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Key Points:
- Climate change and population growth will combine to increase the likelihood of water shortages in many areas of the United States
- Expected improvements in water use efficiency will be insufficient to avoid impending water shortages
- Reductions in agricultural irrigation will be essential to contain shortages in other water use sectors and avoid excess groundwater drawdown or environmental flow losses

Supporting Information:
- Supporting Information S1

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Adaptation to Future Water Shortages in the United States Caused by Population Growth and Climate Change

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Abstract Population growth and climate change will combine to pose substantial challenges for water management in the United States. Projections of water supply and demand over the 21st century show that in the absence of further adaptation efforts, serious water shortages are likely in some regions. Continued improvements in water use efficiency are likely but will be insufficient to avoid future shortages. Some adaptation measures that have been effective in the past, most importantly large additions to reservoir storage, have little promise. Other major adaptations commonly used in the past, especially instream flow removals and groundwater mining, can substantially lower shortages but have serious external costs. If those costs are to be avoided, transfers from irrigated agriculture probably will be needed and could be substantial.

Plain Language Summary This study estimates the likelihood of water shortages over the remainder of the 21st century in 204 watersheds covering the contiguous United States. The estimates are based on monthly projections of water demand and renewable water supply in light of population growth and climate change, taking into account water storage and transbasin diversion capacities. The study then examines several possible adaptations to projected shortages, including water withdrawal efficiency improvements, reservoir storage enhancements, demand reductions, instream flow reductions, and groundwater depletions. Results provide a broad measure of the relative efficacy of the adaptation measures and show when and where the measures are likely to be helpful.

1. Introduction

Past water demand and supply trends in the United States reflect a history of adaptation. On the demand side, total withdrawals in the United States increased ninefold over the first eight decades of the twentieth century as the population grew and the western states continued to develop (Brown, 2000), but around 1985 they stabilized (Maupin et al., 2014), despite continued population growth, as a result of a remarkable drop in withdrawal per capita. The withdrawal increases had been facilitated by supply-side adaptations, especially the construction of reservoirs and water conveyances (canals, tunnels, and pipelines). However, the rate of reservoir construction peaked in the 1960s and has been declining ever since (Ruddy & Hitt, 1988; U.S. Army Corps of Engineers, 2016), as promising sites for new reservoirs became scarce and pressures mounted to protect remaining instream flows (Gillilan & Brown, 1997). The precipitous drop in construction no doubt contributed to the relative stability of recent total withdrawals, but that stability was made possible mainly by demand-side adaptations that improved water use efficiency in all water use sectors (Brown et al., 2013) and by structural changes in the thermoelectric and industrial sectors.

While our ability to adapt has allowed us to largely avoid crippling water shortages, the future may bring even greater adaptation challenges than past ones, as in addition to continued population growth, climate change will reduce water supplies and increase water demands in many locations. Although studies show that climate change is likely to bring increasing precipitation in many areas of the contiguous 48 states of the United States (hereafter just *U.S.*), especially in northern regions, other areas are expected to receive less (Easterling et al., 2017; Hay et al., 2011; Mahat et al., 2017). Furthermore, increasing temperatures, which are expected everywhere in the U.S., will tend to lower streamflow via the effect of temperature on evaporative demand, in some areas completely negating the positive effect of increasing precipitation and leading to decreasing streamflow, such as is likely, for example, in parts of the Colorado River Basin (Ficklin et al., 2013; Rasmussen et al., 2014). In addition, climate change is expected to increase hydrologic extremes

(Foti et al., 2014a; Leng et al., 2016; Naz et al., 2016), leading to more intense and prolonged droughts in some areas (Cook et al., 2014; Dai, 2013; Wehner et al., 2017).

Recent assessments of future water supply and demand across the U.S. found that some regions are likely to face serious water shortages in the absence of major new adaptations (Blanc et al., 2014; Foti et al., 2014a, 2014b). The importance of adaptation is enhanced in part because of the realization that despite whatever mitigation occurs in the coming years, substantial climate change is already set in motion due to inertia in the climate system (Meehl et al., 2005), and also because the hydrologic effects of climate change are likely to increase over time.

Adaptation options being proposed for responding to the effects of climate change on water resources are similar to measures that have long been employed in dealing with population and economic growth (Binder et al., 2010; Lawler, 2009; Purkey et al., 2008; Schwarz et al., 2011). Regarding water shortage, aside from enhancing adaptive capacity (National Research Council, 2010), options for responding to impending water shortage can be grouped into two broad categories, those that enhance water supply and those that reduce water demand (Bates et al., 2008; Brekke et al., 2009; Hanak & Lund, 2012). Water supply options focus on developing new water supplies or improving existing supplies (e.g., enlarging reservoir storage capacity) and on diversifying existing water supplies (e.g., linking supplies via new canals). Demand management options focus on improving water use efficiency (e.g., switching to new water-saving technologies and appliances), changing laws and administrative procedures (e.g., relaxing constraints on water transfers), and strengthening economic incentives (e.g., altering water rates), and on limiting withdrawals from stressed sources (e.g., limiting groundwater pumping from at-risk aquifers).

In this study, we model water demand and supply across basins covering the U.S. over the remainder of the 21st century and observe how the demand-supply balance is altered by several different adaptation strategies. U.S.-wide assessments of future water demand and supply have not been common. The first concerted efforts at a nationwide assessment were completed by the Water Resources Council (1968, 1978), but the Council was dismantled in the early 1980s. More recently, the U.S. Geological Survey (USGS) proposed another major effort at a comprehensive national assessment (U.S. Geological Survey, 2002), but as of yet only selected regional assessments have been completed (U.S. Geological Survey, 2017). Less detailed efforts, however, have been completed. These new assessments have tended to focus on the potential effects of climate change on future water supply and demand (Foti et al., 2012; Roy et al., 2012; Strzepek et al., 2010) but generally have not examined the potential effects of adaptation strategies.

We model U.S. water supply and demand at a fairly fine spatial (204 HUC-4 basins) and temporal (monthly) scale for each of 14 alternative climatic futures created by matching two future greenhouse gas emission scenarios with seven global climate models (GCMs). Water supply is modeled by estimating water yields and routing those yields via natural (upstream to downstream) and artificial (transbasin diversion) flow paths to final demands or reservoir storage, in light of instream (environmental) flow constraints. Using this framework, we project future shortages assuming that only renewable water supplies are available but that water use efficiency will continue to improve in line with past trends and then examine the effect on projected shortage increases of several adaptation measures (increases in reservoir storage capacity, reductions in irrigated area, and reductions in instream flows) and of further drawdowns of groundwater supplies.

Our main objective is to assess the relative effectiveness of alternative adaptations in ameliorating projected water shortages. All of the measures we investigate involve serious external costs, but it is important to examine them, if only to understand the pressures that will come to bear as the prospect of shortages becomes more intense, for the more effective adaptations are the ones most likely to be advocated. We leave to future work a thorough assessment of the social and economic costs of the adaptations, and of their likelihood of adoption.

2. Methods

2.1. Overview

In our approach, shortages occur when water demand exceeds water supply—supply being the water available to meet demand. The frequency of water shortages is quantified here as the number of months over a given multiyear time period when shortages occur. Throughout, we summarize conditions for four

25-year time periods: *past* (1986–2010), *near future* (2021–2045), *midfuture* (2046–2070), and *far future* (2071–2095).

To determine the effect of a given adaptation, we first establish the *baseline* demand and supply condition for each of 14 future climates selected for analysis. As explained in more detail further on, the baseline condition incorporates a number of assumptions, including on the supply side fixed reservoir storage and transbasin diversion capacities and future GCM-based estimates of temperature, precipitation, and other climate variables, and on the demand side fixed allocation priorities and projected changes in population. Having quantified water demand, supply, and shortage of the baseline condition, we then, for each future climate, analyze the impact on shortages of a set of possible adaptations using one of two approaches: (1) alter components of demand or supply (e.g., reduced irrigated area or enhanced reservoir storage capacity) and recompute water shortages or (2) directly compute the amount of change in some aspect of demand or supply (e.g., groundwater mining) that would be needed to negate the shortages. Use of 14 different future climates allows a rough characterization of the possible range of future effects of the adaptations.

2.2. Study Area

Water supply and demand, and thus water shortages, are estimated for each of the 204 four-digit hydrologic units (HUC-4s) of the U.S.—also known as *subregions* (Seaber et al., 1987) and hereafter referred to simply as *basins*. The basins are subdivisions of the 18 water resource regions (WRRs) of the U.S. (Figure 1a). Where we broadly distinguish east from west, the east consists of WRRs 1–9 and the west of WRRs 10–18.

Of the 204 basins, 66 drain to the sea or the Great Lakes, 9 drain to Mexico or Canada, 12 are closed basins, and the remaining 117 basins drain into other basins. As modeled, 167 of the basins are arranged in seven multibasin networks (Figure 1b). Within these networks, each basin is connected to at least one other basin by a natural (upstream to downstream) or artificial (transbasin diversion) flow path. The remaining 37 basins are unconnected to any others (three are closed basins without transbasin diversions, and the others are at the periphery of the U.S.). Natural flow paths were determined from the National Hydrography Dataset (U.S. Geological Survey, 2013). Locations of transbasin diversions were taken from Petsch (1985) and Mooty and Jeffcoat (1986).

2.3. Climatic Futures

Although climate models are continually being improved, substantial uncertainty remains about the projections, as becomes obvious when comparing results from different climate models for a given greenhouse gas emissions scenario (e.g., Byun et al., 2019; Hamlet et al., 2013; Hay et al., 2011; Leng et al., 2016; Mahat et al., 2017; Naz et al., 2016). It is therefore necessary when assessing the potential impacts of climate change on future conditions to use several climate models, providing a rough picture of the potential range of results and a notion of the uncertainty about the projection. Note that climate projections may also differ by downscaling procedure, but herein we do not investigate variability among downscaling procedures.

We projected water shortages for 14 climatic futures created by matching two representative concentration pathways (RCPs 4.5 and 8.5) with seven GCMs (Table 1) included among the models used for the *Fifth Coupled Model Intercomparison Project* (CMIP5; Taylor et al., 2011). The seven GCMs were chosen based on availability of downscaled precipitation and temperature data and related coarse-resolution wind speed data, as summarized next and explained more fully by Mahat et al. (2017).

Bias-corrected spatially downscaled projections at the $1/8° \times 1/8°$ scale of daily precipitation and minimum ($T_{\min}$) and maximum ($T_{\max}$) temperatures from CMIP5 models were obtained from the U.S. Bureau of Reclamation (U.S. Bureau of Reclamation, 2013). Coarse-resolution wind speed projections from CMIP5 models (Program for Climate Model Diagnosis and Intercomparison, 2014) were spatially interpolated on the basis of 20th century observed wind speed. For a given CMIP5 model and RCP, wind speed for each $1/8° \times 1/8°$ grid cell was estimated as equal to the corresponding coarse grid (e.g., $3.8° \times 3.8°$) wind speed of the CMIP5 projections multiplied by the long-term mean of the ratio of historical $1/8° \times 1/8°$ wind speed to historical coarse grid wind speed. Future soil, vegetation, and snow albedo values are assumed to be the same as in the past.

U.S.-wide mean annual temperatures are projected to rise with all 14 futures (supporting information, Figure S1a), but at different rates, such that by the far future period there is considerable variation, with

Figure 1. Spatial extent and scale of the study. (a) Water resource regions (numbered) and huc-4 basins. (b) Basin networks.

mean temperature rising from the past period to the far future period by from 1.5 °C (GFDL45) to 6.2 °C (MIROC85). Average temperature increases of the RCPs are 2.8 °C for RCP 4.5 and 5.0 °C for RCP 8.5 (Figure S1a). Projected trends in U.S. precipitation, on the other hand, are not consistently up or down (Figure S1b). Four futures expect late century mean annual precipitation to be lower than in the recent past, while the other 10 futures expect increases. Mean annual precipitation changes from the past period to the far future period range among the futures from −2.6 cm (IPSL85) to 12.8 cm (CAN85), but the corresponding average precipitation changes of the RCPs are nearly identical, at about 3.0 cm. Both RCP averages show gradual increases over the century (Figure S1b). For more on these 14 climate futures, see Mahat et al. (2017).

2.4. Baseline Water Supply

For the baseline condition, water supply of a basin in a given month is equal to water yield produced in the basin plus inflow from upstream basins, net import via transbasin diversions, and within-basin reservoir storage from the prior month (net of evaporation from that storage) and minus required basin instream flows and releases to downstream users. Notice that for our baseline condition groundwater mining—prolonged groundwater overdraft, causing a long-term drawdown of the water table or reduction in hydraulic head of a confined aquifer—is not considered a source of supply. In excluding groundwater mining, the baseline focuses on renewable water sources, which can include pumping of recent water yield that has percolated into the groundwater reservoir.

The effect of climate change on streamflow (and thus water supply) will vary by season, possibly increasing streamflow in some seasons while lowering it in others (Leng et al., 2016; Naz et al., 2016). For example, in snow dominated areas middle to late century peak runoff is projected to occur up to a month or two earlier than in the recent past, generally leading to lower flows in summer (e.g., Byun et al., 2019; Ficklin et al., 2013; Hamlet et al., 2013; Mahat et al., 2017; Rasmussen et al., 2014). To capture this seasonal variation, we model water supply at a monthly time step.

Water yield was estimated with the variable infiltration capacity (VIC) model (Cherkauer et al., 2003; Liang et al., 1994; Liang et al., 1996; Nijssen et al., 1997). The VIC model is a semidistributed, macroscale, grid-based hydrological model that solves the vertical energy and water balances in each grid cell at a daily time step and has been successfully applied elsewhere (Cayan et al., 2010; Christensen & Lettenmaier, 2007). Our calibration of the VIC model is described by Mahat et al. (2017). Climatic forcings required to run the VIC model for the U.S. for the historical (1950–2010) period (precipitation, T_{min} and T_{max}, and wind speed) and other model inputs (soil properties, vegetation characteristics, and snow albedo data) were obtained from the University of Washington Surface Water Modeling Group (2013). These data sets were gridded at ⅛° × ⅛°, latitude by longitude (roughly 12 × 12 km). Downscaled climatic forcings used to run the VIC model for future years (2011–2100) were obtained for the CMIP5-based futures referenced above. All VIC runs

Table 1
Climate Models Used

Model	Short name
BCC-CSM1.1	BCC
CanESM2	CAN
CSIRO-Mk3.6.0	CSIRO
GFDL-ESM 2 M	GFDL
IPSL-CM5A-LR	IPSL
MIROC-ESM	MIROC
MPI-ESM-LR	MPI

were performed at the daily time step and grid cell spatial scale. VIC estimates of surface runoff and base flow were summed to calculate water yield. Results were aggregated to the monthly time step and the basin spatial scale.

Basin reservoir storage capacities were set equal to the sum of the normal storage volumes of all reservoirs listed in the 2013 National Inventory of Dams database (U.S. Army Corps of Engineers, 2016) as having at least 100 acre-feet of storage volume available for at least one of the following purposes: water supply, irrigation, or fire protection/stock/small farm pond (in some cases the purpose designation was amended by additional web-based information). The resulting list included 10,544 reservoirs with a total storage capacity of 422 Bm^3. See Figure 7a for resulting storage capacity by basin.

Transbasin diversion amounts were set equal to the mean annual diversions reported by Petsch (1985) and Mooty and Jeffcoat (1986) for years 1980–1982, as amended by more recent information for California (California Department of Water Resources, 1998), Colorado (Colorado Water Conservation Board, 1998, 2010; Litke & Appel, 1989), the Lower Colorado River Basin (International Boundary and Water Commission, 2006), and other locations from miscellaneous sources.

Our estimate of past groundwater mining volume equals past groundwater withdrawal (Hutson et al., 2004; Kenny et al., 2009; Maupin et al., 2014) minus the amount of mean annual yield that is likely to recently have infiltrated and become available for pumping and relies heavily on recent estimates of groundwater depletion (Russo et al., 2014). See supporting information section B for an explanation.

2.5. Baseline Water Demand

Baseline annual water demand was estimated as the net amount of water depletion that would occur if water supply was no more limiting than it has been in the recent past. That is, except for the effects of climate change, future demands were estimated assuming that future supplies will be much like recent past supplies. Net water depletion was computed as withdrawal times a consumptive use factor, or essentially withdrawal minus return flow, with consumptive use factors computed based on USGS water use circulars for years 1990 and 1995 (Solley et al., 1993, 1998).

Total annual water demand was estimated for each basin. Modeling at the basin scale of course ignores any legal arrangements that may distinguish among individual water right holders within a basin. Annual water demand was estimated by summing projections for six water use sectors: domestic and public; agricultural irrigation; thermoelectric; industrial, commercial, and mining; livestock; and aquaculture. The methods we used to project baseline annual water demand follow those described by Brown et al. (2013). Data on past water use (from surface and groundwater sources) came from the quinquennial USGS water use circulars for years 1960 to 2010 or for thermoelectric power water use from Diehl and Harris (Diehl & Harris, 2014; Maupin et al., 2014). Future water withdrawals in each sector were estimated as the product of a water use driver (e.g., population and irrigated area) and a water withdrawal rate (e.g., domestic withdrawals per capita and irrigation withdrawal per unit area). Effects of climate change were then added to some of the projections: domestic and public and irrigation demands were modeled as affected by future changes in precipitation and potential evapotranspiration, and thermoelectric demand was modeled as affected by future changes in ambient temperature (Brown et al., 2013).

Most important among the water use drivers are population, irrigated area, and electricity use. U.S. population is projected to rise from 308 million people in 2010 to 514 million in 2100, reflecting an annual growth rate that gradually declines from about 0.8% to 0.3% over that 90-year period (Brown et al., 2013, A1B scenario); irrigated area is projected to increase in the East and decrease in the West following established trends (Brown et al., 2013); and per capita total electricity consumption is assumed to increase from 12,522 kWh/year in 2010 to 13,398 kWh/year in 2100, following an annual growth rate that gradually declines from 1.2% to 0.01% over the 90-year period.

Although some past trends in factors affecting water use clearly tend to increase water use, such as population growth and per-capita electricity consumption, others do not. Recent past trends in water withdrawal rates in most sectors, and past trends in irrigated area in the west, have been downward sloping, thus tending to lower withdrawals (supporting information Table S1), as water users responded to changing circumstances and incentives such as increasing costs (due largely to impending water scarcity) and environmental controls (due largely to water quality concerns) and took advantage of improvements in water using

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machinery and appliances (Brown, 2000). For example, from 1985 to 2010, U.S. domestic and public withdrawal per capita dropped by 11%, U.S. thermoelectric freshwater withdrawals per kilowatt hour produced dropped by about 20% (due principally to movement from once-through to recirculating cooling systems), and irrigation withdrawal per unit area in the West dropped by 21% (based on USGS water use circulars). As a result of those sectorial changes, aggregate water withdrawal per capita over the same period declined by 17%, and total withdrawal rose by only about 8% despite a 30% increase in population. For the baseline, we assumed a continuation of those past trends—that is, we take it as given that water use efficiency will continue to improve in response to growing water scarcity. In most cases the trends are nonlinear, reflecting a gradual attenuation of the decreasing trend (Table S1).

Annual withdrawal estimates were apportioned to months by water sector. Monthly proportions for the domestic and public sector were computed based on data from 232 water providers, mainly cities, across the U.S. (Foti et al., 2012). For the thermoelectric sector, the proportions were based on net generation data from plants across the U.S. from the Department of Energy. For agricultural irrigation, proportions for each basin were based on estimates of moisture deficit, computed from VIC model runs over the period 1981–2010 as potential evapotranspiration minus effective precipitation—effective precipitation being the portion of precipitation that is useable to plants (Brown et al., 2013). And for the industrial and commercial, livestock, and aquaculture sectors the proportions were assumed to be equal over the year. The monthly proportions were held constant over time, a simplifying assumption that we expect to have minimal effect on the estimates of changes in shortage with the adaptations under analysis.

A basin's monthly instream flow requirement was set at 10% of the month's mean historical (1953–1985) water yield (Tennant, 1976). These constant amounts were applied to both past and future conditions, without adjusting for shifts in the average water yield due to climatic changes.

2.6. Network Analysis

The Water Evaluation and Planning (WEAP) model (Yates et al., 2005) was used to route water within a network and compute monthly water shortages. The model uses linear programming to solve the water allocation problem, whose objective is to maximize satisfaction of demands subject to allocation priorities, mass balances, water availability, and other constraints. The constraint set is written such that in a shortage situation (i.e., where a set of linked demands of equal priority cannot be fully met in a given month), an equal percentage of each demand quantity of the given priority is satisfied. Months are solved sequentially without foresight.

In WEAP, a demand is satisfied from current water yield before reservoir storage is utilized. If reservoir storage is tapped, all upstream reservoirs of the same priority are candidates and WEAP attempts to leave each such reservoir with the same percentage of active storage. Thus, WEAP imposes a kind of sharing not only in satisfying demands but also in maintaining reservoir storage levels. That sharing may or may not reflect the allocations that would occur as a result of implementing actual interbasin sharing agreements. It was beyond the scope of this assessment to accurately model the legal arrangements affecting the many transbasin sharing agreements across the U.S. In essence, the proportional sharing fallback position in WEAP implements an equity-based allocation of available supplies.

Input to the WEAP model includes the following for each basin: monthly values of water yield, water demand, transbasin diversion amount (may be 0), and instream flow constraint; values of reservoir storage capacity, evaporation rate, and a volume-elevation curve; and priorities of the different water uses. The WEAP model was run at the monthly time step for the period of 1950 to 2100 to calculate past and future water shortages for each basin within each network. Results for early years (1950–1985) are not used but serve to initialize reservoir storage levels.

The instream flow requirement was assigned first priority, transbasin diversions and then within-basin consumptive demands were given the next two lower priorities, and reservoir storage was assigned the lowest priority. This order of priority guarantees a minimal amount of water for environmental and ecosystem needs before any other needs are met and satisfies major water diversion agreements before meeting local demands. Water is stored only if the reservoir is not already full and the water is not able to meet higher priority uses in the given month. Water uses belonging to the same class were assigned the same priority irrespective of their position in the network. For example, the instream flow constraint was satisfied—if possible

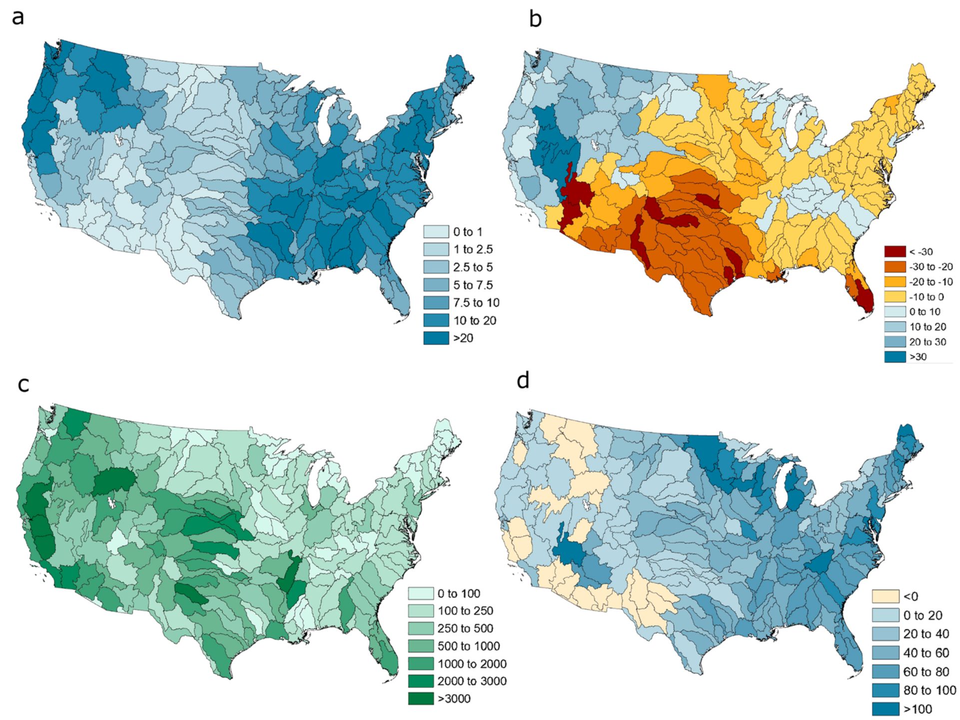

Figure 2. Past and projected annual water yield and demand by basin. (a) Water yield in past period (Bm^3). (b) Percent change in water yield from past period to mid future period, mean of 14 futures. (c) Water demand in the past period (Mm^3). (d) Percent change in water demand from past period to mid future period, mean of 14 futures. Time periods: past (1985–2010) and midfuture (2046–2070).

given water availability and routing capacity—in all basins within a network before other uses were met in any basin of the network.

2.7. Shortage Calculation

Our approach, which is similar to that of Foti et al. (2014a), compares water demand to water supply. Supply of a basin (i.e., the water available to meet off-stream demands in a given month) is computed here as basin water yield plus net transbasin import (may be negative) plus basin reservoir storage from the prior month plus inflow from upstream (this can include releases from upstream reservoirs, per the shortage sharing rule implemented in WEAP) minus required instream flow release minus reservoir evaporation minus any required release to satisfy downstream demands (again per the WEAP sharing rule). Thus, supply is not an input to the routing model; rather, it is obtained from the water routing simulation. If not needed to meet accessible consumptive use demands, the renewable supply of a basin is stored in the reservoir if possible and released otherwise. If the prior month ended in a shortage situation, initial reservoir storage of the current month will be zero; otherwise, initial reservoir storage is likely to be positive.

3. Results and Discussion

3.1. Water Yield and Demand Across the U.S. Under Climate Change

Water yield in this study is the contribution to renewable water supply resulting from recent precipitation, whether that contribution becomes available as surface or ground water, equal to the sum of surface runoff and base flow estimated using the VIC model. Past water yields have of course been greatest in wetter regions of the U.S. (Figure 2a). Projected water yields, which reflect most importantly the GCM-based projections of temperature and precipitation, vary substantially among the 14 futures and show no consistent trends (supporting information Figure S2). For the U.S. as a whole, from the *past* period (years 1985 to 2010) to the midfuture period (years 2046 to 2070), six futures show increases and eight show decreases. Changes in mean annual yields from the past to the mid future period range from −2.6 cm (IPSL85) to

1.5 cm (MPI45). However, the RCP averages, each computed across seven futures, are in close agreement, with mean annual yield projected to initially decrease and then stabilize in middle to late century. RCP average changes in mean annual yield from the past period to the midfuture period are −0.3 cm for RCP 4.5 and −0.7 cm for RCP 8.5 (Figure S2). The projected RCP yields are similar largely because, relative to RCP 4.5, increases in precipitation with RCP 8.5 act to compensate for the effects of temperature increases on water yield (Mahat et al., 2017).

Projected changes in yield are highly variable across basins. Averaging across the 14 futures, from the past to the midfuture period, 145 basins show decreases in yield and 59 show increases, with the most severe decreases occurring in the Southwest, the middle to southern Great Plains, and Florida, and the greatest increases occurring in the larger Northwest, Great Basin, and California (Figure 2b).

Water *demand* herein is water consumption, equivalent to withdrawal minus return flow. Past water demand is highly variable across basins, with areas of greatest demand tending to occur in areas of least yield (Figures 2a and 2c). Future levels of water demand will reflect ongoing changes in water use drivers (e.g., population, economic growth, and climate) and in water use rates in the various water use sectors (e.g., domestic withdrawal per person and thermoelectric withdrawal per kilowatt hour produced). As described in section 2.5, water use rates in most sectors declined in recent decades.

In projecting future water demand, we assume that the declining past trends in water use rates will continue, although at a gradually attenuating rate as the practical limits of adaptability in the various sectors are approached. From 2010 to 2060, for example, if the climate were to remain stable, we project that aggregate U.S. withdrawal per capita would fall by 25% and that total withdrawal would increase by only 8% despite a population increase of 44%. The 25% drop in overall withdrawal rate reflects projected reductions in withdrawal rates in all major water use sectors (supporting information, Table S1).

Projected changes in climate will affect water use in several sectors (Georgakakos et al., 2014; Parry et al., 2007), as rising potential evapotranspiration rates, plus decreasing precipitation in some areas, raise agriculture and landscape irrigation demands and rising temperatures raise electricity demands. Based on modeling the effects of climate change on water use in the domestic and public, thermoelectric, and agricultural sectors, and averaging across the 14 different climate futures considered here, we project that aggregate U. S. withdrawal per capita will fall from 2010 to 2060 by 16%—thus, at substantially lower rates of decline than without climate change—and desired total withdrawal will increase by 22%. As with water yield, there is substantial variation across the different climate futures; for example, the change in projected U.S. desired total withdrawal ranges across the futures from 16% to 32%. Of course, the increases would be higher in the absence of the assumed declines in water use rates.

Projected percent changes in water demand vary substantially across basins, reflecting the combined effects of changes in drivers of water use and changes in water use rates in the various water use sectors. Projected changes in total demand from the past to the midfuture period, for example, are positive in most basins but slightly negative in some western basins (Figure 2d), where the effect of the projected decrease in irrigated area outweighs the effects of increasing water application rates in response to climate change as well as the increases in demand in other sectors (Brown et al., 2013).

3.2. Baseline Projected Water Shortages if Relying Only on Renewable Water Supplies

If off-stream users had relied solely on renewable water supplies—that is, if groundwater mining (i.e., sustained pumping beyond levels of recent recharge) had not occurred—but employed the full component of existing water storage and diversion capacity, past period shortages would have been significant, with 40 basins incurring at least 1 month of shortage and 17 basins incurring shortages in at least 20% of the months over the period (Figure 3a), with the shortages occurring largely during the summer months. Those shortages are concentrated in the middle and southern Great Plains, the Southwest, and much of California (Figure 3b).

In future periods, as population and economic growth plus the changing climate alter water yield and demand, shortages are projected to increase substantially, in the absence of adaptation measures, with many of the 14 futures we examined. Averaging across the 14 futures, 83, 92, and 96 basins are projected to incur some level of monthly shortage in the near, middle, and far future periods, respectively (Figure 3a). At the low end, at least one-quarter of those basins are projected to face only a very low (<1%) chance of

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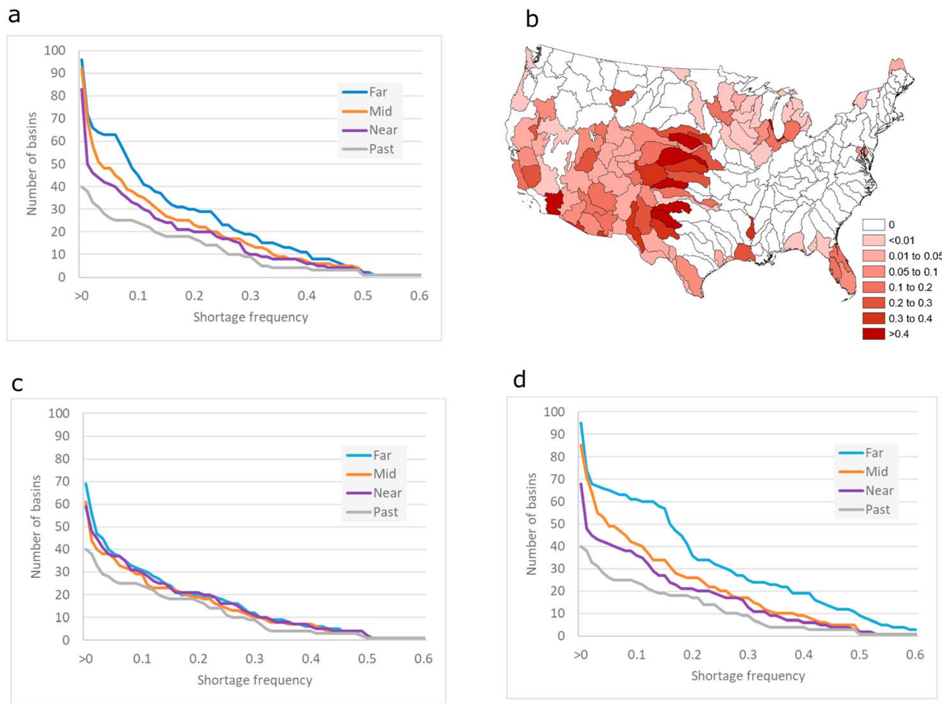

Figure 3. Mean shortage frequency if relying only on renewable water supplies. (a) Shortage frequency by time period, mean of 14 futures. (b) Shortage frequency by basin, midfuture period, mean of 14 futures. (c) Shortage frequency by time period, mean of four wet futures. (d) Shortage frequency by time period, mean of four dry futures. Wet futures (relatively high water yield in the middle and far future periods) are CAN45, CAN85, GFDL45, and GFDL85. Dry futures (relatively low water yield in the mid and far future periods) are CSIRO85, IPSL45, IPSLS85, and MIROC85. Time periods: past (1985–2010), near future (2021–2045), midfuture (2046–2070), and far future (2071–2095).

shortage in the respective periods, and at the high end about one quarter of those basins are projected to face a >20% chance of shortage (Figure 3a). The increases in shortages occur despite the assumed water use efficiency improvements.

Projected shortages vary widely among the 14 climate futures, but they do not vary much across the two RCPs except in the far future period (supporting information Figure S3). Rather, to depict the variation across the possible future climates, we summarize projected shortages for the four futures of highest water yield in the middle and far future periods and the four futures of lowest water yield in those periods. Given the wet (high water yield) future, shortage frequency increases (above past period levels) somewhat in the near future period but not much after that, as precipitation generally increases to balance out the effects of rising temperatures on water yields and demands, and thus on water shortages, all else equal (Figure 3c). However, given the dry (low water yield) future, all three future periods (and especially the far future period) incur markedly higher shortage frequencies than in the past period (Figure 3d). The differences in projected shortages between these wet and dry scenarios highlight the current uncertainty about future water shortages.

The next four sections examine the effects of four major adaptations on shortages in the roughly one half of the basins in the U.S. that are projected to incur shortages in the baseline condition, shown in Figure 3b.

3.3. Effect of Reduced Irrigation on Water Shortages

As shortages become more common and severe, users in high-value sectors—typically the municipal, industrial, and energy sectors—look to lower-valued uses for additional supply (Flörke et al., 2018). Irrigated agriculture, which is the primary user in most basins, often accounting for over 75% of annual consumption (Figure 4a), has been the primary source of water transfers to higher-valued sectors (Brewer et al., 2008; Brown, 2006). Because future water transfers from agriculture are very likely, the prospect of water transfers raises concerns about food security. Thus, a primary question is, how much of a reduction in agricultural

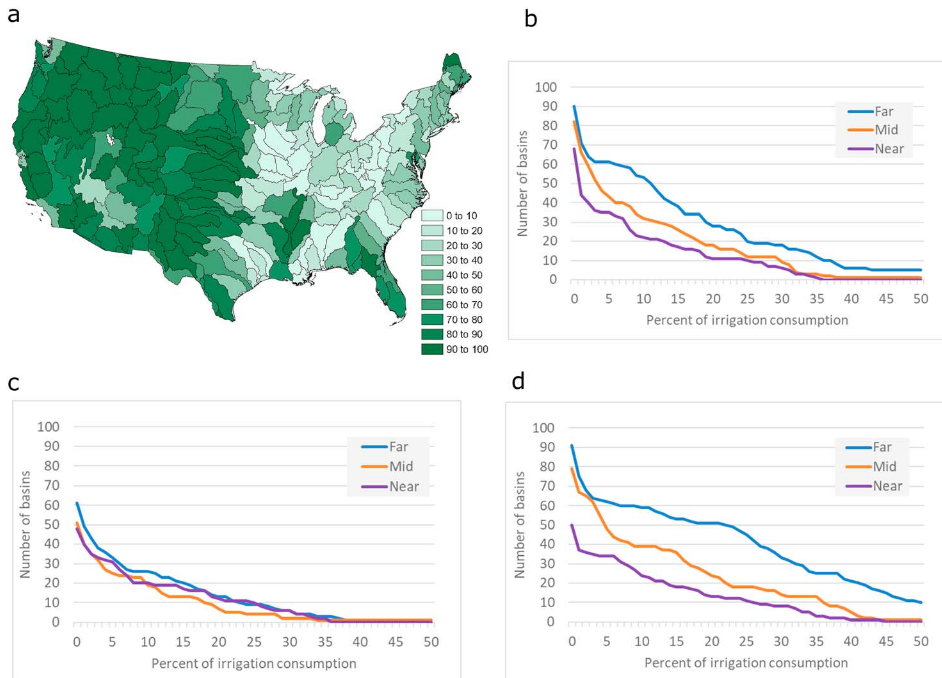

Figure 4. Irrigation water consumption in relation to projected water shortages. (a) Percent of total consumption in 2010 going to irrigation. (b–d) Mean annual percent of irrigation consumption needed to offset the projected increases in shortage, by future time period, mean of 14 futures (b), mean of four wet futures (c), and mean of four dry futures (d). See Figure 3 for definitions of time periods and of wet and dry futures.

irrigation, beyond that already projected to occur in the baseline futures based on an extension of past declining trends in western irrigated area and application rate, would be needed to accommodate the projected increase in water shortages, all else equal?

Areas of greatest projected shortages tend also to be areas of extensive irrigation (Figures 3b and 4a), suggesting that shortages could be avoided by reducing agricultural irrigation. On average across the 14 climate futures, we find that projected increases in shortages in 68 (near future period) to 90 (far future period) basins could be removed by cutting back on agricultural irrigation (Figure 4b). Further, a mere reduction of 2% of irrigation consumption could on average remove shortages in about one third of those basins. However, in a minority of basins the reduction would need to be substantial. For example, at least a 30% reduction would be needed in 6, 9, and 18 basins in the near, middle, and far future periods, respectively, to balance out the projected shortage increases (Figure 4b). Those basins are concentrated in the Southwest and central and southern Great Plains.

As with projected shortages (Figures 3c and 3d), the required changes in irrigated agriculture needed to avoid projected increases in water shortage depend critically on the future climate. Given the wet (high water yield) future scenario, in the midfuture period, for example, a >30% reduction in irrigation water consumption would be needed in only two basins (Figure 4c), whereas given the dry future a >30% reduction would be needed in 14 basins (Figure 4d).

Assessing the effect of irrigation reductions on food security is complicated by several factors including (1) some crops, or parts of crops, are used to produce biofuels, (2) large portions of some field crops, such as corn, are exported, and (3) much irrigated area is used for animal feed, only some of which is related to human food consumption. A comprehensive assessment of the impact of water shortages on food security is beyond the scope of this paper, but we can gain some insight by looking at the portion of basins' irrigated area growing the following seven crops used primarily for animal feed or biofuels: hay, field corn, soybeans, sorghum, millet, rapeseed, and switchgrass. In 2012 about 60% of the irrigated agriculture area in the U.S. was planted in these seven crops, with percentages particularly high in the Midwest and northern Plains (National Agricultural Statistics Service, 2012; supporting information Figure S4). On average across the

14 futures, we find that if irrigation of these crops were eliminated wherever needed to offset the projected shortages, the U.S. total irrigated area of these crops would be reduced by 7%, 8%, and 10% in the near, middle, and far future periods, respectively. Doing so would completely offset the shortages in all but 6, 8, and 10 basins in the near, middle, and far future periods, respectively (these basins are located mainly in Florida, Louisiana, Texas, Arizona, and California, and thus not in areas where the seven crops most dominate irrigated agriculture). We hasten to point out, though, that the effects of shortages on food security depend on the eventual crop mix in future periods, which may be quite different from what it was in 2012. In addition, to some extent decreases in irrigated area could be avoided by improving irrigation efficiency more than already assumed here.

In reality, irrigated agriculture is unlikely to bear the full burden of accommodating future water shortages. The value of water in all sectors covers a range, including some low-valued uses. Nevertheless, given the large quantities of water used in agriculture and the fact that most of that water is used to grow relatively low-value crops (Schaible & Aillery, 2012), the agriculture sector is likely to face serious challenges, all else equal. Next, we look at some options for limiting projected shortages that could potentially reduce the pressure on irrigated agriculture.

3.4. Effect of Groundwater Mining on Water Shortages

Groundwater mining has commonly been used where possible to supplement renewable supplies, especially in drier regions of the U.S., but was not included in baseline supplies because such mining is not sustainable in the long run. However, given that groundwater mining will certainly be relied upon in the future, it is useful to examine the extent to which groundwater mining could prevent the increases in future shortages that we estimate would occur if only renewable supplies were available. For this purpose, we isolated 45 basins that are likely to have relied on groundwater mining and estimated the amount of water in those basins that has typically been made available by mining. Among the 45 basins, estimated annual groundwater mining ranges from 5% to 95% of recent past groundwater withdrawal (Figure 5a).

On average across the full set of 14 futures, groundwater mining has the potential to eliminate the projected increases in shortages in roughly 30 to 40 basins depending on the time period (Figure 5b). However, the required level of mining would be substantial in some basins. For example, in 6, 12, and 15 basins in the near, middle, and far future periods, respectively, the required groundwater mining would be at least 100% of estimated past levels. Those 6 to 15 basins are located in the Great Plains, the Southwest, and to a more limited extent in Florida and along the lower the Mississippi River. These levels of groundwater mining would be in addition to the mining already occurring to avoid actual shortages in the past period.

We provide these estimates to give a rough idea of the potential of groundwater mining to limit shortages in basins where such mining is estimated to have occurred in the past, and not to suggest that such levels of groundwater mining are advisable or sustainable. Indeed, water tables in some of the basins have already dropped significantly (Konikow, 2013), and future withdrawals at recent rates would no doubt further diminish groundwater supplies. These estimates indicate that in many basins currently relying on mining of groundwater, continuing to rely on such mining to alleviate shortages would require ever greater levels of mining, thereby hastening the arrival of the day when groundwater mining is no longer economically viable.

3.5. Effect of Instream Flow Reductions on Water Shortages

For the baseline simulations, we imposed a monthly instream flow requirement of 10% of mean monthly past natural flow. As shortages become more common, remaining instream flows may come under increasing pressure from off-stream users, raising the question: how effective could further reductions in instream flows be in preventing shortage increases? We found that in the midfuture period, for example, on average across the 14 futures, allowing instream flow to go below the 10%-of-natural requirement could avoid shortage increases in 41 basins and lower shortage increases to varying degrees in the remaining 49 basins with shortage increases (Figure 6a). While the reduction in instream flow would be small in some basins (in 17 basins the instream flow reduction would be <1%), it would be substantial in others, and of course it would eliminate instream flow in the 49 basins where instream flow reductions were insufficient to completely avoid shortage increases.

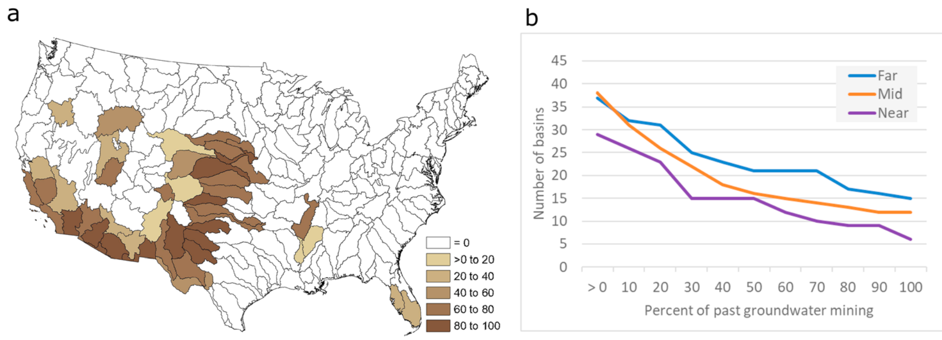

Figure 5. Groundwater mining and its impact on water shortage increases. (a) Estimated mean annual past groundwater mining as a percent of groundwater withdrawal in years 2000, 2005, and 2010. (b) Percent of past groundwater mining needed to avoid increases in shortage among the 45 basins estimated to have mined groundwater in the past, expressed as percent of estimated past groundwater mining, by future time period, mean of 14 futures.

Results vary by region. Generally, in the western basins a complete loss of instream flow does not suffice to remove shortage increases, whereas in eastern basins shortage increases are typically eliminated without using all of the instream flow (Figure 6b).

Eliminating or severely reducing instream flows is not unprecedented, as the condition of the Colorado River Delta, where the river meets the Gulf of California, makes clear (Getches, 2003). However, the external costs of consuming remaining instream flow would be onerous. In addition to the obvious concerns about aquatic life and riparian ecosystem health (and resulting effects on recreation, property values, and other human endeavors), eliminating remaining instream flows removes a safety net that could prove critical in the event of truly catastrophic drought.

3.6. Effect of Reservoir Storage Capacity on Water Shortages

Nearly all basins rely on reservoirs to store excess supply for release when needed (Figure 7a). Increasing reservoir storage capacities, either by enlarging the capacity of existing reservoirs (e.g., dredging sediment or raising dam height) or by building new ones, is an oft-proposed solution to water shortages. Our network analysis of water flow, storage, diversion, and delivery allows us to simulate the effect of alternative reservoir sizes on water shortages. We examined three levels of increase in basin reservoir storage capacity, of 10%, 25%, and 50% in all basins. Although unrealistic in practice, modeling such large levels of increase will illustrate the potential impact of storage capacity enhancements.

In general, increasing reservoir storage capacity has a modest impact on projected shortages. For example, in the midfuture period, increasing reservoir storage capacities by 10%, 25%, and 50% reduces mean annual U.S. shortage in the midfuture period by 8%, 12%, and 16%, respectively, and decreases the number of basins with at least 200 Mm^3/year of shortage from 29 to 25, 23, and 21, respectively (Figure 7b). As

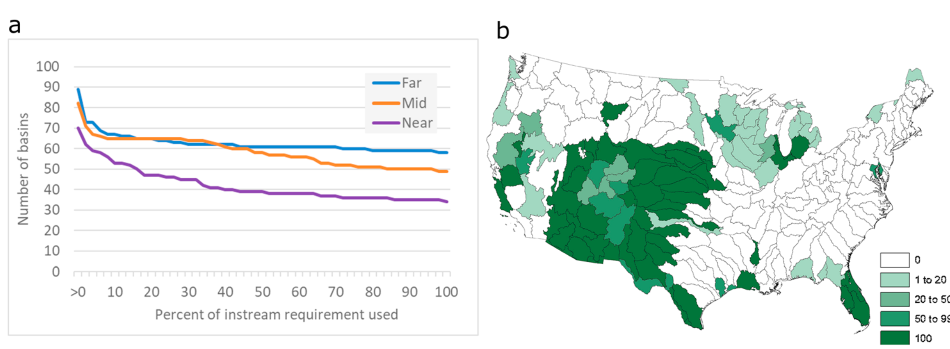

Figure 6. Potential effect of reduction in instream flow on projected water shortages, mean of 14 futures. (a) Percent reduction in instream flow needed to limit or avoid increases in shortage, by future time period. (b) Spatial distribution of instream flow needed in the midfuture period.

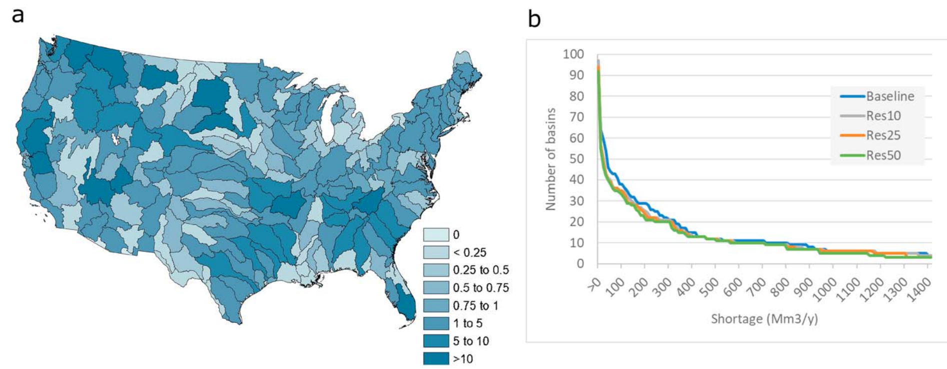

Figure 7. Potential effect of enlarged reservoir storage capacity on projected water shortages. (a) Existing (baseline) reservoir storage capacity (Mm^3). (b) Shortage volume at four levels of reservoir storage capacity in the midfuture period, mean of 14 futures. Res10, Res25, and Res50 indicate storage capacity enlargements from the baseline of 10%, 25%, and 50%, respectively.

would be expected, storage capacity increases are more effective in reducing shortages where storage capacity is initially low in comparison to mean annual flow, streamflow is unevenly distributed over the year, and demand is large in relation to supply. However, as others (e.g., Foti et al., 2012; Kim et al., 2019) have found, if water is the limiting factor—as is often the case in our projections of future shortage—increasing reservoir capacity cannot help. Further, as seen in Figure 7, increasing reservoir storage capacity has little or no impact on water shortages in basins with the highest shortage volumes (those >400 Mm^3/year), largely because those basins, while being the ones most in need, are also ones most lacking in water.

Note, however, two caveats to our findings. First, our results apply to aggregate basin storage and do not preclude the possibility of useful additions to storage in selected within-basin upstream locations. Second, our analysis focuses on the effect of reservoir storage capacity increases on projected water shortages and fails to reveal an effect of storage capacity increases on water availability in general. As Ehsani et al. (2017) show for the case of increasing winter flows but decreasing summer flows with climate change in the Northeast, an increase in storage capacity can be used to store some of the additional winter flows and release that water during the summer. Because our results indicate very limited water shortages in the Northeast, we show no effect there of storage capacity increases. Modeling at a finer spatial scale could potentially have detected some shortages.

3.7. Uncertainty in the Projections

Projections are inherently uncertain and become more uncertain the further one projects into the future. We explicitly addressed uncertainty about future climate by employing projections from seven different GCMs for each RCP level (Figure S1 depicts U.S. temperature and precipitation projections for the 14 futures) and showing how projections of shortage differ with relatively wet versus dry futures (Figures 3c, 3d, 4c, and 4d). However, showing variability across the selected climate models does not ensure that actual future conditions will fall within the range that such variability captures. And while computing an average result across the different climate models is likely to provide a more reliable result than that of any one model, the average is of course dependent on individual models included. Furthermore, climate modeling is only one potential source of error in our study. The downscaling, water yield, and water demand models we employed and the assumptions incorporated in the water routing model we used (e.g., regarding water allocation priorities and lack of foresight in reservoir management), though chosen with care, could all be introducing error in our estimates of future shortages.

An additional potential source of error arises from our assumption of unchanging future vegetation cover. Rising CO_2 concentrations, increasing temperatures, and precipitation changes will combine to cause a complex assortment of vegetation changes across the landscape in the decades ahead (e.g., Kerns et al., 2018; Lenihan et al., 2003). Those vegetation changes will affect water yield, either positively or negatively in specific locations, potentially altering the basinwide yields we estimated based on the existing vegetation cover. Given the complexity of vegetation responses to climatic and ambient CO_2 changes, and the concomitant difficulty of accurately estimating how basin water yield would change in response to those vegetation changes, we opted to leave that topic for future study.

While the uncertainty in the levels of the projections of future shortages must be recognized, it is important to note that—as demonstrated by Arabi et al. (2007) in a similar context—the effects of some of the adaptation options we analyzed, those which are based on differences between sets of shortage projections, are likely to be more accurately estimated than the absolute levels upon which the differences are based.

4. Conclusion

Although there remains substantial uncertainty about future precipitation and thus water yield, climate change and population growth are likely to present serious challenges in some regions of the U.S., notably the central and southern Great Plains, the Southwest and central Rocky Mountain States, and California, and also some areas in the South (especially Florida) and Midwest. The continued reductions in per-capita water withdrawal rates assumed here, which follow trends established over the past three decades, are essential but insufficient to avoid impending shortages. Attention will therefore focus on the other options examined here—additional reservoir storage capacity, groundwater mining, instream flow reduction, and ag-to-urban transfers—all of which have serious external costs. Of these four options, the first has limited promise, especially where most needed. Simulations show that major additions to storage capacity are ineffectual in the most vulnerable basins due to a lack of water to fill the reservoirs. The other three options, however, can be quite effective in many locations, indicating that pressures to implement them will mount as shortages become more severe.

If further reductions in groundwater storage and instream flow are to be avoided, improvements in irrigation efficiency beyond those assumed here will become a high priority, but in addition transfers from agriculture to other sectors probably will be essential (Tanaka et al., 2006). While not without external costs, such transfers fortunately occur voluntarily and would primarily involve water formerly used to grow relatively low-value crops. As has been argued elsewhere (Binder et al., 2010), an important adaptation strategy will be to reduce institutional impediments to such transfers.

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