



# EVALUATING SUSTAINABILITY OF PROJECTED WATER DEMANDS UNDER FUTURE CLIMATE CHANGE SCENARIOS

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TETRA TECH

# Evaluating Sustainability of Projected Water Demands Under Future Climate Change Scenarios

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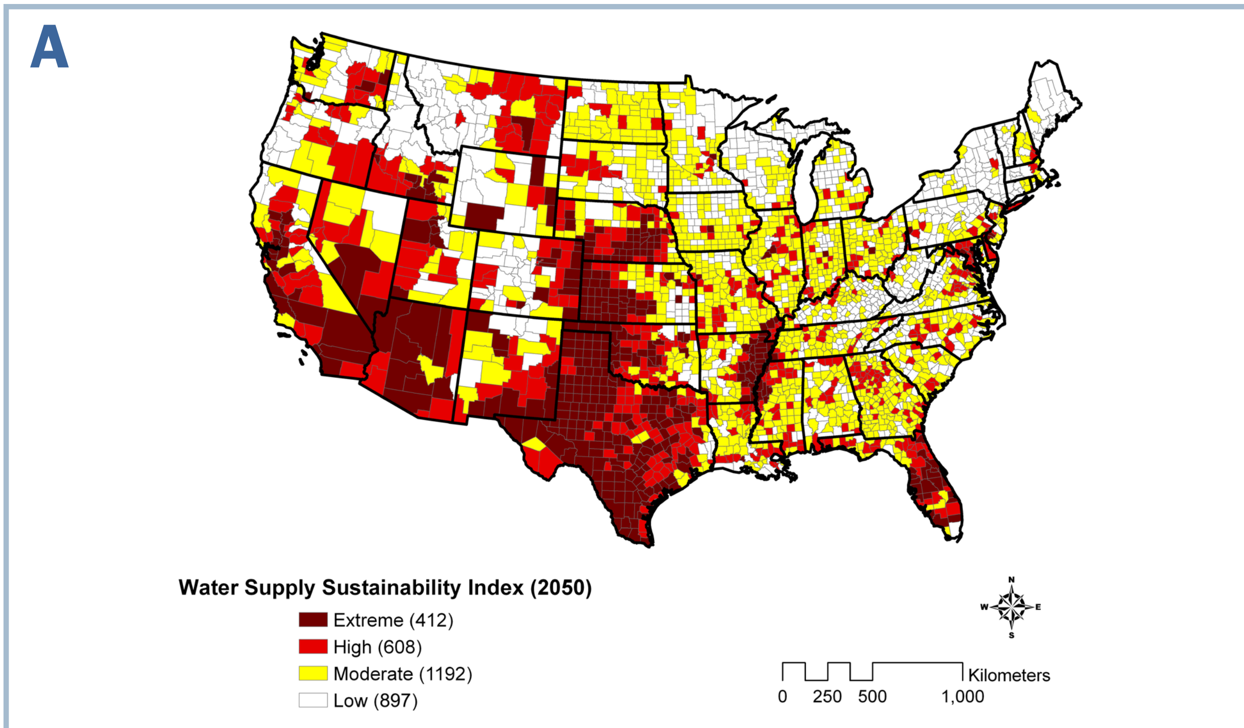
# Executive Summary

Climate change will impact water supplies, exacerbating existing pressures on water resources caused by population and economic growth. Given the combination of these stressors, the sustainability of water resources in future decades is a concern in many parts of the world. This study presents an integration of water withdrawal projections and future estimates of renewable water supply across the United States to assess future water availability in the face of a changing climate. The water demand projections in this work are based on business-as-usual trends in growth, particularly of population and energy demand, and renewable water supply projections are based on the average results of an ensemble of sixteen established climate models. The analysis is performed using annual water use data at the U.S. county level, and using global climate model outputs for temperature and precipitation, both projected 20-40 years into the future. The analysis provides a national-scale evaluation of the results of changing water demand and supply, and helps identify regions that are most susceptible to climate change.

As part of this analysis, a water supply sustainiability index comprised of five attributes of water use and growth was developed, and used to compare impacts across regions. We found that, under the business-as-usual scenario of demand growth, water supplies in 70% of counties in the U.S. may be at 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 (Figure ES-1). This calculation indicates the increase in risk that affected counties face that water demand will outstrip supplies, if no other remedial actions are taken. To be clear, it is not intended as a prediction that water shortages will occur, but rather where they are more likely to occur. As a result, the pressure on public officials and water users to creatively manage demand and supply—through greater efficiency and realignment among competing uses, and by water recycling and creation of new supplies through treatment—will be greatest in these regions. In addition to developing national-scale maps of potential climate impacts, this work serves as a starting point for more detailed analysis, either at more local scales, or by consideration of specific sectors of the economy that are directly dependent on sustainable water resources.



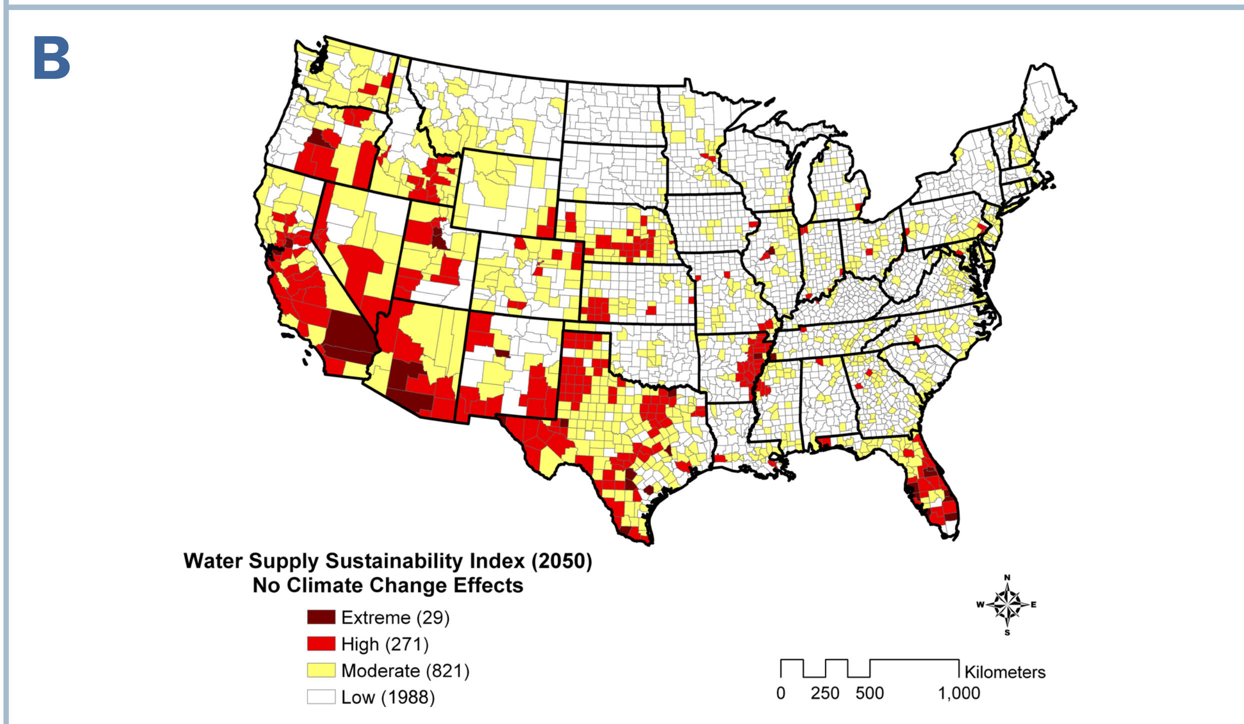




Figure ES-1. Water Supply Sustainability Index in 2050, (a) with available precipitation computed using projected climate change, and (b) with available precipitation corresponding to 20th century conditions, i.e., 1934-2000. The risks to water sustainability are classified into four categories from Extreme to Low. The numbers in parentheses are the numbers of counties in each category.

# Introduction

Human needs for water continue to grow with increasing population, primarily for direct consumption, but also secondarily for energy production, and agricultural, commercial, and industrial activities. The sustainability of water resources, defined as the maintenance of natural water resources in adequate quantity and with suitable quality for human use and for aquatic ecosystems, is adversely impacted 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. Climate change impacts on water resources through changing precipitation, snowmelt, and other processes related to warming temperature, have been identified in previous work (Gleick, 1989; Hurd et al., 1999; Jacobs et al., 2001; Bates et al., 2008; Brekke et al., 2009a). For example, as temperatures increase, more water is evaporated, and less runs off into rivers and reservoirs. Previous work has identified areas of the globe where atmosphere-ocean general circulation models (AOGCMs or GCMs, also known as "global climate models") project changes in temperature and precipitation as a result of changing concentrations of heat trapping greenhouse gases in the atmosphere (Christensen et al., 2007; Intergovernmental Panel on Climate Change, IPCC, 2007). Projected future precipitation changes are variable over regional scales. Unlike temperature—which all climate models agree will increase—precipitation is projected to both increase and decrease across different regions over the 21st century. However, even in the face of increased precipitation due to climate change, water available for human use for many areas may not change or even decrease due to increased temperatures resulting in greater evapotranspiration. Synthesis reports for the United States have also been prepared that 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 (National Science and Technology Council, 2008; Brekke et al., 2009a; U.S. Global Change Research Program, 2009). This study adds to this general body of knowledge by providing quantitative and region-specific information on the impacts of climate change to water availability and to future water supplies versus projections of demand across the United States.

This work is an analysis of future business-as-usual water demand as it relates to renewable water availability at the national scale across the United States, under scenarios that consider potential changes in precipitation and temperature in 2030 and 2050 as projected by GCMs. The extent of climate change over this time frame is less severe than end-of-21st century projections, however, this time frame was chosen because it is within the time horizon of most major infrastructure planning activities, especially infrastructure related to water resources and energy production (e.g., Brekke, et al., 2009b). Although there is a time lag between greenhouse gas emissions and climate change impacts, this is also within the time horizon of emissions reductions being proposed in the United States and internationally.

For the purpose of this analysis, we project future water withdrawals under scenarios of continued population growth and associated municipal/domestic water, electricity and cooling water demands, focusing on freshwater withdrawals from groundwater and surface water sources. Water demand projections are based on five-yearly water use surveys reported by the U.S. Geological Survey, most recently for 2005 (USGS; Kenney et al., 2009). Population projections are based on Census Bureau estimates (U.S. Census Bureau, 2008), and electricity production estimates are from the Department of Energy (EIA, 2009). Using these 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. Future water demand projected using this approach is a business-as-usual type of scenario, and 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. Thus, future thermoelectric cooling demand is based on water use rates typical of generating plants being developed today, and future municipal demand is based on per capita water use rates in 2005 combined with future populations. The goal of such an analysis is to represent future conditions that might be expected if water use practices continue along their present trajectory. This is a somewhat artificial scenario, in that water use efficiency is not static and has continued to improve; the needs of a larger population and economy are being met mostly through total withdrawals at national aggregate levels that have remained flat over past two decades, although there are regions where withdrawals are higher and others where they are lower over this period. However, by highlighting discrepancies between potential future demand and future supply using the business-as-usual 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. 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 (Gleick, 1998).

Projected future withdrawals are related to a simple measure of renewable water production, or "available precipitation," which is calculated under current and future temperature and precipitation scenarios (Roy et al., 2005). In a given region, precipitation as rain or snow is the main source of renewable water. Some of the precipitation is lost to the atmosphere by evaporation or through transpiration by plants (these two processes are usually lumped together and termed evapotranspiration). The remainder percolates into the ground and is stored as groundwater or moves as runoff into surface water bodies. For the purpose of 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 available renewable water in a region. We calculate this as the precipitation minus potential evapotranspiration (PET) for each month, and then sum the net values for the entire year. For months where the PET exceeds precipitation, the net addition to the available water for that month is zero, to avoid counting unavailable water. PET can be thought of as an index that corresponds to the maximum evapotranspirative loss that might occur from land; in this work it is computed using a relatively simple method that can be applied over current and future conditions and across broad geographic scales.

Relating future demand and available precipitation provides an initial estimate of water supply sustainability across the nation—resolved at the county-level, the best available resolution for water use information—and helps identify areas most likely to be affected by climate change (Roy et al. 2004, 2005). 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. This document summarizes the assumptions associated with the analysis relating to water demand projections, future climate, and water availability, and presents the results as a series of maps.

The remainder of this report is organized in the following manner. We first present the key elements of the methodology used, including the estimation of water demand in the future, climate projections from GCMs, the estimation of available precipitation, and the development of an index to composite multiple facets of water use. We then present the results as a series of maps for 2050, followed by the principal conclusions of this work. An appendix includes a set of maps for 2030.

# Methodology

## Water Use Data in the United States

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. These surveys were first conducted in 1950, and the most recent survey that is available is for 2005 (Kenny et al., 2009). This data gathering effort generally obtains information on surface water and groundwater withdrawals and consumptive use, and identifies use by six major categories: public and domestic water supply, commercial, industrial, mining, irrigation, and thermoelectric cooling for electric generation (including fossil-fuel and nuclear power generation). The type of water withdrawn, either fresh water or saline water, and the source, either surface or groundwater, is also reported. The most recent water use surveys also estimated livestock and aquaculture use, although these are relatively minor. In the terminology of the USGS, all these uses these are termed "offstream" uses, as opposed to "instream" uses for hydroelectric power generation (USGS, 1998). Instream uses for non-human, environmental purposes, such as flows for maintaining aquatic ecosystems, are not cataloged by the USGS. This analysis is primarily focused on offstream freshwater use.

On a national aggregate basis, Figure 1(a) shows the offstream withdrawal of freshwater for each of the major categories described above for the 2005 water use survey, as well as the trends in total freshwater withdrawal from 1950-2005 (Figure 1b). Electric generation, specifically thermoelectric cooling water and irrigation withdrawals are the dominant components of the total fresh water withdrawal nationwide (40% and 36%, respectively), followed by public and domestic water supply (14%). Although thermoelectric cooling use is a major fraction of the withdrawal, most of this use is not consumptive. In the 1995 water use survey, for example (USGS, 1998), where consumptive use was last reported, thermoelectric cooling was a relatively modest fraction of the total consumptive use (3%), and irrigation the most significant consumptive user of water (82%). Trends in freshwater withdrawal from surface and

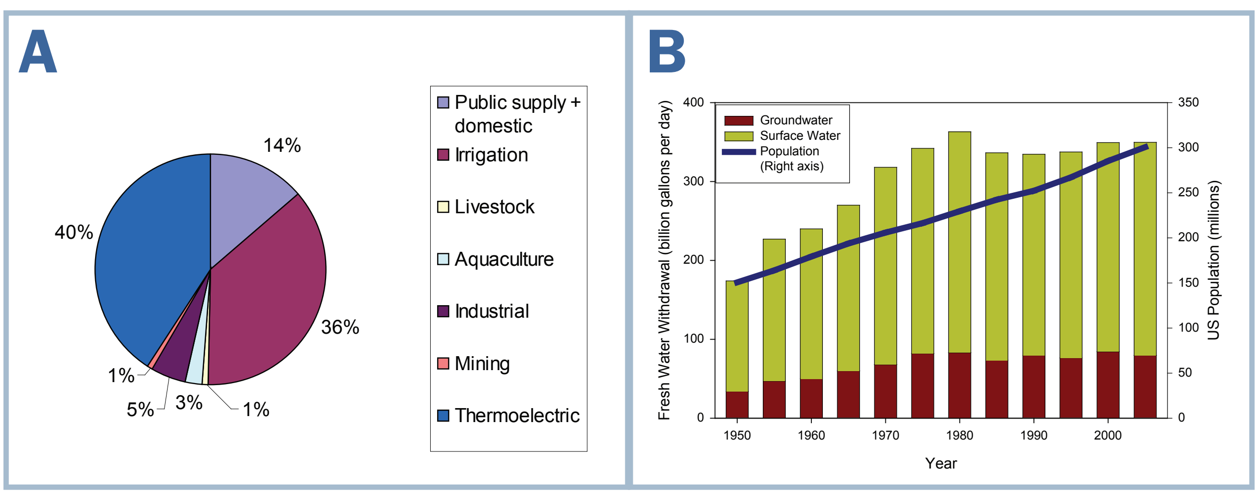



Figure 1. (a) Water use by sectors in 2005 (Source: Kenny et al., 2009), and (b) trends in total freshwater withdrawal (1950-2005).

groundwater sources provide interesting insight into the future development of water resources in the United States (Figure 1b): as population has continued to grow, total water withdrawals have remained relatively flat. The two sectors using the most water, thermoelectric generation and agriculture, have both increased their efficiency of water use over the last two to three decades, such that increased electricity generation and food production have been obtained without the use of additional water supplies. Water used instream for hydroelectric generation is not considered in this analysis and is assumed to not directly affect offstream uses.

The 2005 water use survey data at the county level (Kenny et al., 2009) forms the baseline for this analysis. Total freshwater withdrawals reported in the 2005 survey are shown in Figure 2 where the volumes of freshwater withdrawn are normalized to the county area and shown in inches per year. The withdrawals associated with thermoelectric cooling and irrigation are shown in Figure 3. There are clear geographic variations in the major sectors associated with freshwater withdrawal: irrigation withdrawals occur largely in the western states, whereas large thermoelectric withdrawals are in the eastern states and clustered near the major rivers, such as the Ohio and Mississippi River basins, and the Great Lakes. These data are shown in the units reported by USGS, i.e., in million gallons per day or mgd, for each county.

## Water Demand in 2030 and 2050

Any projection of future use is based on assumptions in the growth or decrease in demand in each of the major sectors of water use, which depend on uncertain demographic and economic forces. For the purpose of this analysis, as noted above, business-as-usual projections of future water demand were 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.

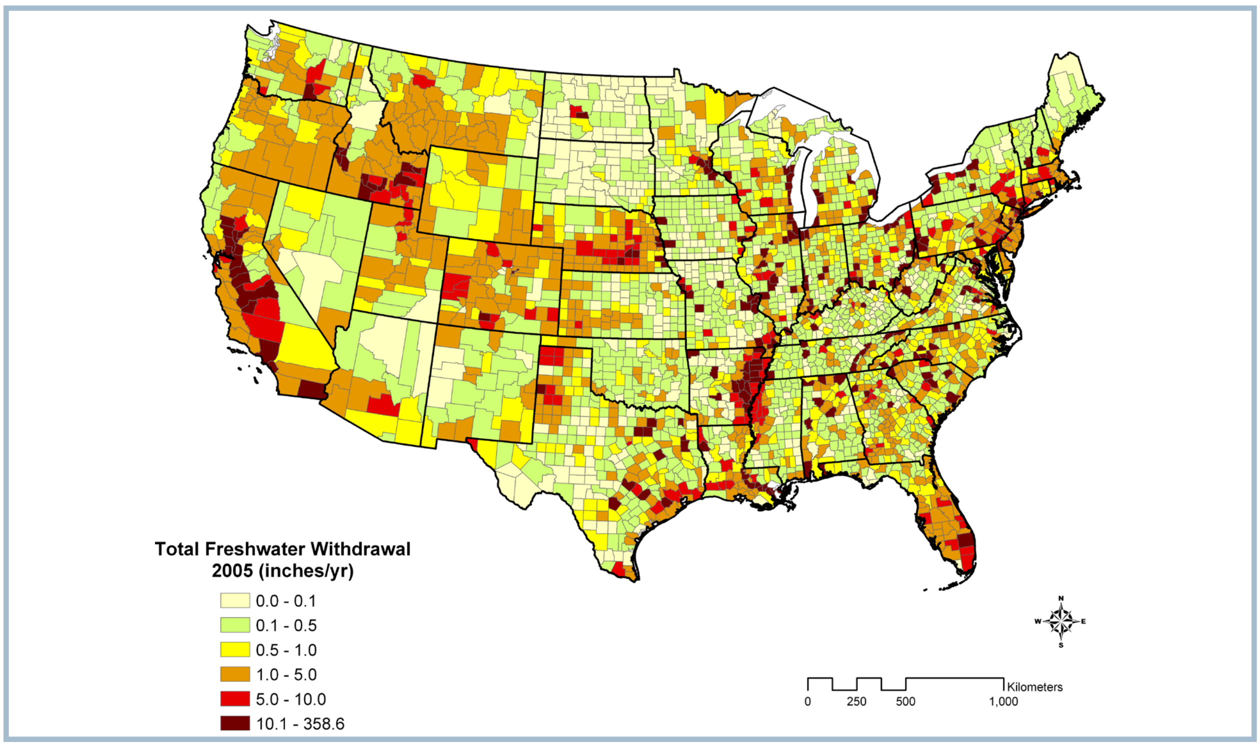



Figure 2. Total freshwater withdrawal in 2005 at the county level (Kenny et al., 2009). The specific sectors considered in the USGS water use survey include thermoelectric cooling, irrigation, public supply, industrial, commercial, livestock, aquaculture, and mining water use. Total volumes of water withdrawal in mgd are normalized to county area and reported in inches for direct comparison with precipitation and related climatic variables.

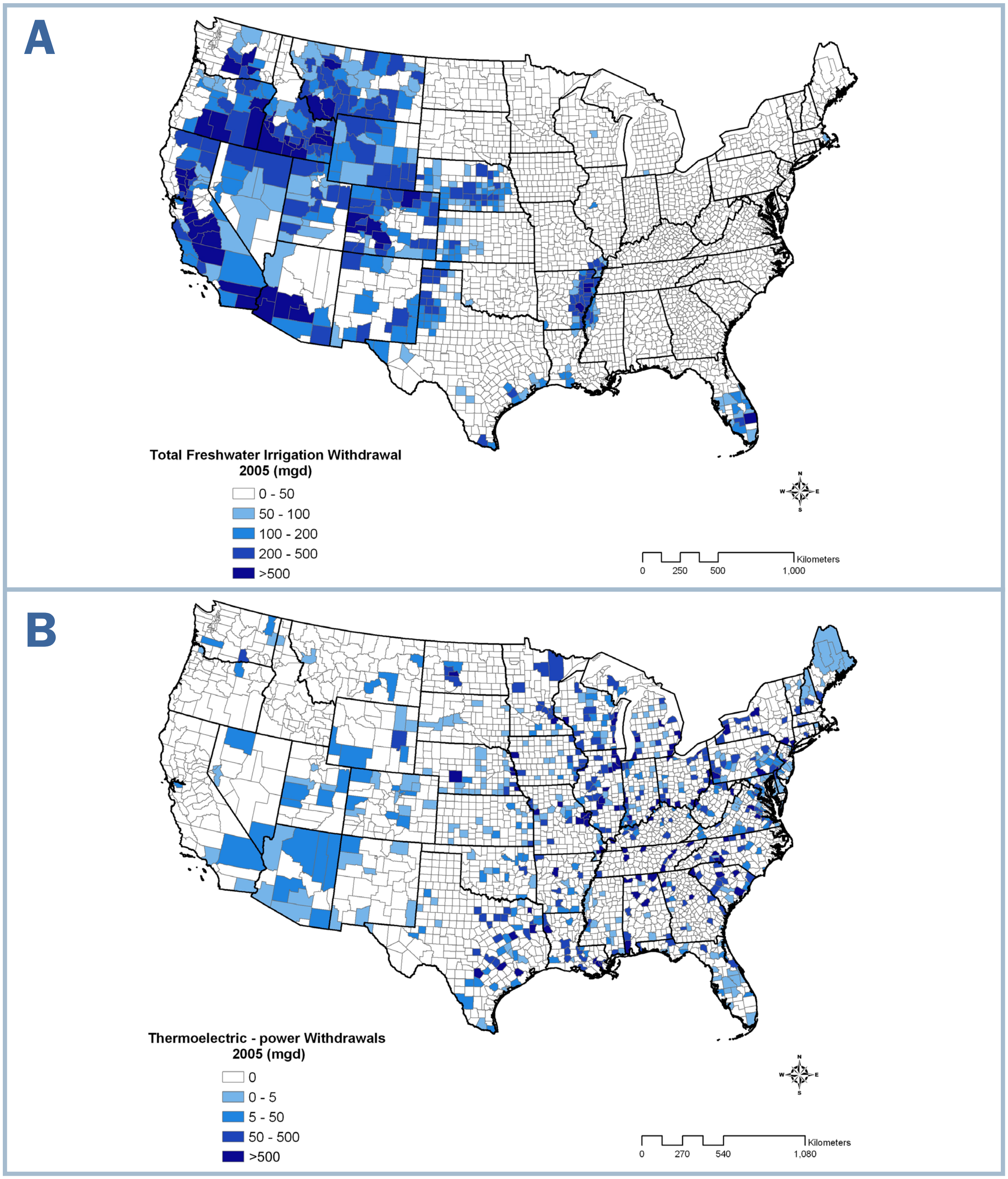



Figure 3. Withdrawals associated with irrigation and thermoelectric cooling, reported in units of mgd by the USGS (Kenny et al., 2009).

Municipal water demand was projected based on estimated future population and with current levels of per capita water use, similar to approaches used in prior analysis (Roy et al. 2003; 2005). Thermoelectric water use was projected based on new power generation and water withdrawal per unit generation at levels typical in modern power plants. New electricity generation demand estimates until 2030 were obtained from the Energy Information Administration (EIA), and extrapolated linearly to 2050. The EIA estimates are based on a model of the energy-economic system of the U.S., and also include projections of fuel type used for electricity generation (Annual Energy Outlook, EIA, 2009). Until 2030, EIA projections show the continued dominance of fossil and nuclear fuel sources in the electricity supply mix. For the purpose of this analysis, it assumed that future generation will have cooling water needs at a value similar to that reported in modern plants with evaporative cooling. These projection approaches are detailed below.

## Population Change Forecast

Total population in 2050 was projected for the U.S. by the Census Bureau (CB). Population in the U.S. in 2050 is projected to increase by 48.8%, from 282.1 million in 2000 to 419.9 million (U.S. Census Bureau, 2008). The anticipated increase is relatively linear through this period (Figure 4). Population projections at the state level have also been made by the Census Bureau for the period 2010-2030. Population projections for future years at the county level for the entire U.S. are not readily available. At the county level, total population data are available from the CB for the period of 2000-2008. In previous analysis (Roy et al., 2003; 2005), population growth rates at the county level for the period of 1990-2000 were used to project population for the period of 2000-2025. In this analysis, population change rates for the period of 2000-2008 were used to project future populations for the period of 2008-2050. The projected population at the county level was aggregated to the state level and compared to data from CB for the period of 2010-2030. Projected population at the state level at five year intervals compared well to projections by the CB ($r^2$> 0.99), with the largest discrepancy in projections occurring in Florida. Projected total population in the U.S. using the county-by-county

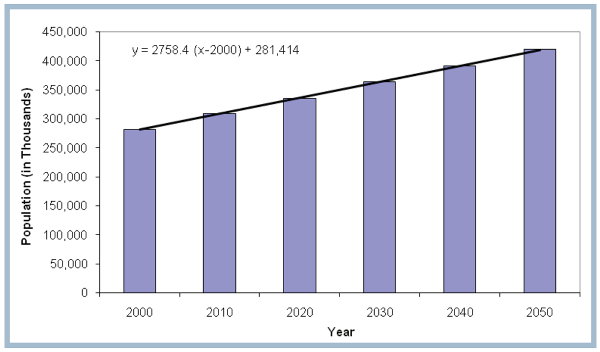



Figure 4. Projected U.S. total population for the period of 2000-2050 by U.S. Census Bureau.

method for 2050 is 419.0 million, which compares well to the CB national projection of 419.9 million. The county-level population projection approach was therefore used for this analysis, and for subsequent estimates of water use.

## Municipal Water Demand Projection

Total freshwater demand for the municipal sector (including domestic supply) was projected based on population in 2030 and 2050 and per capita water use in 2000. 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. Per capita municipal water use varies through the country, and at the state level, varies from 54 gallons per capita per day to 187 gallons per capita per day (Kenny et al., 2009), with consistently higher values in the more arid parts of the country. In forecasting future municipal water demand in a given county, the per capita water use was assumed to remain at the 2005 levels, i.e., no change in per capita rates were assumed to occur as a result of climate change. Total municipal water demand is projected to increase by 32.8% in 2030 and by 54.8% in 2050 from 2005 levels.

## Total Power Generation Forecast

To estimate the total power generation over 2006-2050, electric generation projected by the EIA for the period of 2006-2030 at the Energy Market Module (EMM) Regions was used (EIA, 2009). The projected electric generation is largest in the Southeastern Electric Reliability Council Region (excluding Florida) and the East Central Area Reliability Coordination Agreement Region (Figure 5). When forecasting the energy demand, the EIA assumes for

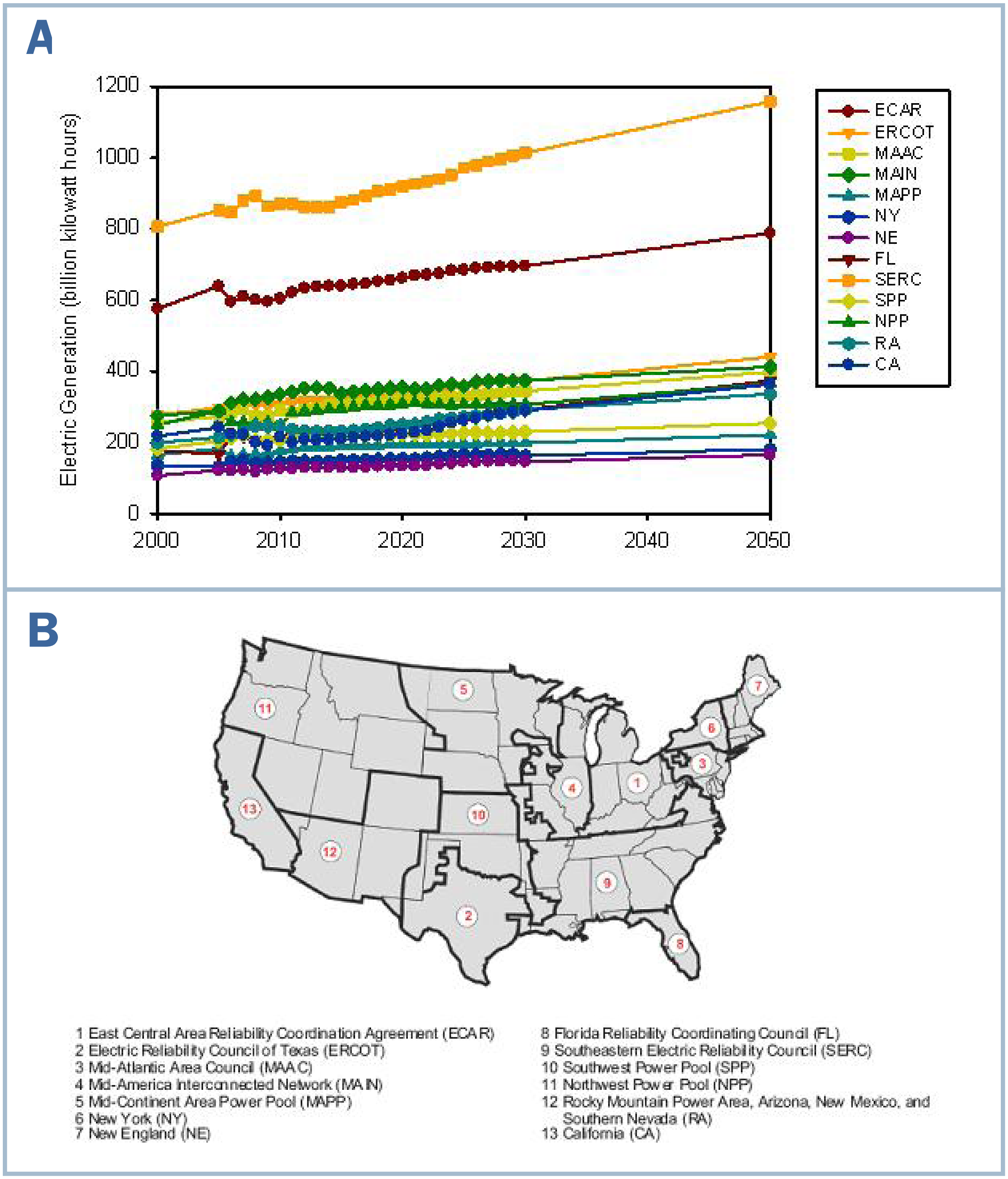



Figure 5. Projected electricity generation by EMM regions in the U.S. for the period of 2006-2050 (Source: EIA, 2009). EIA projections cover the period to 2030. These were linearly extrapolated to 2050 for the purpose of this analysis.

its reference case that growth in the world economy and fuel demand will recover by 2010, and that this growth will continue through the rest of the projection period (EIA, 2009). To extend the projections by EIA to 2050, the growth estimated for the period of 2010-2030 was extrapolated forward.

The projected thermoelectric generation in 2050 at the EMM region was first converted to the state level by applying percent changes for the period of 2005 to 2050. 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.

### Projecting Thermoelectric Water Withdrawal

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, a mid-point range in a recent DOE analysis of water use in modern closed-loop cooling power plants where values ranged from 226-1,100 gallons/Megawatt-hour (Feeley et al., 2008). This analysis included coal, natural gas, and nuclear power plants, all which have a need for cooling water. Power plants with closed-loop cooling use water multiple times, typically in cooling towers, before discharge back to the source water body. In closed-loop processes, the total quantity of water withdrawn is significantly lower than once-through cooling power plants (averaging 27,000 gallons/Megawatt-hour; Feeley et al., 2008).

The amount of thermoelectric water use in 2030 and 2050 was calculated as the total thermoelectric freshwater withdrawal in 2005, plus the amount of water withdrawal due to new power generation. The water use per unit power generation of 500 gallons/Megawatt-hour was used based on the assumption that water withdrawal per unit generation in future will be low due to the use of improved cooling technologies (typically the use of closed-loop cooling). Based on increasing generation needs alone, projected water withdrawal for thermoelectric generation for 2030 and 2050 increased by 8.45% and 13.5% from 2005 levels.

### Projecting Total Water Demand in 2030 and 2050

Total water demand from different sectors in 2030 and 2050 can be estimated as total freshwater withdrawal in 2000 plus the projected changes in municipal and thermoelectric sectors. The analysis assumes that changes in irrigation, industrial, commercial, livestock, aquaculture, and mining water uses are less significant, and these were held at 2005 levels. Of these water uses, assumption related to irrigation is the most consequential, and merits further explanation. 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 dataset, 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 . It is conceivable that irrigation water withdrawals will continue a gradual decline in the coming decades as demand in other sectors increases. However, to be conservative, the irrigation withdrawal values were essentially maintained at 2005 levels.

### Climate Projections

For future 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 (IPCC AR4, 2007). Because of the complexity of processes simulated by GCMs, their results vary, especially when variables such as precipitation are considered. For impact studies, such as this one, 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 (e.g., Christensen et al., 2007; Reichler and Kim, 2008; Maurer et al., 2007; Brekke et al., 2008; Pierce et al., 2009). For this study, we follow this trend in recent research and use an ensemble of GCM projections.

The set of 16 GCMs from which we draw our ensemble is shown in Table 1 below. 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) multi-model dataset (Meehl et al., 2007).

Because the spatial scale of GCM output, typically 200 to 500 km, is too large to characterize climate over smaller areas, we used spatial downscaling to make the data more relevant at the regional scale being considered in this report. For this work we used published statistically downscaled data from the 16 models in Table 1 spanning a 150-year period from 1950 to 2099 (Maurer et al. 2007) downscaled to a 1/8° resolution (resulting in cells of approximately 12 by 12 km). Statistical downscaling uses long sequences of observed climate to establish statistical relationships between large- and fine-scale climate features. These are then applied to future projections to infer the fine-scale response implicit in the large-scale GCM projections. The historical data used for the downscaling is the gridded National Climatic Data Center Cooperative Observer station data, developed as described by Maurer et al. (2002).

For each GCM, outputs using different greenhouse gas emissions scenarios are available, three of which have been used for the standardized model comparisons as part of the CMIP3 work. These are labeled Scenarios A1B, A2, and B1, following the convention of Nakicenovic et al. (2000). Each scenario embodies a different storyline for growth, technology diffusion, and interconnectivity among different regions. Broadly speaking, the three emission scenarios in the CMIP3 work represent a higher (A2), medium (A1B), and lower (B1) rate of emission growth through the 21st century. For the purpose of this analysis the A1B scenario projections for temperature and precipitation were used. Over the time period of interest in this analysis, 2020-2059, the differences between emission scenarios are relatively small, and the selection of one scenario over another would not change the results very much. Greater divergences between scenarios occur by the late 21st century, but this was not evaluated in this study.

To account for year-to-year and decadal variations in projections of temperature and precipitation projected by the GCMs, reflecting longer-term cycles in the underlying oceanic and atmospheric processes, projections for 2030 and 2050 were represented using twenty-year averaging periods about the mid-point years: the average climate for 2020 to 2039 represents 2030, and 2040 to 2059 represents 2050. For the analyses requiring monthly data, the average monthly value across the 20-yr period was used. Thus, for January 2030, we use an average of January values for each of the 20 years from 2020 to 2039. In the descriptions that follow, when we refer to temperature or precipitation from 2030 or 2050, we are referring to the average values over a 20-year period that is centered around 2030 or 2050.

The 1/8° resolution downscaling results in approximately 54,000 grid cells to cover the land area of the 48 conterminous U.S. Because we are also looking at monthly values at each cell over a 20-year period and 16 GCMs, this results in an enormous amount of data. For the purpose of this analysis, the climate data were processed using the Climate Wizard tool (http://ClimateWizard.org, Girvetz et al. 2009). The Climate Wizard tool was used to calculate the median, minimum and maximum of the 16 GCMs at each grid cell for the monthly average temperature and precipitation projected during 2020-2039 and 2040-2059. Similarly, the 20th, 25th, 40th, 60th, 75th, and 80th percentiles were calculated across all 16 GCMs for the projected monthly temperature and precipitation.

## Available Precipitation: Historical Values and Projections for 2030 and 2050

Available precipitation, defined as the difference between precipitation and potential evapotranspiration (PET) for each month of the year (Roy et al. 2005), was computed based on averages of historical data at 344 climate divisions over the period of 1934-2000. Monthly temperature and precipitation data at the climate division level was obtained from the National Oceanic and Atmospheric Administration (http://www.cpc.ncep.noaa.gov/soilmst/index_jh.html; methodology in Huang et al., 1996).

Table 1 - Table of 16 candidate GCMs for use in this study.

| | Modeling Group, Country | IPCC Model I.D. | Primary Reference |
|---|---|---|---|
| 1. | Bjerknes Centre for Climate Research | BCCR-BCM2.0 | [Furevik et al., 2003] |
| 2. | Canadian Centre for Climate Modeling & Analysis | CGCM3.1 (T47) | [Flato and Boer, 2001] |
| 3. | Météo-France / Centre National de Recherches Météorologiques, France | CNRM-CM3 | [Salas-Mélia et al., 2005] |
| 4. | CSIRO Atmospheric Research, Australia | CSIRO-Mk3.0 | [Gordon et al., 2002] |
| 5. | U.S. Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA | GFDL-CM2.0 | [Delworth et al., 2006] |
| 6. | U.S. Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA | GFDL-CM2.1 | [Delworth et al., 2006] |
| 7. | NASA / Goddard Institute for Space Studies, USA | GISS-ER | [Russell et al., 2000] |
| 8. | Institute for Numerical Mathematics, Russia | INM-CM3.0 | [Diansky and Volodin, 2002] |
| 9. | Institut Pierre Simon Laplace, France | IPSL-CM4 | [IPSL, 2005] |
| 10. | Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan | MIROC3.2 (medres) | [K-1 model developers, 2004] |
| 11. | Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA | ECHO-G | [Legutke and Voss, 1999] |
| 12. | Max Planck Institute for Meteorology, Germany | ECHAM5/MPI-OM | [Jungclaus et al., 2006] |
| 13. | Meteorological Research Institute, Japan | MRI-CGCM2.3.2 | [Yukimoto et al., 2001] |
| 14. | National Center for Atmospheric Research, USA | PCM | [Washington et al., 2000] |
| 15. | National Center for Atmospheric Research, USA | CCSM3 | [Collins et al., 2006] |
| 16. | Hadley Centre for Climate Prediction and Research / Met Office, UK | UKMO-HadCM3 | [Gordon et al., 2000] |

The available precipitation in 2030 and 2050 was estimated using a similar approach, except that GCM-downscaled values of precipitation and temperature were used rather than historical values. The ensemble median values of the 16 climate models in Table 1 were used to represent future precipitation and temperature for each month.

## Projecting Evapotranspiration and Available Precipitation in Future Years

In projecting the available precipitation in 2030 and 2050, the $50^{th}$ percentile from the 16 GCMs in Table 1 was used. For each of years analyzed, 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 of that month was counted as 0. The monthly potential evapotranspiration (PET) was estimated based on projected monthly temperature, using the Hamon equation (Hamon, 1961):

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

E = evaporation, day t (mm/day)

Ht = average number of daylight hours per day during the month in which day t falls

es = saturated vapor pressure at temperature $T_t$ (kPa)

$T_t$ = temperature, day t (°C)

Ht was calculated by using the maximum number of daylight hours on day t.

Saturated vapor pressure es was estimated as:

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

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. The limited data requirements are an important constraint because we are applying the model across a broad geographic scope and into the future, where additional data (e.g., soil moisture and wind speed) are not easily available. Furthermore, comparisons of multiple PET estimation approaches have demonstrated that the Hamon method is generally preferable for contemporary climate studies (Vorosmarty et al., 1998). A similar cross-comparison of PET estimation methods in the Southeast (Lu et al., 2005), where different techniques were used to compute water budgets for 36 watersheds, identified the Hamon equation as one of three methods suitable for use. For these reasons, future estimates of PET, used to compute the available precipitation, were based on the Hamon equation. PET projections do not consider changing land use as a factor, given the time frame and spatial scale applied in this analysis, changing land use was not variable over time.

## Ratio of Future Water Demand and Available Precipitation

As a metric representing the intensity of water development in a region, the ratio between water demand and available precipitation can be computed. To compute the ratio of future demand and available precipitation, 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 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 precipitation, and are representative of what is called water resources “development” in a region.

Besides ratios of future water demand 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 demand. The irrigation demand is reported as an annual value, and as noted above, is assumed to remain flat over the time horizon of the analysis on an annual basis. However, during the year, irrigation water is applied to meet the deficit between precipitation and evapotranspiration, and the demand is not constant over the year. In estimating irrigation demand in June, July, and August, it was assumed that irrigation needs are proportional to 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 an Index of Water Sustainability and Climate Susceptibility

The water resources literature presents several examples of indices that are used to integrate different measures of water availability and access to human populations (e.g., Loucks and Gladwell, 1999; Vorosmarty et al., 2005). Well known examples include the Water Stress Index defined as the ratio of available river runoff to population in basin, with a level of 1700 $m^3$ per capita per year being defined as the threshold below which a basin may be considered to be water stressed (Falkenmark et al., 1989).

Another simple index is the basic water requirements (BWR) value of 50 liters per capita per day to meet basic human needs (Gleick, 1996, 1998). A multidimensional index in common use is the Water Poverty Index that combines physical and socioeconomic factors and has been used to rank water stress in many regions of the world (Lawrence et al., 2002; Sullivan et al., 2003). Similarly, Hurd et al. (1999) assessed relative regional vulnerability to climate change using a set of unweighted indices representing offstream and instream uses, representing variables such as levels of freshwater withdrawal, groundwater depletion, flood risk, etc.

Several of the published indices were developed to meet different purposes, ranging from human access to clean water or ecosystem health. In the particular context of this study in the United States, where access to water for basic human needs is not a major concern, and where detailed data on water use is readily available through the USGS water use surveys, a more targeted index may be developed that is focused on water supply concerns in coming decades. For this reason, building on past work (Roy et al., 2003, 2004), a water supply sustainability index was developed to evaluate multiple water constraints in a composite index. The index can be computed using historical precipitation (e.g., 1934-2000) or using future projected precipitation for the 21$^{st}$ century from GCMs. Metrics considered in the index include natural available precipitation, the extent of water development already in place, dependence on groundwater, the region's susceptibility to drought, projected increases in water use, and the difference between peak summer demand and available precipitation, a measure of storage requirements. Regardless of the structure of the index used, it is important to emphasize that it is at best an indicator, and a means to summarize information across a broad geographic domain, in this case the lower 48 states of the U.S.. The goal of the index is to present information compactly, and to highlight areas that need further attention, and more refined local-scale analysis (e.g., see case studies in the the West discussed by Anderson and Woosley, 2005).

In compositing the sustainability index for future years, five criteria were used. The risk to water sustainability for counties meeting two of the criteria are classified as "moderate," those meeting three of the criteria are classified as "high," and those meeting four or more are classified as "extreme." Counties meeting fewer than two criteria are considered to have low risk to water sustainability. The criteria are as follows:

1. Extent of development of available renewable water: greater than 25% of available precipitation is used (calculated based on projected water demand and available precipitation in 2050). The larger the fraction of available precipitation that is used to meet human needs, the greater the risk to supply when this quantity changes.

2. Sustainable groundwater use: ratio of groundwater withdrawal to total withdrawal is greater than 25% (based on current groundwater withdrawal). Greater withdrawals may be indicative of unsustainable use of aquifers.

3. Susceptibility to drought: Summer deficit, as described above, is greater than 10 inches, and this water requirement must be met through stored surface water, groundwater withdrawals, or transfers from other basins. In estimating irrigation demand in June, July and August, it was assumed that irrigation needs are proportional to monthly deficit in available precipitation (P– PET).

4. Growth in water demand: The increase of total freshwater withdrawal between 2000 and 2050 is more than 20%. Based on the discussion above, growth in water demand is driven largely by population growth and the need for new thermoelectric generation.

5. Increased need for storage: summer deficit increases more than 1 inch over 2005 and 2050. As noted in item 3 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.

# Results

## Projected Precipitation and Temperature Changes by the Climate Models

A plot of projected precipitation changes between 1961-1990 and 2020-2039 (Figure 6) indicates decreases in precipitation in the West and parts of the Gulf states and increases in the Northeast and parts of the Midwest. Projected precipitation changes between 1961-1990 and 2040-2059 indicate similar spatial patterns, although with greater differences from 20th century values: there are decreases in the Gulf states (Texas) of more than 1 inch/yr and increases in the Northeast by 2-4 inches/yr (Figure 7). California stands out as an exception with changes in the Sierra region and parts of the coast moving from a decrease to an increase. A closer scrutiny of the underlying data show limited systematic variation in the precipitation for this region as a result of climate change, and the absolute changes (going from -1 inch to +1-2 inches) are relatively small compared to the total precipitation.

Projected temperature increases between 1961-1990 and 2020-2039 are 0.9 – 1.95 °C, with the highest temperature increases occurring in parts of the Midwest and parts of the western mountain regions (Figure 8). Projected increases in temperature for 2040-2059 are greater and range from 1.5 to 3 °C. The highest temperature increases are in the Midwest and mountain regions of the West (Figure 9).

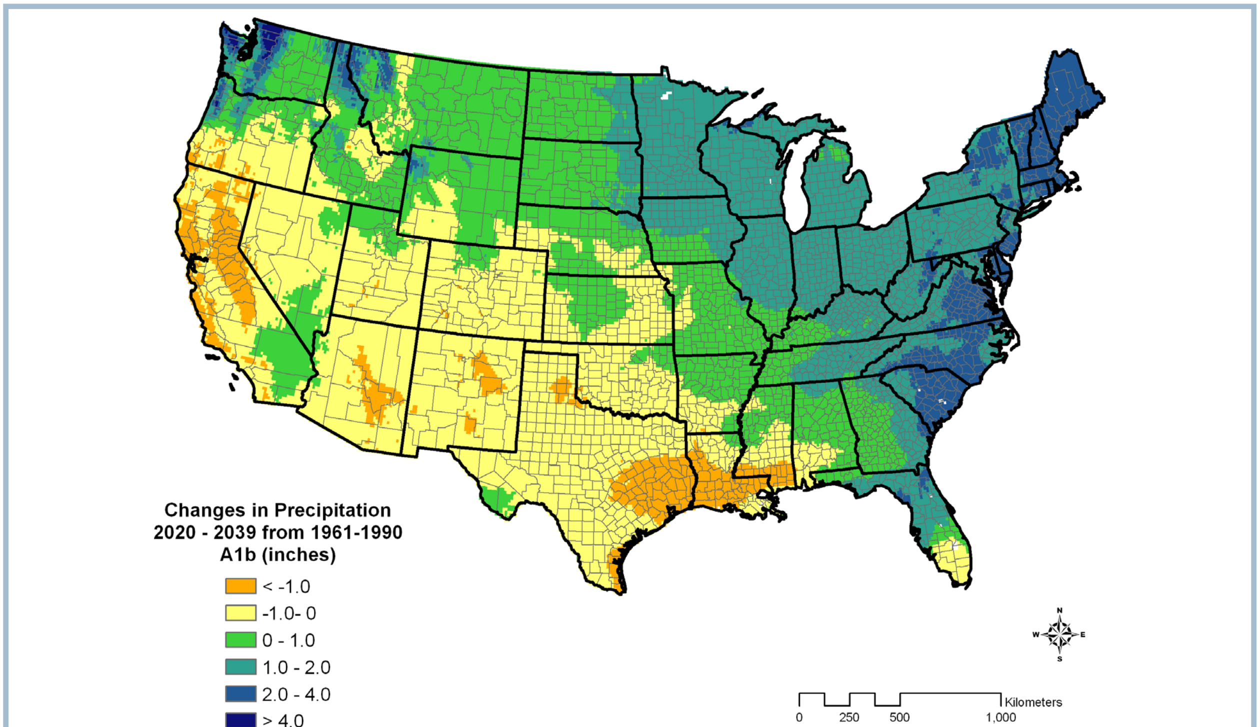



Figure 6. Predicted changes in mean annual precipitation from 1961-1990 to 2020-2039 (median of 20-year means computed from the 16 GCMs in Table 1).

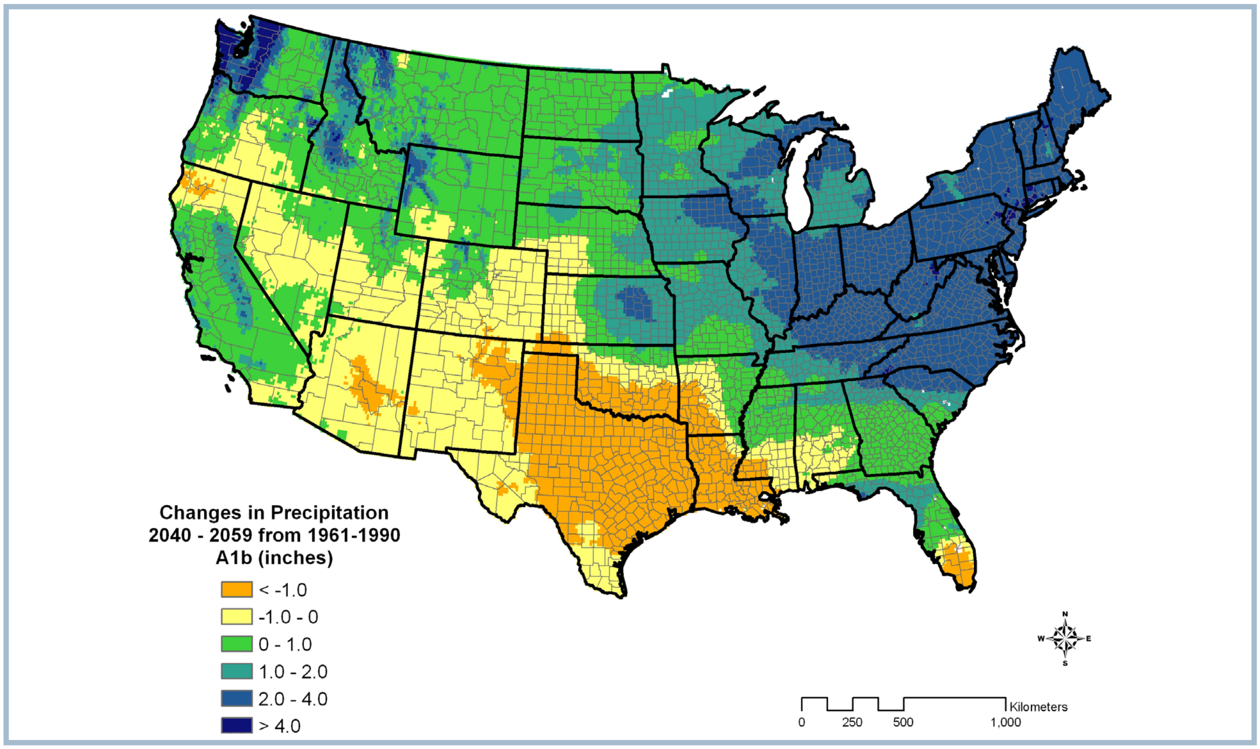



Figure 7. Predicted changes in mean annual precipitation from 1961-1990 to 2040-2059 (median of 20-year means computed from the 16 GCMs in Table 1).

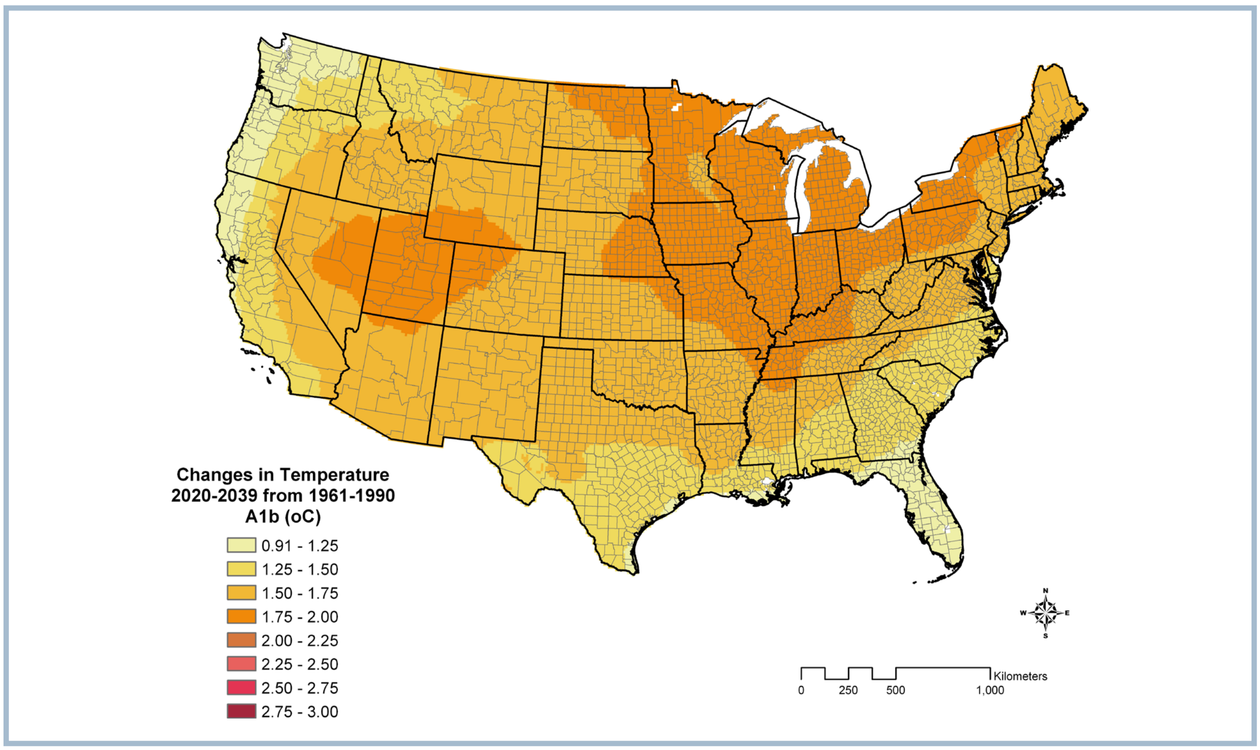



Figure 8. Predicted changes in mean temperature from 1961-1990 to 2020-2039 (median of 20-year means computed from the 16 GCMs in Table 1).

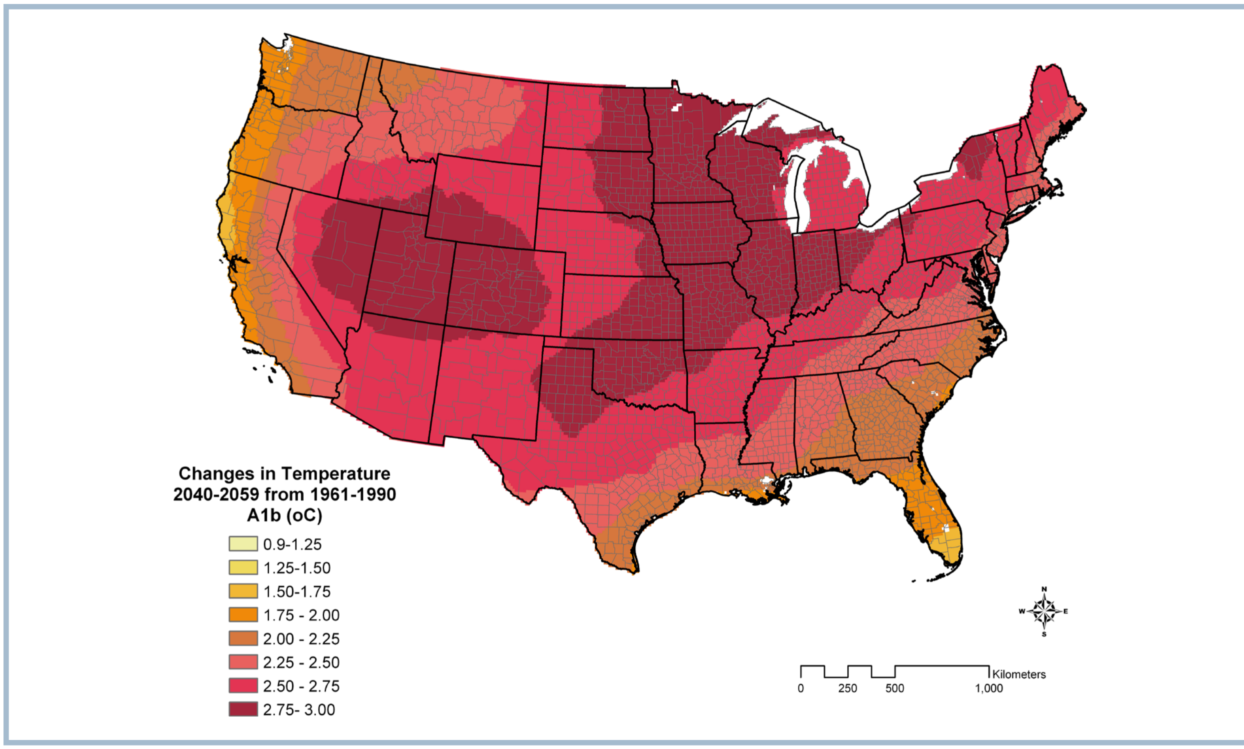



Figure 9. Predicted changes in mean temperature for the period of 1961-1990 to 2040-2059 (median of 20-year means computed from the 16 GCMs in Table 1).

A quantitative measure of the variation in projected precipitation across different GCMs defined as (75th percentile value minus 25th percentile value)/ Median, termed the interquartile ratio, is shown in Figure 10, and was computed using the Climate Wizard tool. Low values of the interquartile ratio at a given location imply that the 16 GCM projections for this location are in general agreement, whereas large values of this ratio suggest greater differences across models. The precipitation trend projected by the GCMs may be considered more certain when the interquartile ratio among models is low. The interquartile ratio shows agreement in precipitation projections for most of the country with the Southwest and the Great Plains being the exceptions. In other words, the 16 models predict future precipitation with greater uncertainty in these regions, a finding that is important because these are also among the most water short and water stressed regions in the country.

## 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 11. Projected changes in total available precipitation for 2050 from the twentieth century records (1934-2000) are shown in Figure 12. Projected available precipitation is less than 2 inches for many areas in the West and more than 15 inches in the Northeast, Northwest, and South Atlantic. Projected decreases in available precipitation from historical records are generally less than 2.5 inches/yr with some regions in Texas and the Mississippi Basin showing more than 5 inches of decrease. Similar maps for 2030 are presented in the appendix.

Changes in available precipitation are a result both of changing precipitation and of changing PET, as a consequence of higher temperatures. In areas

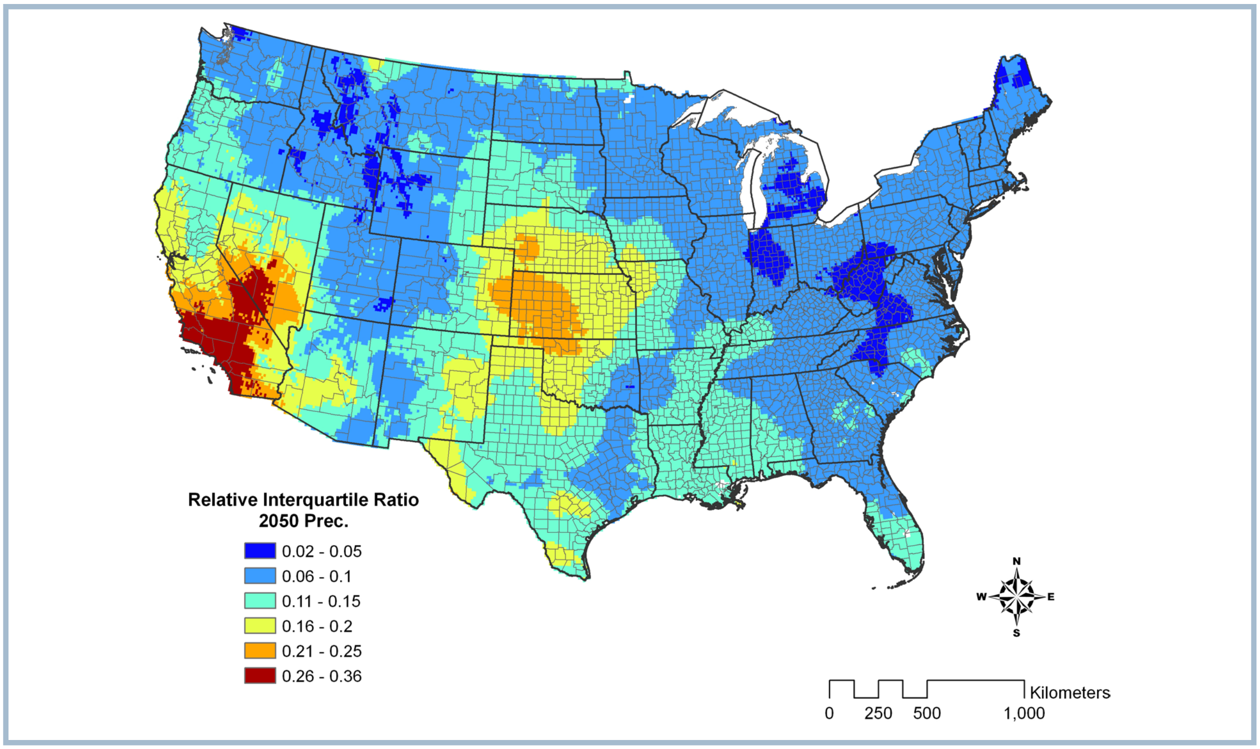



Figure 10. Relative inter quartile ratio (RIQR) for the 2050 precipitation based on analysis of monthly data from 16 GCMs. The RIQR is a quantitative measure of the variation in projected precipitation across different GCMs defined as (75th percentile value -25th percentile value)/Median. Low values of the ratio at a given location imply that the 16 GCM projections for this location are agreement, whereas large values of this ratio suggest differences across models. The RIQR shows agreement in annual precipitation projections for most of the country with the Southwest and the Great Plains being the exceptions. These are among the most water short and water stressed regions in the country.

where both changes are adverse, i.e., higher PET and lower precipitation, the impacts to available precipitation are most significant. Figure 13 shows the projected changes in PET in comparison with changes in precipitation over the 2000-2050 period. The most significant adverse changes are in the central and southwestern regions of the U.S.

The projected available precipitation shows patterns similar to historical precipitation patterns (Roy et al. 2005). The main changes are increases in certain low available precipitation zones (0-5 inches/yr) and decreases in high available precipitation zones (15-25 inches/yr).

## Projected Total Water Demand in 2050

Projected total freshwater withdrawal in 2050 based on changes in municipal and thermo-electric water demand are shown in Figure 14. Projected changes in water demand in 2050 are shown in Figure 15. Similar maps for 2030 are presented in the appendix. Under the business as usual scenario presented here, total water demand is projected to increase by 7.3% in 2030 and by 12.3% in 2050 from 2005 levels.

Total freshwater withdrawals in 2050 are significant in the major agricultural and urban areas

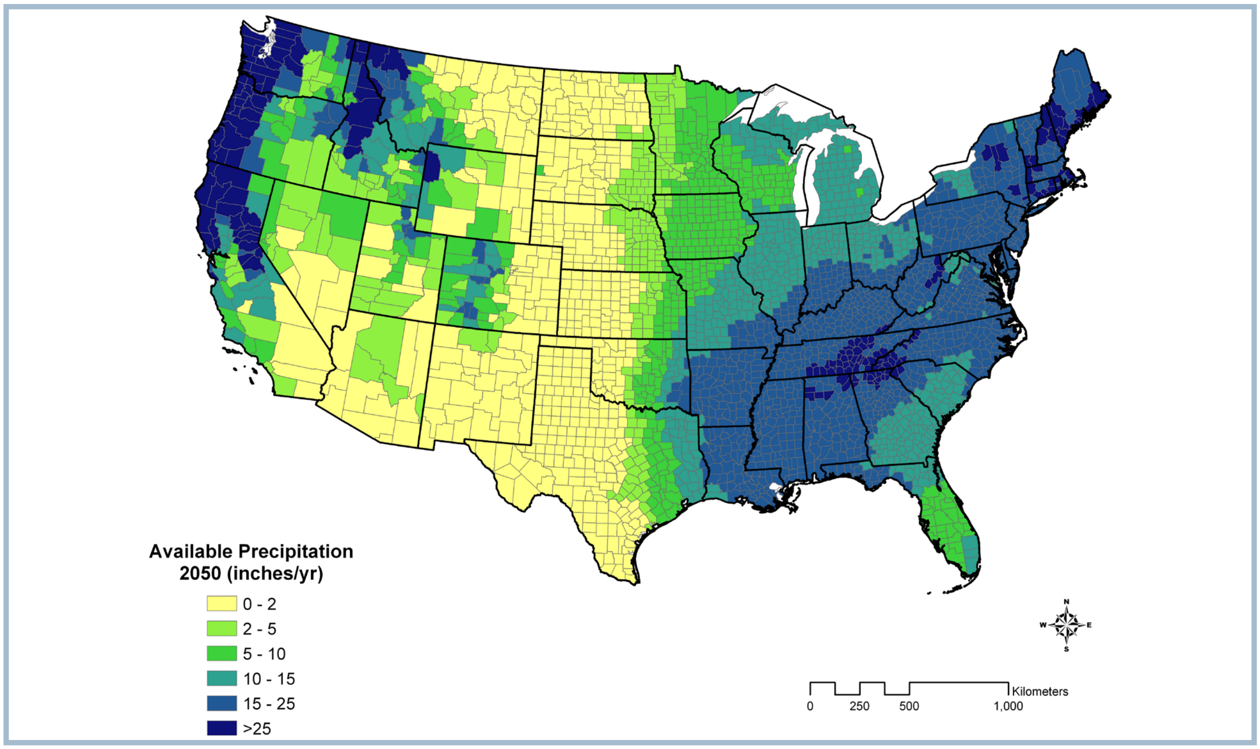



Figure 11. Projected available precipitation in 2050 aggregated to the county level, based on the 50th percentile of projected precipitation by climate models (ensemble of 16 GCMs).

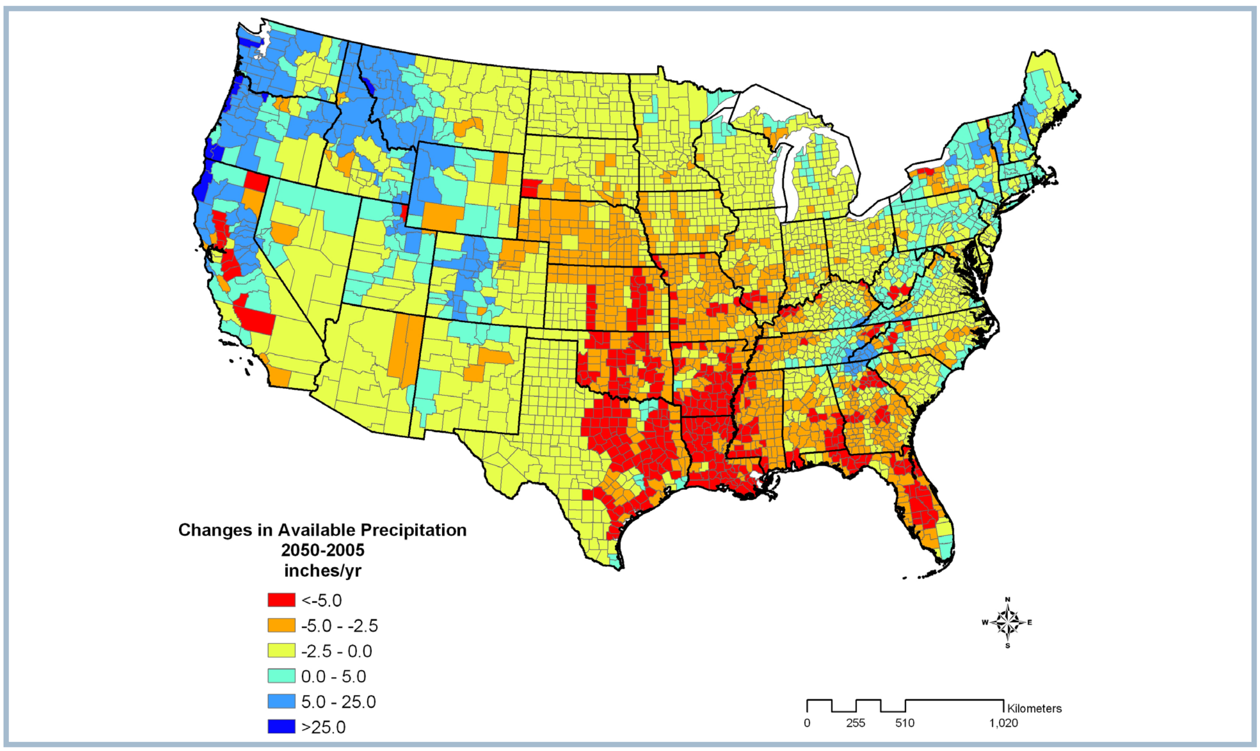



Figure 12. Changes in available precipitation from 2005 to 2050 in inches/yr. 2050 values are based on an ensemble of 16 GCMs and represent conditions between 2040 and 2059.

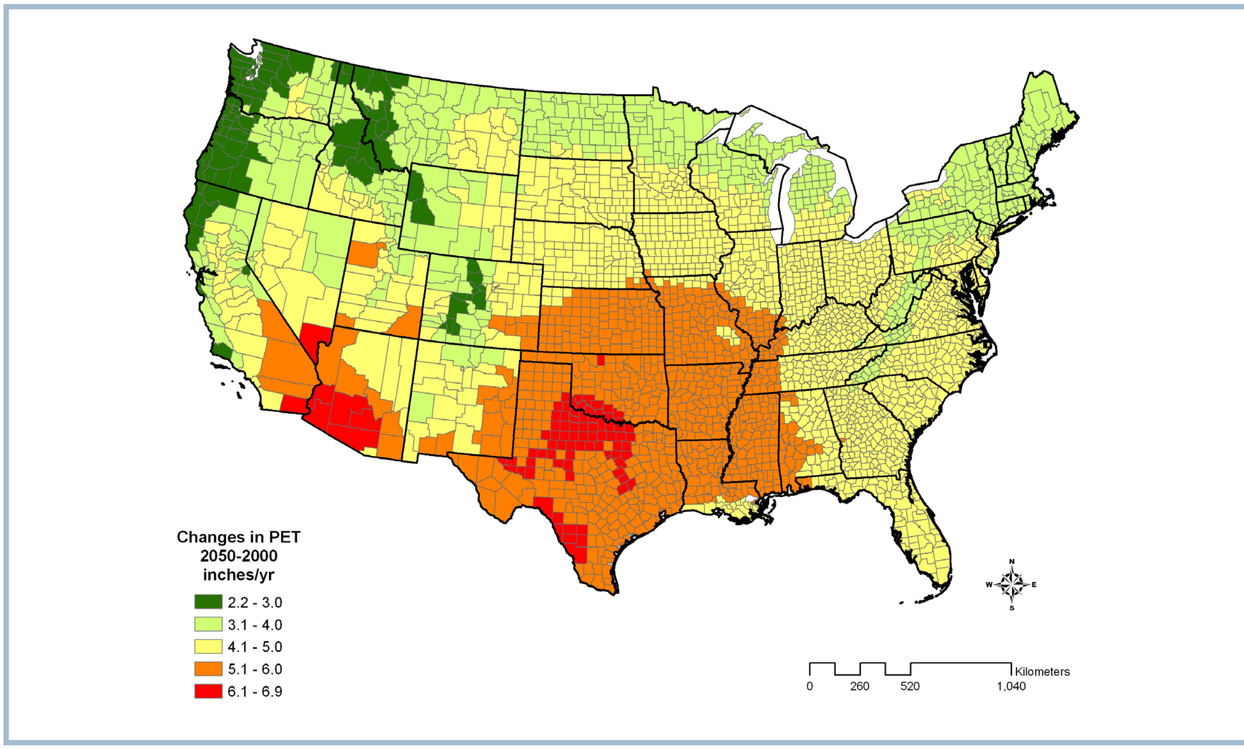



Figure 13. Projected changes in PET during 2000-2050 as a result of projected climate change. The change in PET, estimated using the Hamon equation, largely as a consequence of temperature change, can be compared with the projected change in precipitation (Figure 7).

throughout the nation. Total freshwater withdrawals in 2050 are between 0.2-0.5 inches/yr with some areas in the West showing withdrawals of 1-5 inches. Some areas in California, Texas and the Mississippi River basin show water demand of more than 10 inches/yr. The projected changes in water withdrawal include decreases in the Midwest and increases in some areas in the Southeast, the South, and the West. The projected increases in water demand are 0.1 inches/yr for most regions, with a few areas showing more than 3 inches 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.

## Projected Ratios of Water Demand and Available Precipitation

The projected total freshwater withdrawal as a percentage of available precipitation for 2050 assuming climate change impacts and for historical precipitation (1934-2000) is shown in Figure 16a and Figure 16b. Similar plots for 2030 are presented in the appendix. These maps can be used to compare directly the location and magnitude of impacts due to climate change. As the maps for the historical precipitation show, 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. 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 Southwest.

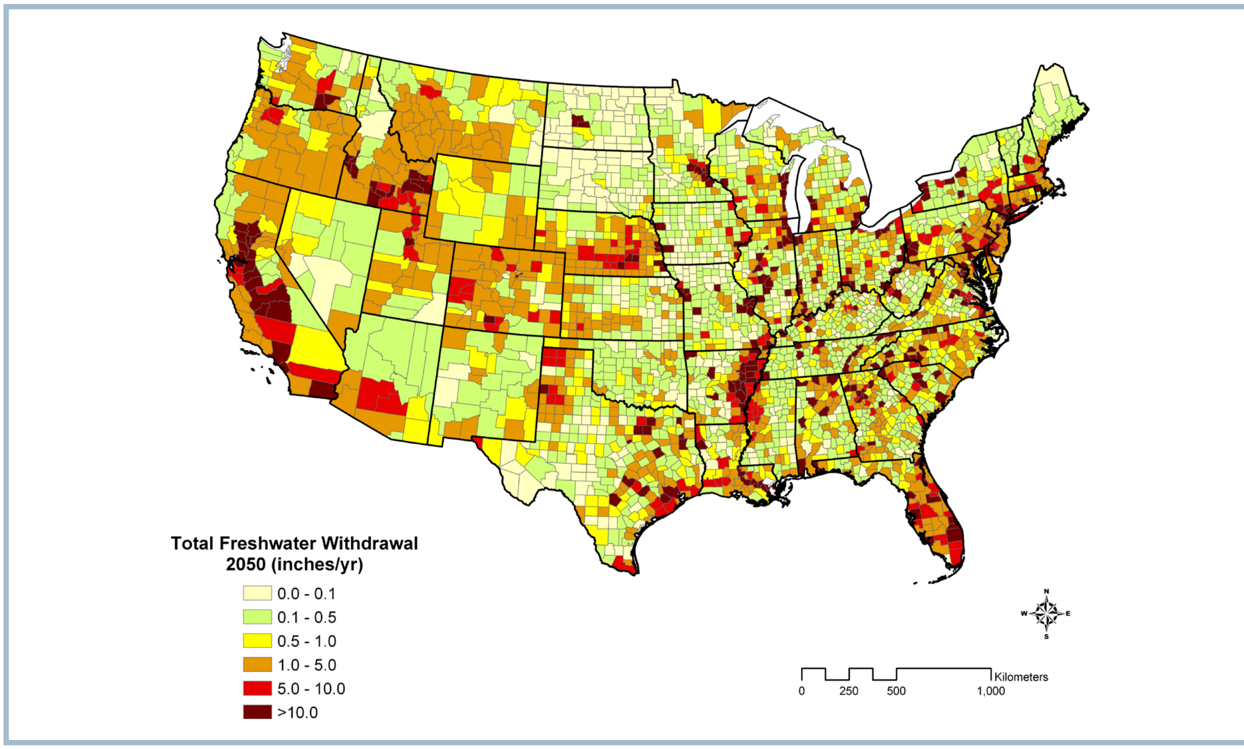



Figure 14. Projected total freshwater withdrawal in 2050 (inches/yr). The 2050 values are based on population growth and increased electric generation capacity, and assuming water use rates for domestic use at 2005 levels, albeit varying by county, and new cooling water use at 500 gallons/ Megawatt-hour. Withdrawals for other sectors are assumed to remain at their 2005 levels.

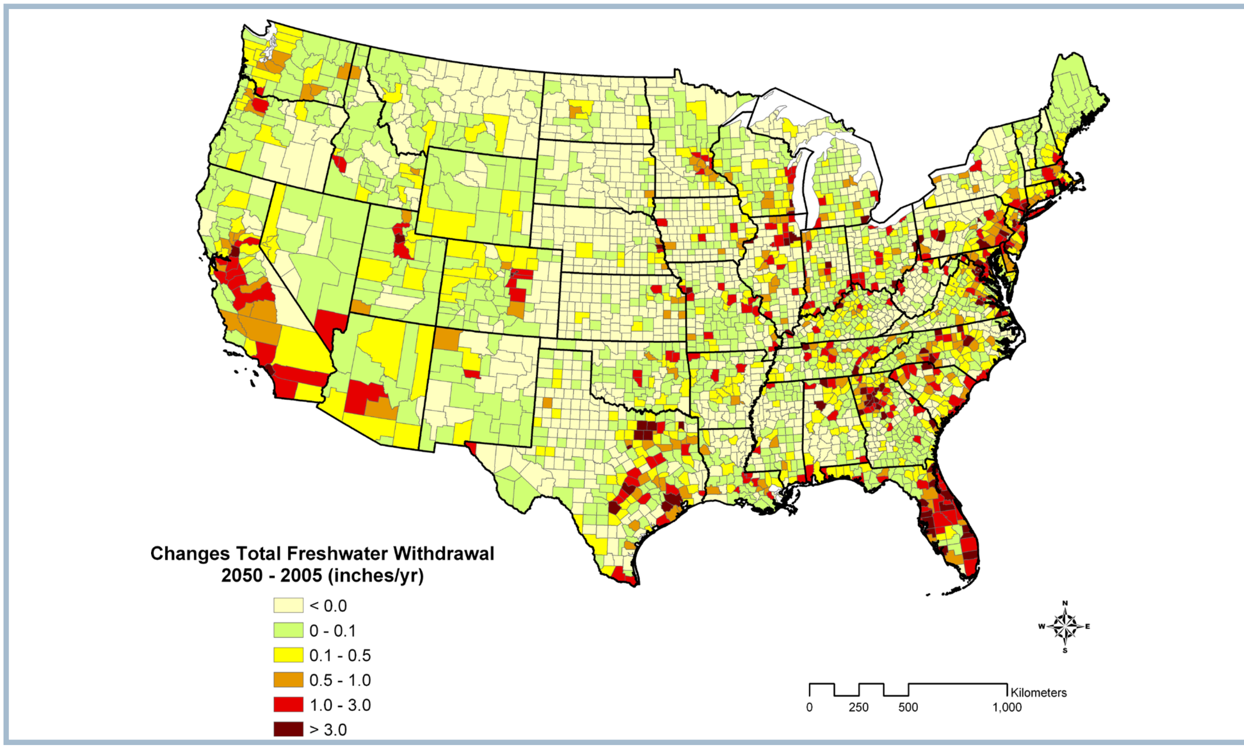



Figure 15. Changes in total freshwater withdrawal from 2005 to 2050 (inches/yr).

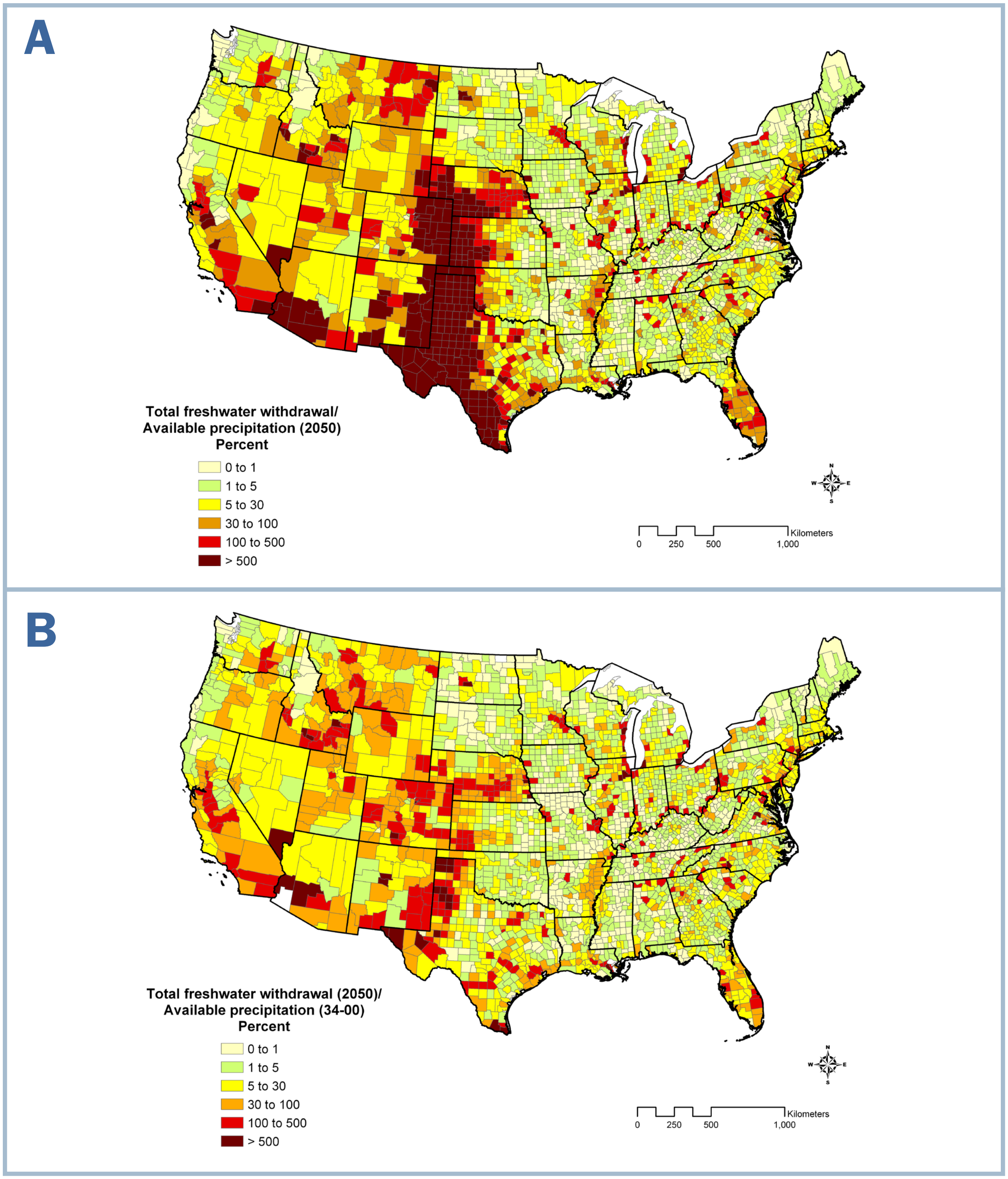



Figure 16. (a) Projected total water withdrawal as percent of available precipitation in 2050. 2050 values are based on an ensemble of 16 GCMs and represent conditions between 2040 and 2059. (b) Projected total freshwater withdrawal in 2050 as percent of historical (1934-2000) total available precipitation.

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 West. 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 (e.g., Texas), due to projected changes in precipitation and increases in temperature, projected PET exceeds precipitation, and results in 0 available precipitation.

## Projected Water Sustainability Supply Index

The water supply sustainability index is computed for 2050 demands using GCM-projected available precipitation and using historical available precipitation (Figure 17). The map of the water supply sustainability index suggests several areas that are at high or extreme risk to climate change impacts in 2050. These areas include California, Nevada, Arizona, Texas and part of the Florida. The majority of the Midwest and the South are considered to be at moderate risk, whereas the Northeast and some regions in the Northwest are at low risk of 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 Edward Aquifer), and much of the Southeast are considerably more amplified in the presence of climate change.

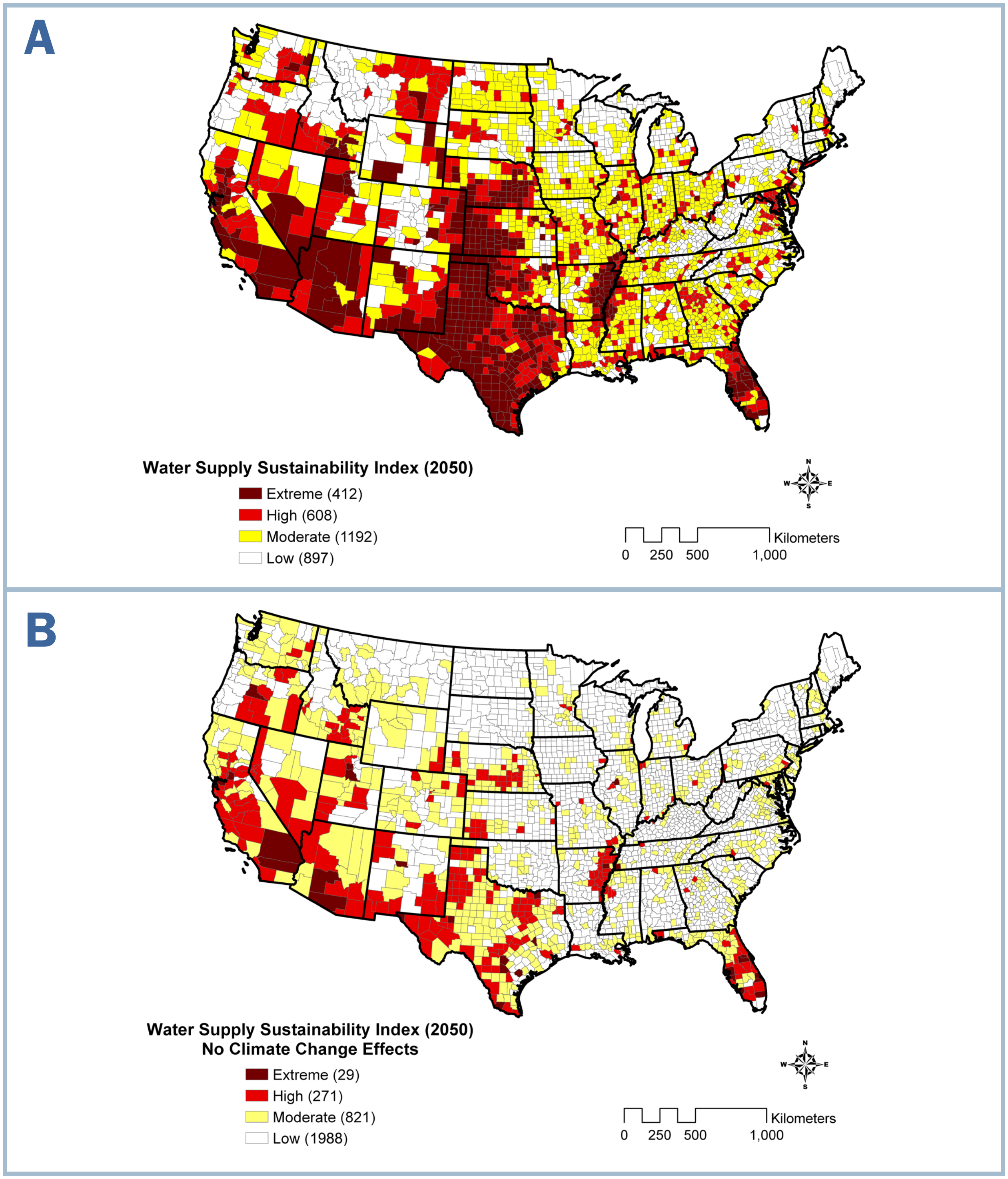



Figure 17. Water Supply Sustainability Index in 2050, (a) with available precipitation computed using projected climate change, and (b) with available precipitation corresponding to 20th century conditions, i.e., 1934-2000. The risks to water sustainability are classified into four categories from Extreme to Low. The numbers in parentheses are the numbers of counties in each category.

# Conclusions

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 business as usual conditions, and to relate this to renewable water availability under future climate conditions. Water resources constraints differ from region to region, and include concerns about growth in demand, insufficient storage to tide over low rainfall periods, and over-extraction of groundwater. In many regions of the U.S., where some of these constraints are apparent—such as areas in the Southwest, 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 from one or more of these factors. Broad scale impacts to water resources that may be anticipated have been addressed in previous work (e.g., Gleick, 1989; Jacobs et al., 2001; Bates et al., 2008). This analysis provides a quantitative and region-specific assessment of the nature of impacts that might be expected across the United States. The maps produced as part of this work are based on fairly straightforward and easily replicable metrics that represent different aspects of water withdrawal and use.

The projected climate changes by 16 GCMs show significant variations in predicted precipitation, although temperature was projected to increase by all climate models. Mean changes in annual precipitation projected by the climate models show decreases in precipitation in many regions of the U.S., including areas that may currently be described as water-short. Projected changes in water demand for the period of 2005 to 2050 are generally at a scale of 0.1 inches, mostly as increases, while projected changes in available precipitation are at a scale of 2.5 inches, often as decreases. Therefore, the higher ratios of water demand as a fraction of available precipitation projected for 2050 are largely a result of changes in available precipitation. The projected changes in available precipitation are due to both changes in precipitation and increased PET. Projected changes in PET due to climate change are generally 4 to 5 inches/yr, with areas in the South showing 5 to 6 inches/yr increases in PET.

From this analysis, it appears highly likely that climate change could have major impacts on the available precipitation and the sustainability of water withdrawals in future years under the business-as-usual 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 20$^{th}$ century temperature and precipitation are used. This calculation indicates the increase in risk that affected counties face that water demand will outstrip supplies, if no other remedial actions are taken. To be clear, it is not intended as a prediction that water shortages will occur, but rather where they are more likely to occur. As a result, the pressure on public officials and water users to creatively manage demand and supply--through greater efficiency and realignment among competing uses, and by water recycling and creation of new supplies through treatment--will be greatest in these regions.

The maps produced in this work can be used in different ways. They provide a large-scale overview to help assess the extent of water resources impacts that are associated with future climate change, and to identify regions that are most likely to be affected. They are also a starting point for more detailed mechanistic water budget analysis at a localized scale, such as that of a city or water district, or a specific watershed. The metrics computed in this work are for a single business-as-usual scenario on the growth side, albeit one that is plausible. It is expected that more detailed analysis will consider and perhaps identify alternative region-specific growth trajectories that are more likely to be sensitive to anticipated climate change. These analyses can serve as the foundation for developing regional-scale alternatives for adaptation, such as modification of withdrawals, changing water use efficiency in different sectors, creating new supplies through technologies such as desalination, or creating more storage to address potentially greater year-to-year variability in precipitation.

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# Appendix: Maps for 2030

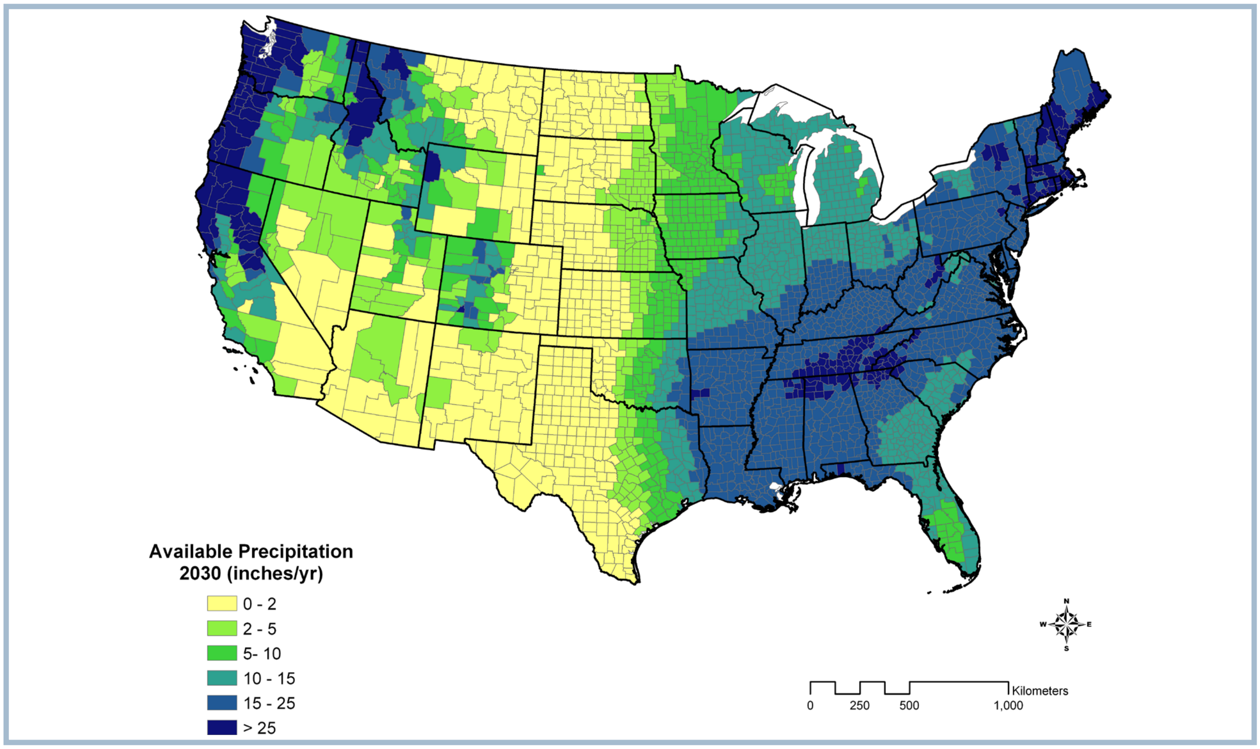


Figure A-1. Projected available precipitation in 2030 aggregated to the county level, based on the 50th percentile of projected precipitation by climate models (ensemble of 16 GCMs).

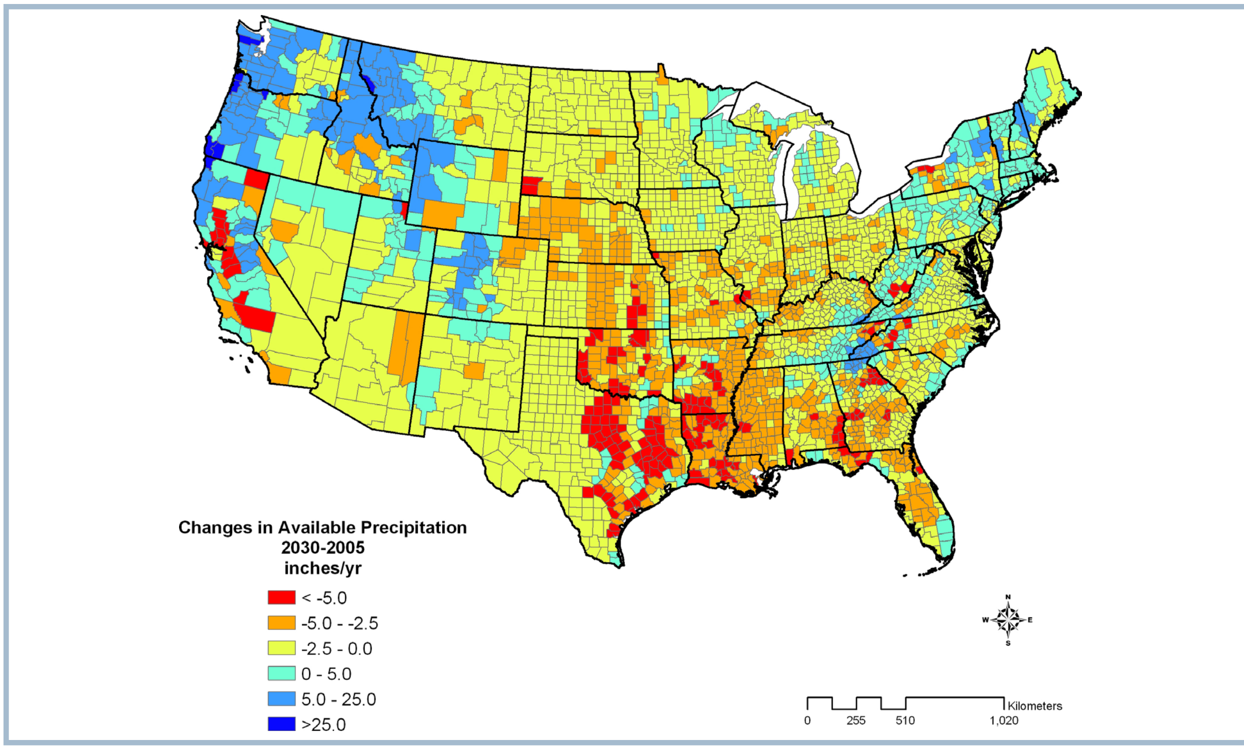


Figure A-2. Changes in available precipitation from 2005 to 2030 in inches/yr. 2030 values are based on an ensemble of 16 GCMs and represent conditions between 2020 and 2039.

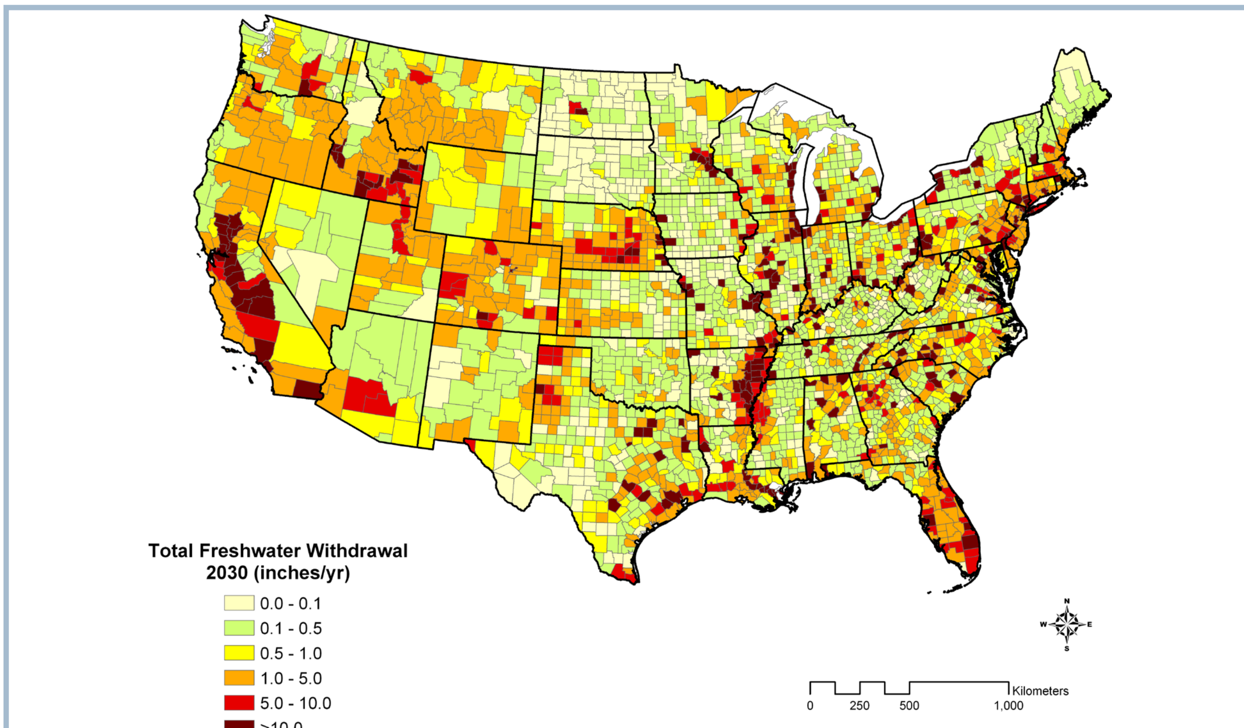


Figure A-3. Projected total freshwater withdrawal in 2030 (inches/yr). The 2030 values are based on population growth and increased electric generation capacity, and assuming water use rates for domestic use at 2005 levels, albeit varying by county, and new cooling water use at 500 gallons/Megawatt-hour. Withdrawals for other sectors are assumed to remain at their 2005 levels.

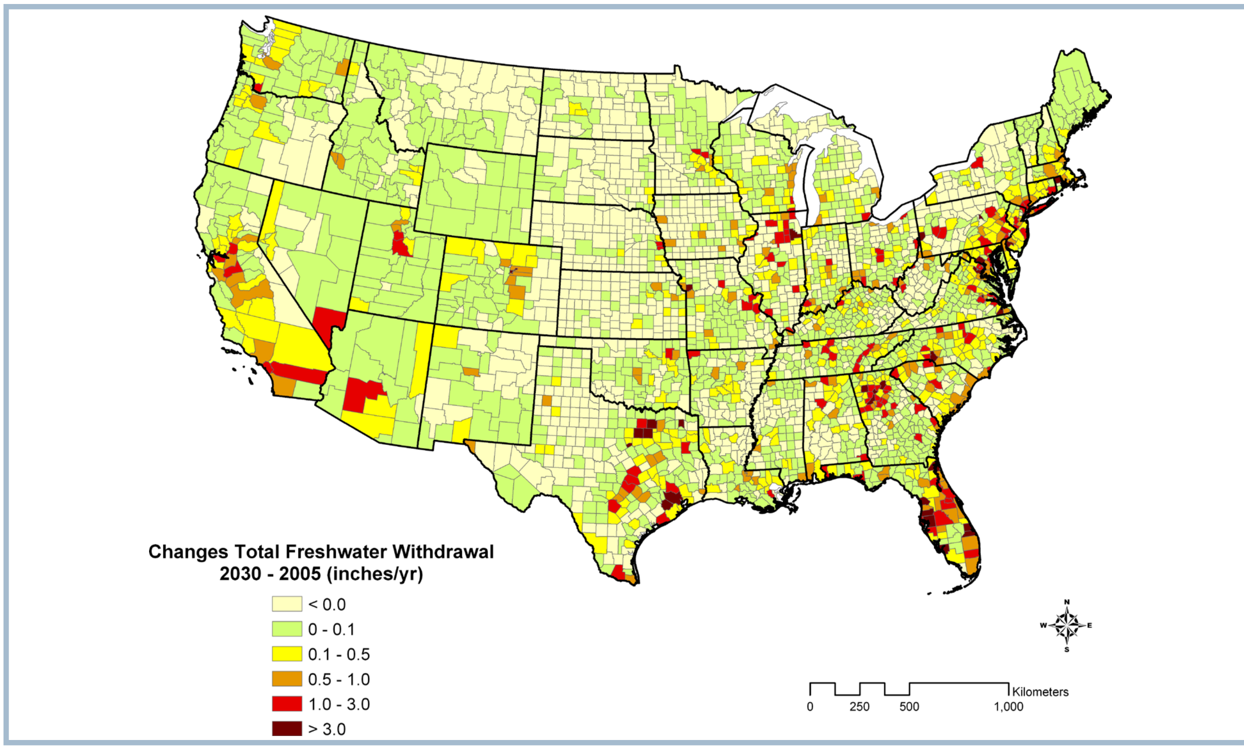


Figure A-4. Changes in total freshwater withdrawal from 2005 to 2030 (inches/yr)

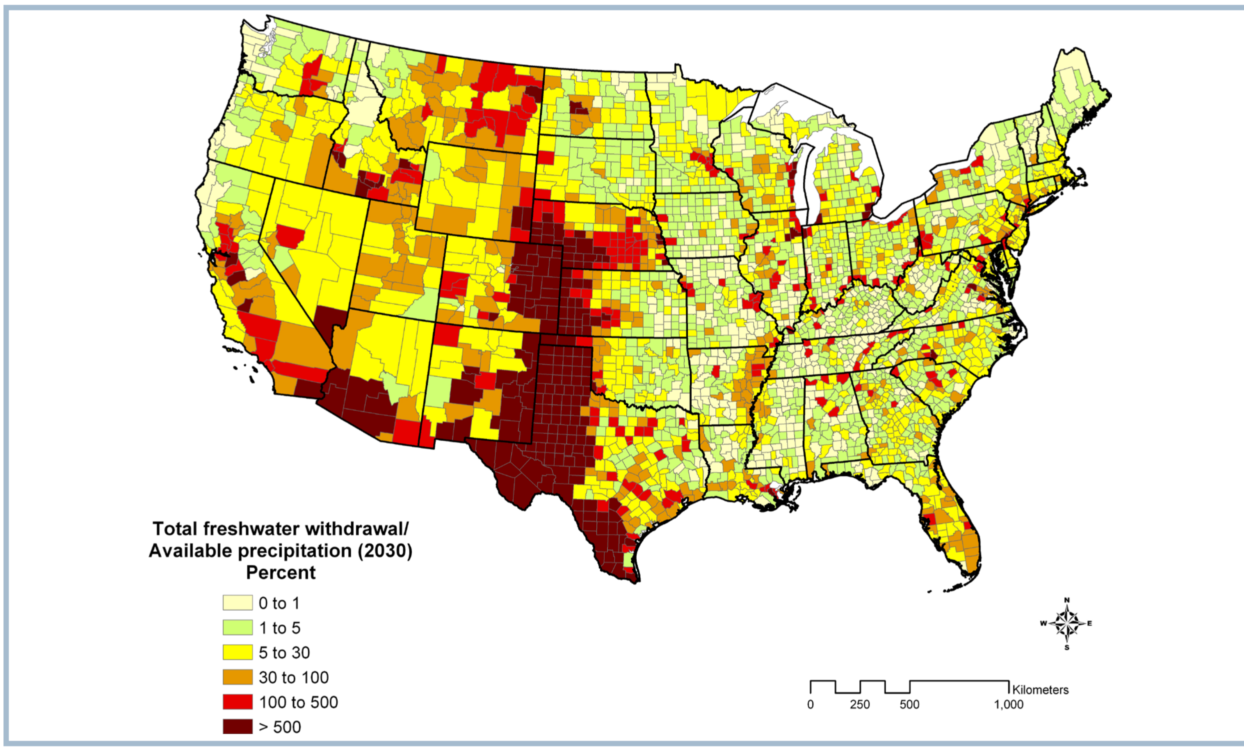


Figure A-5. Projected total water withdrawal as percent of available precipitation in 2030. 2030 values are based on an ensemble of 16 GCMs and represent conditions between 2020 and 2039.

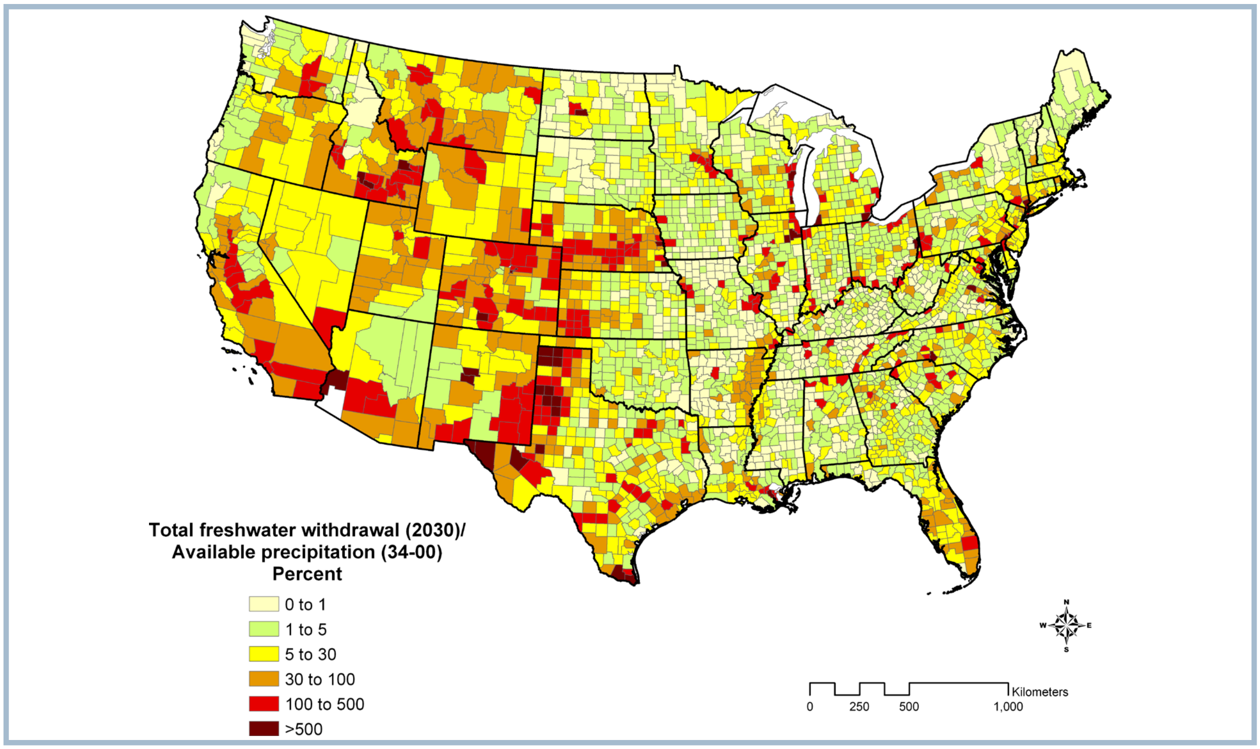


Figure A-6. Total freshwater withdrawal in 2030 as percent of historical (1934-2000) total available precipitation.

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