Planning for community resilience to future United States domestic water demand

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Abstract

Costs of repairing and expanding aging infrastructure and competing demands for water from other sectors such as industry and agriculture are stretching water managers’ abilities to meet essential domestic drinking water needs for future generations. Using Bayesian statistical modeling on past and present water use, we project domestic water demand in the context of four climate scenarios developed by the Intergovernmental Panel on Climate Change as part of the their Special Report on Emission Scenarios (SRES). We compare 2010 demand to projections of domestic water demand for the years 2030, 2060 and 2090 for the four SRES scenarios. Results indicate that the number of counties exceeding fifty percent or greater demand over 2010 levels increases through 2090 for two of the scenarios and plateaus around 2050 for the other two. Counties experiencing the largest increases in water demand are concentrated in the states of California, Texas, and isolated portions of the Mid-West, Southeast, and Mid-Atlantic. Closer examination of the spatial distribution of high demand counties reveals that they are typically found near or adjacent to metropolitan centers, potentially placing greater stress on already taxed systems. Identifying these counties allows for targeted adaptive management and policies, economic incentives, and legislation to be focused towards locations that are potentially the most vulnerable.

Keywords

Water demand; Climate; Sustainability; Resilience

1. Introduction

Climate and anthropogenic change are creating new pressures on global water resources (Vörösmarty et al., 2000). Costs of repairing and expanding aging infrastructure and competing demands for water from other sectors such as industry and agriculture are stretching water managers’ abilities to meet essential domestic drinking water needs for

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future generations (Hejazi, Edmonds, Chaturvedi, Davies, & Eom, 2013; CSIS, 2015; Gleick, 2003). Research has generally focused on supply-side changes to water resources, which include continuing increases in extreme precipitation, intensification of drought, acceleration of snowmelt, and increases in evaporation among others, resulting in impacts to infrastructure, water availability and aquatic ecosystems. These studies rely on atmospheric-ocean general circulation models for hydrologic inputs and employ a range of downscaling techniques to make projections of different plausible future scenarios. Few studies have investigated the impact of spatial and temporal changes in domestic water demand to determine future needs (Hutson et al., 2000; Kenny and Juracek, 2012; Roy, Ricci, Summers, Chung, & Goldstein, 2005). Previous work has relied on fixed, constant per capita water consumption methods for projecting future demands to near (20 year) and far (80+ year) temporal endpoints (Hutson et al., 2000; Roy et al., 2005; Roy et al., 2012). However, while long-term monitoring data exists, previous work has not accounted for observational trends in water demand in addition to increasing resource efficiencies through time.

For the contiguous United States, water use information is collected and summarized on five year recurring intervals by the United States Geological Survey (Kenny & Juracek, 2012). The most recent National Climate Assessment synthesized this information (Melillo, Richmond, & Yohe, 2014) and concluded that total freshwater withdrawals have leveled off nationally since 1980 at 350 billion gallons of withdrawn water for all sectors (e.g. agriculture, thermoelectric, public supply) and 100 billion gallons of water withdrawn each day by the public for domestic purposes (Georgakakos et al., 2014). This plateau in domestic water demand is despite the addition of 68 million people during that same time period. Decreases may be attributed to many factors, such as demand management, new plumbing codes, water-efficient appliances, and efficiency improvement programs. While the aggregated demand data show that the US is becoming more efficient with its water use, the National Climate Assessment did not address the changing spatial dynamics in domestic water demand that have occurred with increasing migration to urban centers. Several recent studies project significant increases in domestic water use for urban areas, both in per capital consumption and total volume, as a result of growing populations and gross domestic product (Alcamo, Florke, & Marker, 2007; Davies and Simonovic 2011; Haddeland et al., 2014; Hejazi et al., 2013; Grafton et al., 2013; Shen et al., 2008). Although domestic water volumes are relatively small when compared to other sectors, such as agriculture and industry (Dalin, Konar, Hanasaki, Rinaldo, & Rodriguez-Iturbe, 2012), the significance to human health and well-being justifies greater investigation. Furthermore, more robust methods to forecast changes in domestic water use that may lead to water shortages across broad spatio-temporal scales is necessary for adaptive resiliency.

In this study, we develop a novel approach to project domestic water demand for each county within the contiguous United States for multiple scenarios of population growth and climate change. We define domestic water demand as the quantity of water withdrawn for a human purpose that does not pertain to irrigation, livestock, aquaculture, industrial, mining and thermoelectric power water use. Using Bayesian statistical models, future domestic water demand is projected based on climate scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) as part of their Special Report on Emissions Scenarios (Navicenovic et al., 2011). We then identified counties within the United States that will be...
vulnerable to significant increases in domestic water demand using three different approaches to prioritization. Each approach allows for the identification of counties that could be the focus of adaptive management policies.

2. Methods

In this analysis we 1) model future domestic withdrawals (water demand), and 2) identify US counties with rapidly increasing domestic water demand that could leave them vulnerable to water shortages. We included multiple time points and population growth from a range of climate scenarios to highlight a range of plausible future scenarios.

2.1. USGS water use data

The U.S. Geologic Survey’s (USGS) National Water-Use Information Program provides the most comprehensive and consistent water use data for the conterminous United States. This data is aggregated by combining local, State, and Federal environmental agency data into county level datasets on a five year recurring basis. These datasets provide estimates of water-use for several categories, including public supply, domestic, industrial, agricultural, livestock, thermoelectric, and mining. For this study, we focus specifically on the domestic water supply, which includes indoor and outdoor uses at residences.

The vast majority of people in the United States use water provided by public suppliers (Kenny & Juracek, 2012). Estimates of the quantity of water delivered by public water suppliers is determined using sales information from reports of surveys of public suppliers. This method allows for sample data to be used to develop coefficients for estimating the deliveries for all public suppliers in a given county (Kenny & Juracek, 2012). Typical coefficients used include the percentages of total withdrawals for domestic use determined by residential sales and per capita use based on the estimated population served. Approximately 14% of the US population supplies their own water for domestic use (Kenny & Juracek, 2012). Therefore, estimates for domestic self-supplied water use was calculated using an estimate of the population that was not served by the public supply and a coefficient for daily per capita use. By combining these two methods of estimation, it is possible to derive spatially explicit domestic water use data for the conterminous US.

We used water-use estimates for the years 1985, 1990, 1995, 2005 and 2010 in this analysis. The reported data for 2000 was specifically excluded because it lacked consistent data and reporting units when compared to the other years within this study. For each year, counties were stratified using two criteria: 1) United States Environmental Protection Agency defined Level I Ecological Regions, referred to as ecoregions (Omernik & Griffith, 2014; Omernik, 1987), and 2) population size. The Level I ecoregions were developed to include the collective patterns of all biotic (including humans), abiotic, terrestrial, and aquatic ecosystem components (Omernik & Griffith, 2014). In addition to grouping similar physiographic areas, the ecoregions can be useful when integrating resource assessment and management strategies across agencies and programs that have different missions for the same geographic areas (Omernik & Griffith, 2014). Grouping the county water use data by ecoregions resulted in ten groups (Fig. 1). Ecoregions were assigned based on where the greatest proportion of county was located. Within each ecoregion, counties were then put
into sub-groups based on population size. Population size rather than density was used so that trends in per capita water demand could be used to project future domestic water use. The three population sub-groups included counties having 1) less than 150,000 people, 2) 150,000 to one million people, and 3) populations greater than one million. Stratifying water use data based on population size and physiography reduced the influences of biotic and abiotic variability, improved the precision of our estimates, and insured that different demographic subgroups were represented in a spatially-balanced manner across the country prior to analysis.

2.2. Rate of change in per capita water demand

Domestic per capita water use rates were derived for each dataset (1985–2010) within each group by dividing the total domestic water used by US Census population estimates. We conducted a univariate regression to quantify model coefficients by relating water use per capita rates (PC) with time. Instead of the classical approach we chose Bayesian regression due to sample size and uncertainty on coefficient estimates (Koop, 2003). In classical regression, estimation of coefficients and inferences of results depend on observed data that follows the asymptotic theory. The uncertainty on accuracy of the coefficient estimate is dependent on sample size (estimations may vary between different samples and on meeting the asymptotic theory assumptions). Bayesian analysis, however, neither depends on sample size nor the assumption of asymptotic theory in its estimation. It uses data with a prior probability. A prior probability is also known as a prior distribution based on expert knowledge on mean, variance and other parameters about the coefficients prior to examining the data. We used a non-informative prior probability based on the limited water use data available and due to the five year USGS demand summarizations. When the sample size is large and likelihood function exists, results from classical and Bayesian regressions should be similar. When the sample size is small, Bayesian analysis is recommended (Koop, 2003) and was determined appropriate given a relatively small sample size for some of our 25 distinct groupings.

Coefficients using PC over a 30 year period were estimated (Eq.(1)) by: 1) defining the distribution of coefficients (i.e. prior probability), 2) using the observed data (i.e. PC) as described above, and 3) applying Bayesian rules to update information about the coefficient to obtain posterior distribution of the coefficients P(β’s|PC). Model coefficient estimates were generated by sampling from the posterior distribution using Gibbs sampling. Model coefficients, summary statistics (mean, high posterior density (HPD), credible intervals) and convergence diagnostics (trace plots, autocorrelations, Geweke, Monte Carlo standard errors) were examined. We used Proc GENMOD (Bayes options; SAS/ETS®, 1999) and for each ecoregion-population size rank, a regression model was fitted to the observed values to define the direction for the coefficients as:

\[ PC_i = \beta_0 + \beta_1(Time_i - 1980) + \epsilon_i \]  (1)

where PC is the average water in gallons used per individual, Time is the forecasted year (n = 5 time groups), and \( \epsilon_i \) is normally distributed with mean = 0 and variance = \( \sigma^2 \). Coefficient
estimates and their credible intervals were examined (Table 1) (credible interval: equal tail interval \( [P_{1-\alpha/2}(\beta | PC), P_{1-\alpha/2}(\beta | PC)] \)). Trace, autocorrelation, and density plots for the model parameters all indicated satisfactory convergence of the Markov Chain. The convergence of the Markov chains is an essential part in inferences, if there is no convergence then inferences can be inaccurate and misleading.

### 2.3. Forecasting water demand

Projected domestic water use was based on the derived model coefficients for rate of change in consumption of water for the 25 groups (Table 1), combined with assumptions of future population growth. By applying the statistical analysis of rate of change in per capita water use to estimates of future populations, total water consumption for each county within this study was determined on five year recurring intervals from 2015 to 2090.

We used the EPA Global Change Research Program’s Integrated Climate and Land Use Scenarios (ICLUS) to determine change in future population for the conterminous US for each decade through 2090 (USEPA, 2009). These population estimates were based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES), which was developed to provide consistent benchmarks for local and regional land-use change studies. The SRES scenarios were part of a larger international climate change effort, the IPCC Assessment Report 4 (AR4) (IPCC AR4, 2007). ICLUS population estimates use a combination of models to apply demography, including domestic and international migration, and spatial allocation models to determine the distribution of people across the conterminous US in housing units (USEPA, 2009). Given the multitude of possible variables that may affect demographic and land-use change patterns in the future, using a scenario approach allows for a range of outcomes to be considered to understand the plausibility of possible futures. The benefit of using these scenarios is that each individual scenario is directly linked to numerous general circulation models that provide corresponding estimates of temperature and precipitation (USEPA, 2009). For the purposes of this study, we focused on the A2, A1b, B1, and B2 SRES scenarios and the population estimates for each modeled by ICLUS. Each scenario makes certain assumptions about population growth, economic development and technological advancements.

For the US, The A2 scenario depicts a world of continued economic development and high fertility rates with global populations continually increasing through 2100. In this scenario the US is highly self-reliant and economic development is focused primarily within the US. The A1b scenario projects population growth through 2050 and then begins to decline. The A1b assumes rapid economic development – this encourages free movement of people across borders, with domestic migration relatively high. Technology development within the A1b is balanced, with a mix of fossil and non-fossil fuels.

The B1 scenario follows a similar storyline to the A1b scenario, but with a greater emphasis on environmentally sustainable economic growth. Fertility rates are low, and domestic migration is low. Global populations reach 9 billion by 2050 and then declines. Technology development is assumed to be environmentally sensitive, with a dominance of clean and resource efficient technologies. Comparatively, the B2 scenario is one of continually increasing populations, similar to the A2, but at a slower rate of increase. There are less
rapid and fragmented technological changes than the other scenarios, with a stronger emphasis on regional development over global partnerships.

Total domestic water demand was projected by applying the estimated future populations of the SRES scenarios to the water demand per capita analysis. This was computed by multiplying the domestic per capita value for a specific year by the county level population projections for each SRES scenario of the corresponding year – making it possible to determine the total domestic water demand for each county within the conterminous US for the years 2010–2090 for each of the four SRES scenarios. These results were then evaluated to determine the magnitude of change to highlight counties with rapid increases in domestic water demand.

2.4. Identification of priority counties for adaptive sustainability

To anticipate changes in water demand, we demonstrate three approaches to prioritizing counties most at risk for future water shortages. Our first approach used percent increase thresholds to identify counties with the greatest increases through the next century for each SRES scenario. Spatially and temporally identifying counties with increases in demand of 0–25, 25–50 and greater than 50% allows for a tiered approach to adaptation and highlights counties most in need of potential mitigation.

Populations migrating from rural to large urban areas has recently been highlighted as a growing trend for the US, and more broadly, the world at large (Buhaug & Urdal, 2013). Current projections indicate that by 2050 two thirds of the world population will live in or near urban areas, and that much of that population growth will occur in large cities (UN, 2010). Therefore, it is important to identify counties that have projected increases in water demand that are located within, or in close proximity to large urban centers. We identified cities greater than ten square miles as large urban centers and identified counties with increased water demand that intersected these areas.

With populations projected to increase across all SRES scenarios there will also be a need to update aging domestic water supply infrastructure. US counties generally rely on municipal bonds or State Revolving Funds (SRF) to finance water infrastructure construction (Stallworth, 2003). Bonds or SRFs are allocated to counties as loans and are directly a result of the amount of money a county can raise for a water infrastructure project (American Rivers, 2013). According to the National Center for Children in Poverty rural county families making $35,000 or less are unlikely to contribute to federal or state income taxes (Dinan, 2009). Rural counties that experience large increases in demand with modest tax bases are particularly at risk to potential domestic water demand shortages. For our study we selected priority counties based on an average annual income below $35,000 (US Census Bureau, 2010) and a projected increase in water demand greater than 50%.

3. Results

3.1. Results of the A2 and A1b scenarios

Results from the A2 scenario are shown in Fig. 2. The A2 scenario assumes the greatest demographic shifts due to migration and continued population growth through 2100. As a
result of migration to urban areas and population reductions in rural settings, approximately 75% of US counties will have decreased water demand in 2030 (Fig. 2). By 2060, 80% of all US counties will have some reduction in domestic water demand compared to 2010 (Table 2). The number of counties with reduced demand levels off after this (81% by 2090).

However, by 2030 we project approximately one fourth of all US counties (approximately 765 counties) will have greater water demand than current needs. The number of counties with increased demand will decrease slightly to 600 and 573 by 2060 and 2090, respectively.

In 2030, 559 counties will have increases in demand between 0 and 25%; reducing to 230 by 2060 and 130 by 2090. Approximately 157 counties are projected to have increases in demand of 25–50% in 2030, decreasing to 139 by 2060, and 103 by 2090. These decreasing counts in the two thresholds are an indication that counties with increasing demand in this scenario increase substantially. We found that 49 counties are projected to double their water demand by 2030, with counts increasing to 231 by 2060 and 340 by 2090 respectively.

Counties located adjacent or within large urban centers with increases in demand were projected to include 390 counties in 2030, 354 in 2060, and 356 in 2090. Fig. 3 provides a representative example of the spatial distribution of counties with increased demand and their typical proximity to large urban centers. In rural locations in 2030, we projected 39 counties to have increased demand greater than 50%, and of those counties five have median incomes less than $35,000. In 2090, the number of rural counties with greater than 50% demand grows to 151, with 18 counties below the low tax base threshold.

The A1b scenario assumes global populations reach approximately nine billion in 2050 and then declines to the end of the century. For the A1b scenario we projected approximately 79% of US counties will have decreased water demand in 2030 (Fig. 4). By 2060, 87% of all US counties are projected to decrease domestic water demand compared to 2010, and 82% of US counties will some reduction by 2090 (Table 2). Comparatively, by 2030 we project 642 counties as having greater water demand than current needs. The number of counties with increased demand will decrease to 403 and 288 by 2060 and 2090, respectively.

In 2030, 449 counties will have increases in demand between 0 and 25%; reducing to 105 by 2060 and 86 by 2090. We found 147 counties projected to have increases in demand of 25–50% in 2030, decreasing to 108 by 2060, and 62 by 2090. Again, in the largest increase category we projected 46 counties to double their water demand or more by 2030, with county counts increasing to 145 by 2060 and then decreasing to 140 by 2090 respectively.

Counties located adjacent or within large urban centers with increases in demand were projected to include 341 counties in 2030, and remain at 250 in 2060 and 2090. In rural locations in 2030, we projected 42 counties to have increased demand greater than 50%, and of those counties seven have median incomes less than $35,000. In 2090, the number of rural counties with greater than 50% demand grows modestly to 58, with 9 counties below the low tax base threshold.

### 3.2. Results of B1 and B2 scenarios

These two scenarios assume modest population growth along with domestic and international migration of people across the conterminous US from the central U.S. Our water demand results reflect these assumptions, suggesting most of the counties across the
US will see reductions in the total demand of domestic water compared to 2010. However, both scenarios identify areas of the US that may potentially experience large spikes in domestic water demand as a result of migration and population growth. Fig. 5 shows each county and the percent change in water demand compared to 2010 for the B1 scenario. This scenario projects 74% of counties across the US will have reductions in domestic water demand by 2030 (Fig. 2). By 2060, 86% of all US counties will have a reduction in domestic water demand compared to 2010, and 91% of US counties will reduce demand by 2090 (Table 2). However, in 2030 we project 798 counties as having greater water demand than current needs. The number of counties with increased demand will decrease to 447 by 2060, and further decrease to 270 by 2090.

In 2030, 713 counties will have increases in demand between 0 and 25%; reducing to 281 by 2060 and 136 by 2090. Approximately 70 counties are projected to have increases in demand of 25–50% in 2030, increasing to 96 by 2060, and 59 by 2090. Fifteen counties are projected to double their water demand or more by 2030, with county counts rising to 70 and 75 by 2060 and 2090, respectively. Counties located adjacent or within large urban centers with increases in demand were projected to include 341 counties in 2030, and remain at 250 in 2060 and 2090. In rural locations in 2030 we projected 26 counties to have increased demand greater than 50%, and of those counties eight have median incomes less than $35,000. In 2090, the number of rural counties with greater than 50% demand roughly doubled to 55, with 14 counties below the low tax base threshold.

The B2 scenario assumes the most modest growth of the four SRES scenarios. As a result, approximately 69% of US counties will have decreased water demand in 2030 (Fig. 6). By 2060, eighty percent of all US counties will have some reduction in domestic water demand compared to 2010, and moderately increasing to 83% by 2090 (Table 2). However, by 2030 we project 936 counties will have greater water demand than current needs. The number of counties with increased demand will decrease to 616 and 516 by 2060 and 2090, respectively.

In 2030, 881 counties will have increases in demand between 0 and 25%; reducing to 438 by 2060 and 292 by 2090. Approximately 48 counties are projected to have increases in demand of 25–50% in 2030, increasing to 112 by 2060, and 109 by 2090. Only 7 counties are projected to double their water demand by 2030, with county counts increasing to 66 and 115 by 2060 and 2090, respectively. Counties located adjacent or within large urban centers with increases in demand were projected to include 396 counties in 2030, 282 in 2060, and 246 in 2090. In rural locations in 2030, we projected 8 counties to have increased demand greater than 50%, and of those counties only three have median incomes less than $35,000. In 2090, the number of rural counties with greater than 50% demand increase to 58, with 9 counties below the low tax base threshold.

3.3. Setting thresholds for adaptive sustainability

The results presented above demonstrate the quantity and spatial configuration of counties that may experience substantial changes in water demand. To potentially adapt to increasing needs, we demonstrated using thresholds to isolate counties with the greatest increases in demand (0–25%, 25–50%, and greater than 50%) (Fig. 7). For all projected scenarios there
was an increase in total counties exceeding the 25–50% and greater than 50% thresholds (Fig. 7b and c) for all years when compared to 2010 demand. As a greater number of counties with increasing demand shifted into higher thresholds (e.g. 25–50 or greater than 50%) categories during the latter part of the century there was a decrease in the number of counties in the lowest threshold (Fig. 7a). Depending on the scenario, counties with increased demand between 25 and 50% through the century were estimated to have a peak near 2030 and 2040 (for A1 and A2) or a peak around the middle of the century (the B1 and B2 scenarios). For the A1 and A2 scenario this demand peak occurs earlier because of increased population sizes earlier in the century. The B1 and B2 scenarios, with slower increases in population, peak later; however, the B2 scenario assumes a more or less constant demand after the middle of the century.

The number of counties exceeding a 50% increase or more in demand grew for all four scenarios (Fig. 7c) through our study period. The A2 and B2 scenarios projected a continually increasing number of counties facing domestic water demand challenges. Comparatively, the A1b and the B1 scenarios saw increases in the number of counties projected to have more demand until the middle of the century, with the total number of counties generally remaining constant afterwards. This relationship is consistent with the SRES scenarios and is predominantly driven by the population scenarios (the A1b and B1 scenarios have decreasing population after 2050; the A2 and B2 have continually increasing populations).

4. Discussion

This work used public data in combination with projections of population change to provide plausible scenarios depicting future water demand. Many portions of the world are already experiencing water stress and, therefore, it is critical to understand the direct human impacts on water resources (Vörösmarty et al., 2000). Here, we demonstrate a plausible causal pathway projecting that the US will experience greater pressures on its domestic water resources over the next century. Research to date has generally focused on global water assessments (e.g. Alcamo et al., 2007) and combined multiple domestic needs into one municipality category (Arbues, Garcia-Valinas, Martinez-Espineira, 2003; Davies and Simonovic 2011, Hejazi et al., 2013). Our results were consistent with these previous efforts, however, given current emissions trajectories it is likely that these types of projections are conservative estimates of overall future domestic water demands.

Increasing populations are creating inherently difficult water resource decisions for policy makers to address. Further complicating these matters are the spatial shifts in population, as more US residents are migrating from rural settings back to large urban centers in the Southwest, Pacific Northwest, and coastal regions (Buhaug & Urdal, 2013). We found that counties within and surrounding large urban centers were most likely to experience some of the greatest increases in demand (for example see Fig. 6). Understanding the spatial shifts of populations to large urban centers and the resulting projected domestic water needs can allow for city and regional planners to preemptively adapt and respond. Typically water infrastructure improvement projects are payed, both directly and indirectly, through revenue from the water system’s customer base (American Rivers, 2013; Stallworth, 2003).
Therefore, while urban centers are likely to experience the greatest increases in demand, they will have corresponding increases in tax bases to help alleviate future costs. Comparatively, a small proportion of counties with large increases in demand were identified to be located away from urban centers across all four scenarios. Several of those counties have tax bases that may not be able to support the necessary infrastructure to meet projected needs (i.e. relatively low median income). As communities attempt to increase their resiliency by responding to changing water demands, these counties identified may be most vulnerable to shortages and lack the necessary capital to respond. It is conceivable to envision that state and the federal government could use prioritization methods such as the one presented here when deciding where to invest funds for water capital improvement projects. To further support efforts such as these, the county level information has been provided publically on the US Environmental Protection Agencies EnviroAtlas [www.epa.gov/enviroatlas] (Pickard, Daniel, Mehaffey, Jackson, & Neale, 2015).

Using the past 30 years of water use data shows that most US counties have steadily decreased their per capita water demand, albeit modestly. This has most likely been achieved through a range of efficiency improvements or decreases in population. Observed declines in per capita demand has been largely attributed to the 1992 USA Energy Policy Act that established national water efficiency requirements and set maximum flow rates for all plumbing fixtures installed in new and renovated homes (Coomes, Rockaway, Rivard, & Kornstein, 1992). Our results show the spatial distribution of increased demand generally being located near large urban centers, where increased efficiencies have been unable to mitigate for the substantial increases in population. Previous work has often used fixed per capita demand rates (Roy et al., 2005) to estimate water demand. Our results are not consistent with the findings of Roy et al. (2005), as we found wide variance in the overall trends of per capita rates when population size and ecoregions are considered. We demonstrate that hundreds of counties are expected to see increases in per capita demand during the next century rather than remain constant. Additionally, assuming a constant per capita rate does not allow for efficiency improvements to be accounted. This can lead to an overestimation of total water demand in the future. In our analysis we found that over the four scenarios, between 70 and 85% of all U.S. counties are likely to actually see decreases in the amount of water demand over time.

We specifically focused on domestic water demand given its significance to human health and well-being. Yet, the total volume of water required for domestic needs is relatively small compared to other water uses such as for agriculture or industrial purposes. However, the cost to meet domestic needs may be higher due to the cost of maintaining, repairing, and creating the necessary infrastructure to supply water to meet demand. Our intent was to demonstrate a novel approach to modeling a critical water use category: similar methodologies could be adapted to other water categories. The USGS maintains water use records for multiple other categories and changes in use for these other categories will likely impact the overall potential for water deficits within any given county. For example, counties with substantial agricultural water demand, such as many of the Central Valley in California, may soon realize a situation where there is simply not enough water to provide for domestic and farming needs simultaneously (Mini, Hogue, & Princetl, 2014).
This analysis extrapolated observed trends in per capita water demand onto different demographic and economic scenarios. While these types of scenarios can be useful for understanding water demand trends, they are unable to account for acute, localized policy and economic responses to water shortages. The SRES scenarios make certain assumptions about technological advancements, but cannot predict currently unknown developments that may substantially improve water use and efficiencies. Anthropogenic responses to water shortages, often in the form of infrastructure improvement projects or policy related changes, are difficult to anticipate and model. Despite the inability to incorporate these factors, the methods presented here demonstrate a possible tool for anticipating generalizable trends in global change impacts that may be useful to water managers.

These methods relied solely on population projections and associated migration for the US. General circulation models were not used to anticipate effects to the supply of water available for each county, nor were they used to anticipate changing spatial patterns in precipitation regimes that could impact the availability of water. Coupling models that incorporate changes in demand for all USGS water use types with downscaled high resolution hydrologic models of future water supply (i.e. precipitation excluding evaporation, ground water recharge, etc.) will ultimately yield the greatest insights (e.g. Christian-Smith and Gleick, 2012) and allow for an informed, adaptive response. It is possible that some counties, while experiencing substantial increases in demand, will have greater water supply in the future due to changing precipitation patterns and may therefore be buffered from projected shortages.

Publically available data provided by the USGS can be difficult to manipulate into useful formats, therefore considerable opportunities exist for improvements to water use data. The USGS provides data at the county level for multiple water use categories for the entire US on a five year recurring interval. Our work highlights the need for increases in the temporal and spatial resolution of this type of data. To effectively manage and possibly mitigate for changing domestic water demands, yearly water use data is necessary. Furthermore, using political boundaries (i.e. counties) as the arbitrary unit for water use data collection does not allow for geographic or hydrological units of significance to be incorporated into analyses. Urban water in the US is managed at the municipal level, many of which are smaller than counties. Municipalities are responsible for building infrastructure, setting water rates, planning for the future and developing conservation plans. Therefore, shortages will most likely be experienced at the level of the urban municipality rather than at the county level. We used counties as the unit of analysis because it was the highest resolution water use data publically available and consistent across the conterminous US currently. Reporting water use data at the municipality level annually could lead to greater insights into water demand and allow better estimation of municipalities most susceptible to water shortages. We also found that data and collection methods have changed since the USGS first began collecting water use information. For example, we discarded all data collected and summarized for the year 2000 due to changes in reporting methods that conflicted with water use data sets from previous years. Standardizing reporting methods of water use data across sectors is critical for future research.
Across all scenarios isolated counties and, in some scenarios, clusters of counties were projected to have substantial increases in water demand due to increasing population and migration. Water resiliency and shortage are a function of supply, behavior, governance, and public policy interventions, in addition to population and its redistribution trends. Our methods demonstrate alternative approaches to identifying high priority counties susceptible to shortages from population redistribution and per capita consumption trends. This may ultimately allow for targeted adaptive policies, economic incentives, and legislation to be focused towards counties that are potentially most vulnerable. Future research efforts could use this type of methodology, coupled with water supply estimates, to better anticipate water shortages within environmental, economic, and political constraints and realities.

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HIGHLIGHTS

- Migration patterns will cause decreased domestic water demand for most US counties.
- Domestic water demand may increase by more than fifty percent in urban counties.
- Some counties may be vulnerable to infrastructure costs from increased water demand.
Fig. 1.
United States Environmental Protection Agency Level I Ecoregions for the conterminous United States with US counties overlaid. Ecoregions divide North America into 10 broad categories highlighting major ecological components of an ecosystem.
Fig. 2.
Projected percent change in domestic water demand compared to 2010 water demand for the A2 scenario for the years 2030, 2060, and 2090.
Fig. 3.
Projected percent change in domestic water demand in 2090 based on the A2 scenario. Results indicate that counties near or contained by large metropolitan areas often have significant increases in demand projected. The two regions of southern Texas (left) and Alabama/Georgia (right) are representative of this observed trend.
Fig. 4.
Projected percent change in domestic water demand compared to 2010 water demand for the A1 B scenario for the years 2030, 2060, and 2090.
Fig. 5.
Projected percent change in domestic water demand compared to 2010 water demand for the B1 scenario for the years 2030, 2060 and 2090.
Fig. 6.
Projected percent change in domestic water demand compared to 2010 water demand for the B2 scenario for the years 2030, 2060, and 2090.
Fig. 7.
Identification of counties projected to have increases in domestic water demand (A) less than or equal to 25%, (B) greater than 25% and less than 50%, and (C) greater than 50% compared to 2010 demand levels. The four scenarios considered in this analysis are shown for the years 2015 through 2100.
Table 1

Results of the Bayesian regression analysis showing the coefficient and credible intervals for each category. Counties were divided into a category based on size and ecoregion. The $b_1$ value is the per capital slope, where a positive number indicates that category is increasing in per capita each year.

| Ecoregion Name                  | $b_1$       | $b_0$       |
|----------------------------------|-------------|-------------|
| **Large Population (> = 1 million)** |             |             |
| Marine west coast forest         | −2.28(6.49,1.89) | 152.17(88.49,216.02) |
| Eastern temperate forest         | −0.29(1.52,0.92)  | 94.79(76.24,113.39)  |
| Great plains                     | −0.83(−1.98,0.30) | 155.88(138.47,173.34) |
| North american deserts           | −0.93(−2.20,0.33) | 185.79(166.49,205.14) |
| Mediterranean California          | −1.39(−2.93,0.13) | 134.08(110.69,157.53) |
| Tropical wet forests             | −2.07(−2.23,−1.91) | 151.83(149.39,154.34) |
| **Medium Population (150,000 to 1 million)** |             |             |
| Northern forests                 | −0.66(−1.14,0.08) | 89.69(78.35,101.07)  |
| Northwestern forested mountains | 1.33(−0.14,2.77)   | 125.92(103.75,148.15) |
| Marine west coast forest         | −1.41(−4.27,1.41)  | 119.85(76.57,163.25)  |
| Eastern temperate forests        | −0.17(−0.32,−0.03) | 87.40(85.29,85.57)   |
| Great plains                     | −0.07(−0.42,0.55)  | 110.57(103.17,118.00) |
| North American deserts           | −1.59(−4.66,1.44)  | 174.40(128.18,221.34) |
| Mediterranean California         | −1.03(−1.48,3.49)  | 127.74(89.81,165.77)  |
| Temperate Sierras                | −1.75(−6.38,3.30)  | 144.74(70.82,218.85)  |
| Tropical wet forests             | −3.07(−8.46,2.25)   | 239.04(157.37,320.83) |
| **Small Population (< = 150,000)** |             |             |
| Northern forests                 | −0.50(−0.63,−0.37) | 83.75(81.80,85.76)   |
| Northwestern forested mountains | −1.02(−6.37,4.24)  | 170.89(89.97,252.03)  |
| Marine west coast forest         | 0.18(−1.13,1.47)   | 112.14(92.32,132.01)  |
| Eastern temperate forests        | 0.09(−0.01,0.19)   | 80.44(78.90,81.99)    |
| Great plains                     | −0.01(−0.01,0.19)  | 105.06(95.17,114.99)  |
| North American deserts           | −1.04(−5.22,3.08)  | 180.99(117.71,244.44) |
| Mediterranean California         | 3.74(0.62,6.82)    | 92.06(44.80,139.44)   |
| Southern semiarid highlands      | −0.16(−6.06,5.65)  | 121.27(31.95,210.83)  |
| Temperate Sierras                | −1.32(−1.73,−0.92) | 143.42(137.20,149.61) |
| Tropical wet forests             | 3.82(2.62,5.00)    | 42.25(24.13,60.42)    |
Table 2

Summarization table of each scenario and the percent of all US counties (n = 3109) included within each threshold for the years 2030, 2060 and 2090.

| Year | Scenario | ≥ 50% | 25–50% | 0–25% | 0 to −25% | −25 to −50% | ≤ −50% |
|------|----------|-------|--------|-------|------------|-------------|--------|
| 2030 | A2       | 1.6   | 5      | 18    | 41         | 30.2        | 4.2    |
|      | Alb      | 1.5   | 4.7    | 14.4  | 38.7       | 33.9        | 6.8    |
|      | B2       | 0.2   | 1.5    | 28.3  | 66.3       | 3.5         | 0.1    |
|      | B1       | 0.5   | 2.3    | 22.9  | 69.1       | 5.1         | 0.1    |
| 2060 | A2       | 7.4   | 4.5    | 7.4   | 12.4       | 19.8        | 48.4   |
|      | Alb      | 4.7   | 3.5    | 4.8   | 9.2        | 17.4        | 60.5   |
|      | B2       | 2.1   | 3.6    | 14.1  | 33.6       | 38.9        | 7.6    |
|      | B1       | 2.3   | 3.1    | 9     | 27         | 42.6        | 16.1   |
| 2090 | A2       | 10.9  | 3.3    | 4.2   | 5          | 8.1         | 68.4   |
|      | Alb      | 4.5   | 2      | 2.8   | 4.7        | 6.7         | 79.3   |
|      | B2       | 3.7   | 3.5    | 9.4   | 20         | 30.1        | 33.3   |
|      | B1       | 2.4   | 1.9    | 4.4   | 10.6       | 27          | 53.8   |