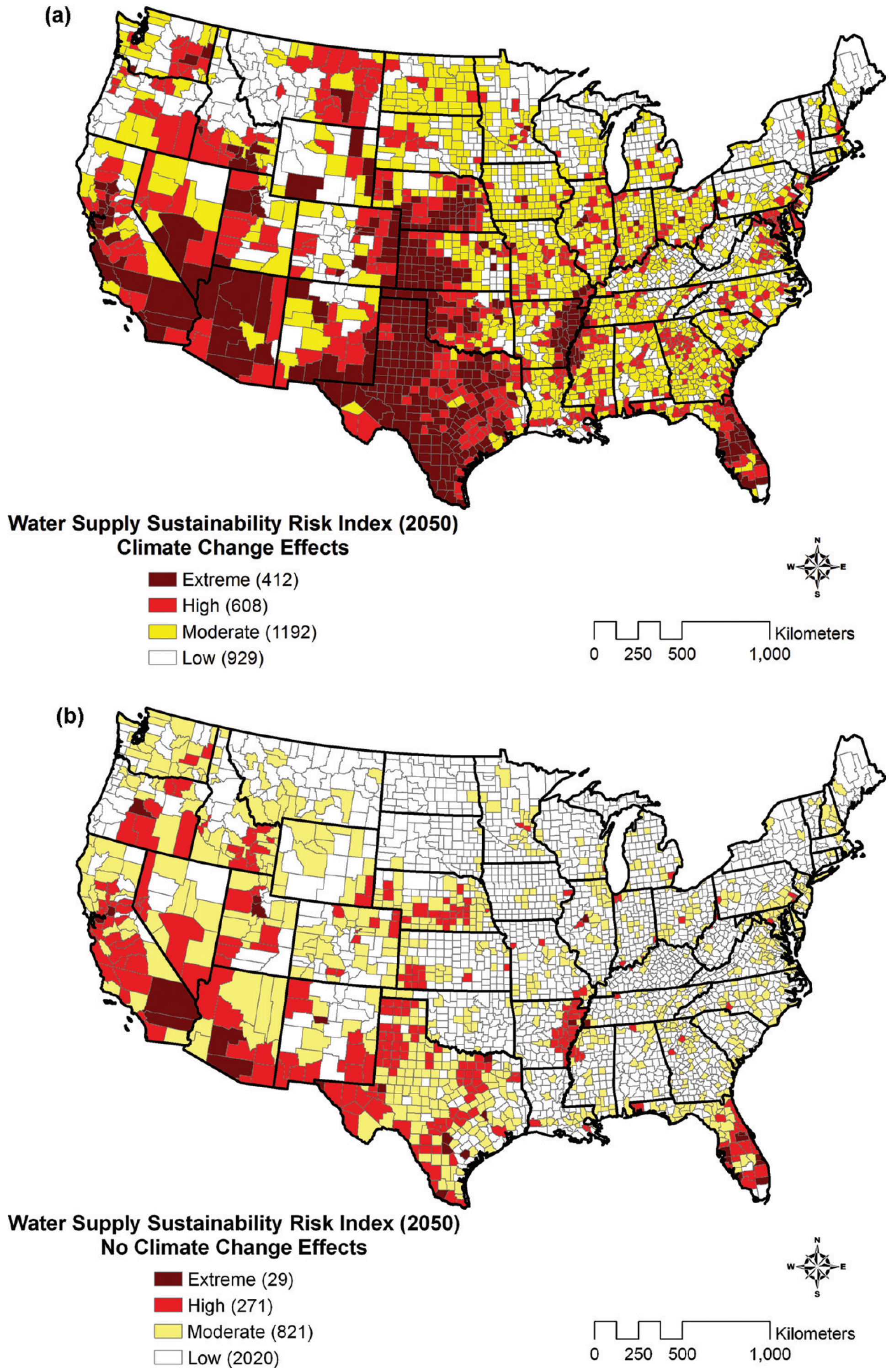

Figure 7. Water Supply Sustainability Risk Index in 2050 (a) with available precipitation computed using projected climate change and (b) with available precipitation corresponding to 20th century conditions, i.e., 1934–2005.

The comparison showed that the metrics are poorly correlated to one another and relatively independent.

RESULTS

Projected Available Precipitation in 2050. Projected available precipitation (P−PET) in 2050 under the A1b scenario, using the median of 16 GCMs, is shown in Figure 3. Projected changes in available precipitation for 2050 from the twentieth century records (1934–2000) are shown in Figure 4. Projected available precipitation is less than 2 in. for many areas in the West and more than 15 in. in the Northeast, Northwest, and South Atlantic regions. Projected decreases in available precipitation from historical records are generally less than 2.5 in./yr with some regions in Texas and the Mississippi Basin showing more than 5 in. of decrease. Changes in available precipitation are a result both of changing precipitation and of

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changing PET, as a consequence of higher temperatures. In areas where both changes are adverse, i.e., higher PET and lower precipitation, the impacts on available precipitation are most significant. The most significant adverse changes are in the Central and Southwestern regions of the U.S. due to changes in both PET and precipitation (SI, Figure S7).

The projected available precipitation in 2050 shows patterns similar to historical precipitation patterns.[20] Key changes are increases in certain low available precipitation zones (0−5 in./yr) and decreases in high available precipitation zones (15−25 in./yr).

Projected Total Water Withdrawal in 2050. Projected total freshwater withdrawal in 2050 based on changes in municipal and thermoelectric water withdrawal, with other withdrawals at their 2005 levels, is shown in Figure 5. Under the BAU scenario, freshwater withdrawal is projected to increase by 12.3% in 2050 from 2005 levels.

Total freshwater withdrawals in 2050 are significant in the major agricultural and urban areas throughout the nation. Total freshwater withdrawals in 2050 are between 0.2 and 0.5 in./yr with some areas in the west showing withdrawals of 1−5 in. Parts of California, Texas, and the Mississippi River basin show water withdrawals of more than 10 in./yr. The projected changes in water withdrawal include decreases in the Midwest region and increases in some areas in Southeast, South, and Western regions of the U.S. The projected increases in water withdrawal are 0.1 in./yr for most regions, with a few areas showing more than 3 in. of increase.

Projected percent changes in total freshwater withdrawal include decreases in the Midwest and some areas in the Northeast. The projected percent increases in water withdrawal are greater than 25% in many areas of the U.S. including the arid Arizona/New Mexico area, the populated areas in the South Atlantic region, Florida, Mississippi River basin, and Washington, DC, and surrounding regions.

Ratios of Water Withdrawal and Available Precipitation. The projected total freshwater withdrawal as a percentage of available precipitation for 2050 assuming climate change impacts is shown in Figure 6. There are some regions in the U.S. where withdrawal is larger than renewable supply, indicative of transport by rivers, interbasin transfer by manmade canals or aqueducts, or groundwater mining in excess of recharge.[20] However, the consideration of climate change impacts greatly expands areas where water withdrawal is greater than renewable supply. This is especially the case for much of the western U.S., in particular areas over the Ogallala Aquifer (Central U.S.) and Edwards Aquifer (Texas), and in the southwestern U.S.

The estimated water withdrawal as a percent of available precipitation is generally less than 5% for the majority of the eastern U.S. and less than 30% for the majority of the western U.S. In some arid regions (e.g., Texas and California) and agricultural areas, water withdrawals are estimated to be greater than 100% of the available precipitation. In some regions, due to projected changes in precipitation and increases in temperature, projected PET exceeds precipitation, and results in zero available precipitation.

Water Supply Sustainability Risk Index. The water supply sustainability index is computed for 2050 withdrawals using GCM-projected available precipitation and using historical available precipitation (Figure 7). The map of the water supply sustainability index identifies several areas that are at high or extreme risk to climate change impacts in 2050. These areas include California, Nevada, Arizona, Texas, and parts of the Florida. The majority of the Midwest and Southern regions are considered to be at moderate risk, whereas the Northeast and some regions in the Northwest are at low risk of supply impacts. Without the consideration of climate change in future years, the range of counties with water supply sustainability is far smaller, although many of the same states are affected, including parts of California, Arizona, Nevada, Texas, Arkansas, and Florida. The impacts on the interior, central parts of the U.S. (especially over the Ogallala Aquifer), Texas (over the Edwards Aquifer), and much of the Southeast are considerably more amplified in the presence of climate change.

■ DISCUSSION

Climate change projected by 16 GCMs show significant variations in predicted precipitation, although temperature was projected to increase by all climate models. Median changes in annual precipitation projected by the climate models show decreases in many regions of the U.S., including areas that may currently be described as water-short. Projected changes in water withdrawal for the period of 2005 to 2050 are generally at a scale of 0.1 in., mostly as increases, while projected changes in available precipitation are at a scale of 2.5 in., often as decreases. Although the projected increases in water withdrawal in future years are significant, these are often less than the projected decreases in available precipitation (caused in turn by changes in precipitation and increased PET). Changes in PET due to climate change, mostly due to temperature increases are 4 to 5 in./yr, with areas in the southern U.S. showing increases in PET of up to 5 to 6 in./yr. This highlights the importance of understanding PET under future conditions, for water supplies as well as for potential use, using mechanistic formulations and by more detailed representations of land cover.

The Hamon equation for PET has been found to be more sensitive to temperature changes and may have predicted greater increases in PET than other estimation methods.[37] However, given the lack of available downscaled data for all necessary variables for computing PET mechanistically at this time, the evolving understanding role of atmospheric carbon dioxide in plant transpiration, and the focus on this work on an index, as opposed to detailed water budgets, the broad conclusions using the Hamon equation are valid. Future work, using downscaled data on additional variables, as anticipated through dynamic downscaling efforts,[39] may address this issue more fully.

The analysis presented in this work used a combination of publicly available data on current water use and future trends in population and energy demand to estimate future water withdrawal requirements under BAU conditions and to relate this to renewable water availability under projected 2050 climate. Water resources constraints differ from region to region and include concerns about growth in demand, insufficient storage to tide over low rainfall periods, and overextraction of groundwater. In many regions of the U.S., where some of these constraints are apparent—such as areas in the southwestern U.S. and over the Ogallala and Edwards Aquifers—climate change is one more factor to contend with. To address this multifaceted aspect of water sustainability, an index was developed to help rank the relative risk of different regions based on five different attributes. Broad scale impacts to water resources that may be anticipated have been addressed in previous work.[4,5] This analysis provides a quantitative and region-specific assessment of the nature of water supply impacts that might be expected across the U.S.

From this analysis, it appears likely that climate change could have major impacts on the available precipitation and the sustainability of water withdrawals in future years under the BAU scenario. Based on an index compositing multiple metrics, we found that water supplies in 70% of counties in the U.S. may be at some risk to climate change, and approximately one-third of counties may be at high or extreme risk. The geographic extent of potential risk to water supplies is greatly increased when climate change is considered than when 20th century temperature and precipitation are used. This is not intended as a prediction that water shortages will occur, but rather where they are more likely to occur, and where there might be greater pressure on public officials and water users to better characterize, and creatively manage demand and supply, through greater efficiency and realignment among competing uses, and by water recycling and creation of new supplies through treatment.

The BAU conditions defined here include growth in municipal and electric cooling withdrawal and the continuation of all other withdrawals, including irrigation, at their current levels. The index also emphasizes the role of local renewable water supply in the form of available precipitation, which may not be fully representative of water supply in locations where water is transferred across large distances through rivers and across basins through aqueducts. The index is best used as a comparative tool across broad regions, and as a starting point for more detailed analysis. In counties or areas where the index indicates high risk, a more focused mechanistic evaluation of water supply and withdrawal, including a water budget, consideration of timing of water availability and use, evaluation of storage, long-range transport, and interbasin transfers, is best performed at a local scale. Such studies are envisioned through the Secure Water Act, passed by Congress in 2009, and managed by the U.S. Bureau of Reclamation,[13] where a set of basins will be targeted for detailed analysis over the coming decade.

■ ASSOCIATED CONTENT

Supporting Information

Identification of GCMs used and supporting calculations are presented in this section. Also included is an appendix detailing calculations for one county and electronic data files used for county-level maps presented in this work. This material is available free of charge via the Internet at http://pubs.acs.org.

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