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The importance of municipal and agricultural demands in future water shortages in the United States

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Abstract

We examine how future changes in water yield and demand will affect the likelihood of water shortages and the efficacy of some of the most common methods for dealing with water shortages and meeting municipal demands, including improvements in water use efficiency and transfers of water between sectors of the economy. We find that more than 45.8 million people, primarily in the Southwest, central Great Plains, and southern California, would already be experiencing regular water shortages in the absence of groundwater mining. By 2060, that number would grow to over 136.2 million people. Among the reasons we find for increased likelihood of water shortages, reduced water yield is the most prevalent, affecting 80% of water basins in the US. In the American West, nearly half of the water basins are projected to see an increase in shortages. We estimate future water withdrawals in the industrial and commercial and thermoelectric sectors will remain fairly steady, but withdrawals in the domestic and public sector are expected to rise. The Colorado River and Rio Grande regions see the largest percentage increases in projected domestic and public water use as well as the greatest percentage decreases in projected water yield. To cover new municipal demands, transfers from agriculture may be needed, in which case, significant impacts to agriculture will occur in northern New Mexico, parts of Utah, Nevada, and Washington where municipal demands are projected to grow to 25%–50% of agricultural water use. The situation is more extreme in northern Arizona and eastern Texas, where additional municipal demands are projected to be six times the amount used by agriculture.

Introduction

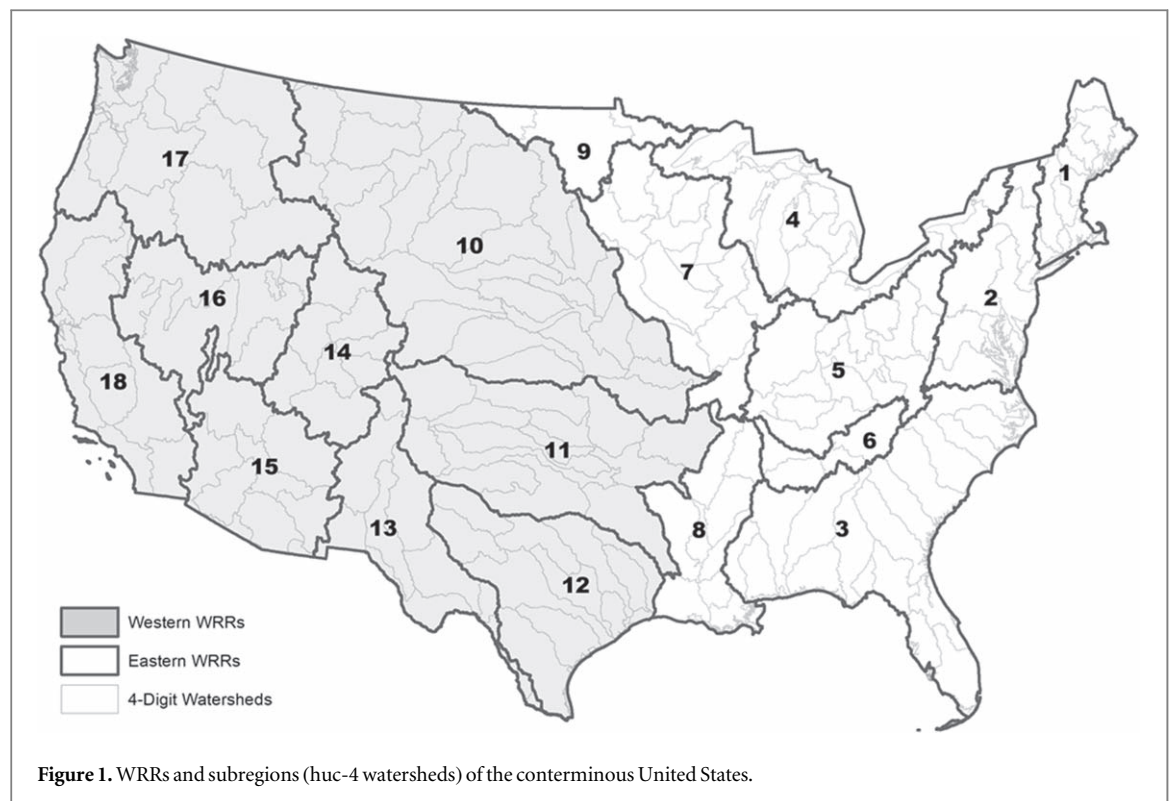
American municipal water providers rank reliability of future supplies as one of their top issues of concern (Murphy 2018). Nationally, climate change is expected to lead to declines in water yield of about 20% by 2060 based on CMIP5 climate models. The largest decreases in absolute yield are expected in the southern and south-central states, and the largest percentage decreases in yield are expected in the Southwest, the central and southern Great Plains, and Florida (Mahat *et al* 2017). Many of the places expected to see decreasing yields are also expected to see rapid population growth, often stretching scarce water resources.

Places that face periodic shortages often turn to water rationing (e.g. restricting outdoor water use) to

curb demand in the short run and technology standards (e.g. requiring low flow toilets) to curb demand in the long run (Mansur and Olmstead 2012). In 2018, for example, over 1000 public water suppliers in Texas instituted water use restrictions in response to ongoing drought⁴. California, after experiencing six years of drought, passed legislation aimed at reducing indoor water use to 50 gallons per person per day by 2030.

There are limits, however, to what can be achieved through technological and conservation improvements, making water markets and ag-to-urban water transfers important tools for meeting future municipal water demands (Hewitt and Hanemann 1995,

⁴ From the Texas Commission on Environmental Quality <https://tceq.texas.gov/drinkingwater/trot/location.html>, (Accessed: 14 December 2018).



Espey *et al* 1997, Howe 1997, Freeman 2003, Brown 2006, Brewer *et al* 2007, Grafton and Ward 2008, Young and Loomis 2014, Ghosh 2018). To date, water transfers in the United States have mostly been limited to the West, where the prior appropriations doctrine creates water rights and state laws facilitate water markets. A little over half of these transfers were from agricultural to urban uses, mostly through short term leases during drier years rather than permanent sale of water rights (Brewer *et al* 2006, Ghosh 2018).

Herein, we examine how future changes in water yield and demand will affect the likelihood of water shortages. We also examine the efficacy of some of the most common methods for dealing with water shortages and meeting municipal demands, including improvements in water use efficiency and transfers of water between sectors of the economy. Our work builds on that of Brown *et al* (2013, 2019), who project future water demands and highlight the importance of climate feedbacks in demand. We improve on the spatial and temporal resolution of their models and focus on the role of specific economic sectors in causing future water shortages.

Relatively few studies take a national look at the vulnerability of US water supply, with important differences between them related to study scope and modeling approaches. In our model, demand projections rely on continuation of current trends in population growth and water use rates. As such, our water demands are likely to be larger than those from models that maximize the value of water subject to total water availability (e.g. Jenkins 2001, Draper *et al* 2003, Pulido-Velazquez *et al* 2004) and from models that

estimate the water requirements needed to maintain current practices in a future with climate change (e.g. Wada *et al* 2013). Optimization models tend to reflect the best case scenario and miss some of the forces already occurring in the economy that are likely to either magnify or alleviate some of the pains associated with climate change. Our approach highlights where the status quo is unsustainable and where management actions are most needed.

Methods

We model water supply and demand in the conterminous United States through the year 2070 at the subregion (huc-4, figure 1) spatial scale and monthly time step for each of 14 alternative climatic futures. The climatic futures correspond to two greenhouse gas emission levels (Representative Concentration Pathways 4.5 and 8.5) each modeled with seven global climate models (table 1) included among the models used for the Fifth Coupled Model Intercomparison Project (CMIP5) (Taylor *et al* 2011). The 204 huc-4 basins, hereafter just ‘basins’, are organized within 18 water resource regions (WRRs, figure 1). When we distinguish between eastern and western basins, the East contains WRRs 1–9, and the West contains WRRs 10–18. The methods are summarized here; see Brown *et al* (2019) for additional methodological details.

Water supply and demand were modeled in order to estimate water shortage, where shortage is the amount of demand that cannot be satisfied from available supply. Given estimates of water yield and water

Table 1. Climate models used.

Model	Short name
BCC-CSM1.1	BCC
CanESM2	CAN
CSIRO-Mk3.6.0	CSIRO
GFDL-ESM2M	GFDL
IPSL-CM5A-LR	IPSL
MIROC-ESM	MIROC
MPI-ESM-LR	MPI

demand, water supply and shortage were estimated using the water evaluation and planning (WEAP) water routing model (Yates *et al* 2005). WEAP solves the water allocation problem throughout a network of linked basins by maximizing satisfaction of demands subject to allocation priorities, mass balances, water availability, and other constraints. 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 our implementation of WEAP, a demand is satisfied from current water yield before reservoir storage is utilized. If reservoir storage is tapped, all upstream reservoirs are candidates, and WEAP attempts to leave each such reservoir with the same percentage of active storage. Thus, the model 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 result from implementing actual inter-basin sharing agreements. It is beyond the scope of this assessment to accurately model the legal arrangements affecting the many trans-basin sharing agreements and reservoir management rules across the US. In essence, the proportional sharing fallback position in WEAP implements an equity-based allocation of available supplies between basins. Trans-basin diversions, however, are given a higher priority than within-basin demands, so those trans-basin diversion demands, such as from the Colorado River Basin to southern California, are nearly always satisfied. This assumption may not hold in actuality for serious shortage years that could trigger sharing rules for Colorado River water, for example. Nonetheless, our results do not differ substantially from those of studies using more detailed models for prioritizing water in California that, because water law favors California among lower Colorado River basin states, assume Colorado River water is readily available (e.g. Medellín-Azuara *et al* 2008).

Using this approach, water supply is not an input to the routing model, but rather is determined as part of the routing solution, as the amount of the water available to meet off-stream demands once instream (environmental) flow requirements are met. A basin's

water supply in a month is equal to the sum of water yield produced in the basin, inflow from upstream basins, net import via trans-basin diversions (may be negative), and within-basin reservoir storage from the prior month (net of evaporation from that storage), less required basin instream flows and releases to downstream users. Each basin's instream flow requirement for each month was set equal to 10% of that month's mean water yield between 1953 and 1985, which is the minimum instantaneous flow that allows short-term survival habitat for most aquatic life (Tennant 1976). If not needed to meet the instream flow constraint and accessible demands, the available water in a basin is stored in the reservoir if possible, and released otherwise.

Water yield was estimated with the variable infiltration capacity model (Liang *et al* 1994, 1996, Nijssen *et al* 1997, Cherkauer *et al* 2003) as the sum of surface and base flow. In modeling water yield as such, our approach focuses on renewable water sources, which can include pumping of recent water yield that has percolated into the groundwater reservoir but excludes groundwater mining (defined as prolonged groundwater overdraft, causing a long-term draw-down of the water table or reduction in hydraulic head of a confined aquifer).

Following methods described by Brown *et al* (2013), water demand was estimated as the net amount of water depletion (equal to withdrawal times a consumptive use factor, or essentially withdrawal minus return flow) that would occur if water supply were 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. Water demand is estimated for five water use sectors that are combined in two groups (table 2) for analysis, reflecting our primary focus on the distinction between agricultural and non-agricultural water use (for the latter we use the term 'M&I' water use).

Future water withdrawals in each sector were estimated as the product of a water use driver (e.g. population, irrigated area) and a water withdrawal rate (e.g. domestic withdrawals per capita, irrigation withdrawal per unit area) (table 2). Withdrawal rates vary across time according to observed trends. Consumptive use factors, needed to estimate final demands, were based on rates reported in the 1990 and 1995 USGS water circulars (the last years for which consumptive use was reported consistently for all sectors) plus additional information about likely future changes in those rates (Foti *et al* 2012).

Climate change affects withdrawal rates for irrigated agriculture, domestic and public, and thermoelectric power (table 3). Withdrawal rates for irrigated agriculture are affected by increasing temperatures, which increase potential evapotranspiration, and precipitation, which determine the irrigation depth needed to meet crop water demands. Effects of climate on

Table 2. Water use sectors.

Sector	Short name	Sector group	Driver	Withdrawal rate
Domestic and public	DP	M&I	Population	Gallons/capita
Industrial, commercial, and mining	IC	M&I	Income	Gallons/\$1000 income
Thermoelectric	TF	M&I	Per-capita electricity use, population	Gallons/kWh
Agricultural irrigation	IR	Ag	Area irrigated	Irrigation depth
Livestock and aquaculture	LA	Ag	Population	Gallons/capita

Table 3. Past and projected withdrawal rates of major water sectors for the eastern and western US, MPI5 future^a.

Year	Domestic and public		Industrial and commercial		Thermoelectric		Agricultural irrigation	
	(g/p/d)		(g/\$1000/d) ^b		(g kWh ⁻¹)		(ft)	
	East	West	East	West	East	West	East	West
1985	102.9	147.7	6.65	3.9	17.2	10.6	1.28	2.95
1990	104.7	156.1	5.42	3.4	17.1	9.7	1.39	2.93
1995	106.0	143.7	4.95	3.7	16.4	9.9	1.37	2.91
2000	103.1	155.1	3.92	2.9	15.8	10.3	1.41	2.80
2005	99.2	153.9	3.35	2.0	15.4	10.2	1.33	2.70
2010	91.9	132.1	2.86	1.8	13.8	8.0	1.34	2.31
2015	90.7	134.7	2.63	1.7	13.4	7.4	1.36	2.34
2020	87.6	130.8	2.33	1.5	13.0	7.2	1.35	2.25
2025	85.1	127.5	2.11	1.4	12.7	7.0	1.35	2.18
2030	83.0	124.7	1.94	1.3	12.6	6.8	1.34	2.12
2035	81.2	122.4	1.80	1.3	12.4	6.6	1.34	2.06
2040	79.7	120.4	1.70	1.2	12.3	6.5	1.33	2.02
2045	78.4	118.8	1.62	1.2	12.1	6.3	1.33	1.98
2050	77.4	117.4	1.56	1.2	12.0	6.2	1.33	1.94
2055	76.5	116.2	1.51	1.1	12.0	6.1	1.33	1.91
2060	75.7	115.1	1.47	1.1	12.0	6.1	1.32	1.88
2065	75.1	114.3	1.43	1.1	11.9	6.0	1.32	1.86
2070	74.5	113.5	1.40	1.1	11.8	6.0	1.32	1.84

^a Years 1985–2010 are based largely on USGS water use reports. Years 2015–2070 are projected using methods from Brown *et al* (2013).

^b Year 2006 dollars.

domestic and public water demands occur through impacts on landscape irrigation, and are based on observed relationships between potential evapotranspiration, temperature, and domestic and public water uses. Climate effects on thermoelectric demand occur through changes in air conditioner use that are dependent on ambient temperature. More details on climate effects on water demand are described in Brown *et al* (2013).

Most important among the water use drivers are population, irrigated area, and electricity use. US population is projected to rise from 308 million people in 2010 to 461 million in 2070, reflecting an annual growth rate that gradually declines from about 0.8% to 0.4% over that 60 year period; 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 12 572 kWh per year in 2010 to 15 525 kWh per year in 2070, following an annual

growth rate that gradually declines from about 0.9% to 0.3% over the 60 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 (e.g. domestic and public withdrawal per capita) in most sectors and regions (table 3), and past trends in irrigated area in the West, have been downward sloping, thus tending to lower withdrawals (Brown *et al* 2013). In the West, for example, from 1985 to 2010, domestic and public withdrawal per capita dropped by 11% and irrigation withdrawal per hectare dropped by 21% (table 3). As a result of those and other sectorial changes, aggregate water withdrawal per capita in the US over the same period declined by 37%, and total withdrawal declined by 8% despite a 46% increase in population. See table 4 for the past annual rates of change in withdrawal rates of key sectors, which were used in projecting future rates.

Table 4. Annual rates of change in water withdrawal rates of M&I sectors.

Year	Domestic and public		Industrial and commercial		Thermoelectric	
	(g/p/d)		(g/\$1000/d) ^a		(g kWh ⁻¹)	
	East	West	East	West	East	West
Recent past ^b	−0.0095	−0.0083	−0.0331	−0.0296	−0.0089	−0.0113
Projected from 2010 to 2060 ^c	−0.0039	−0.0027	−0.0133	−0.0101	−0.0028	−0.0054
Required from 2010 to 2060 ^d	−0.0108	−0.0118	−0.0224	−0.0255	−0.0049	−0.0101

^a Year 2006 dollars.^b Measured rate from beginning year to 2010. The beginning year is the peak year within the range 1985 to 2005 (see table 3).^c Effective annual range of change given the projected withdrawal amounts.^d Effective annual range of change required for total sectoral withdrawal of the respective sector and region to match the 2010 level.

In projecting future water demand, we assumed that the declining trends in water withdrawal rates will continue, although at a gradually attenuating rate. As such, our trends reflect changes in the economy that are underway. When possible, these projections were augmented by industry-specific projections. Projections for the thermoelectric sector, for example, rely heavily on projections released by the Energy Information Administration in their Annual Energy Outlook (US Energy Information Administration 2010), which take into account projected electricity generation at hydroelectric plants, from other renewable sources, and at saltwater thermoelectric plants. The downward sloping trend in withdrawal at freshwater thermoelectric plants reflects, most importantly, the conversion from once-through to recycled water for cooling. Note that in the model here, however, water demand is consumption, not withdrawal. Water consumption per kWh produced at freshwater thermoelectric plants is not projected to decrease.

The WEAP model was run for the period 1950–2070 to calculate past and future water shortages for each basin within each network. Results for early years (1950–1985) serve to initialize reservoir storage levels. Herein we summarize conditions for two 25-year time periods: *past* (1986–2010) and *mid-century* (2046–2070). Within those time periods, shortage frequency is equal to the number of months with shortage divided by the number of months in the period. Throughout the paper, we focus on changes in frequency of shortages greater than 1%, thus ignoring basins that incurred only a very small change in shortage frequency.

Results

Our results show where shortages currently occur and where they are likely to become more common, whether increases in shortage frequency will primarily be caused by changes in demand or by changes in supply, and whether municipal demands are more

Table 5. Number of basins by directional change in drivers, for change from the past to the mid-century period (average over the 14 climate change futures).

Change in drivers	All basins	Basins of shortage increase ^a
D↑,Q↓	132	37
D↓,Q↓	13	11
D↑,Q↑	48	10
D↓,Q↑	11	2
Sum	204	60

Note. D = demand; Q = yield.

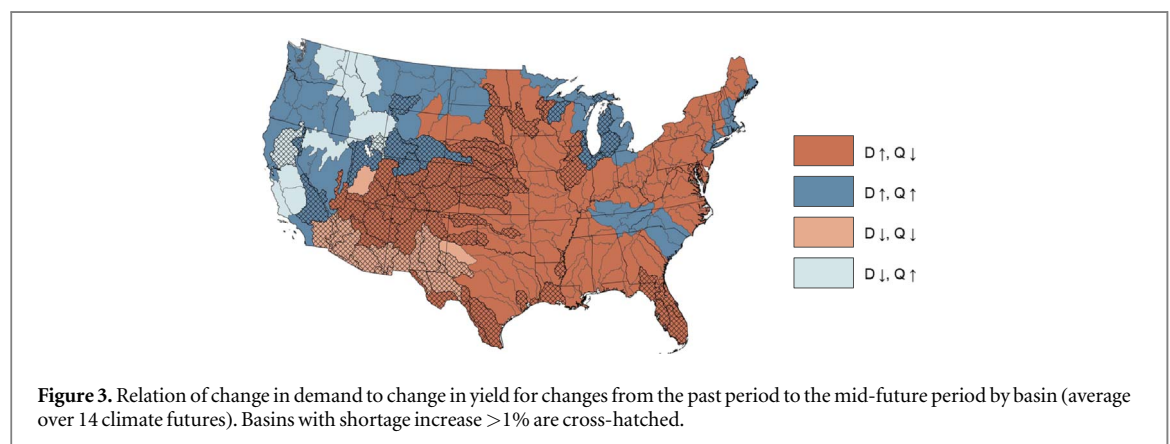
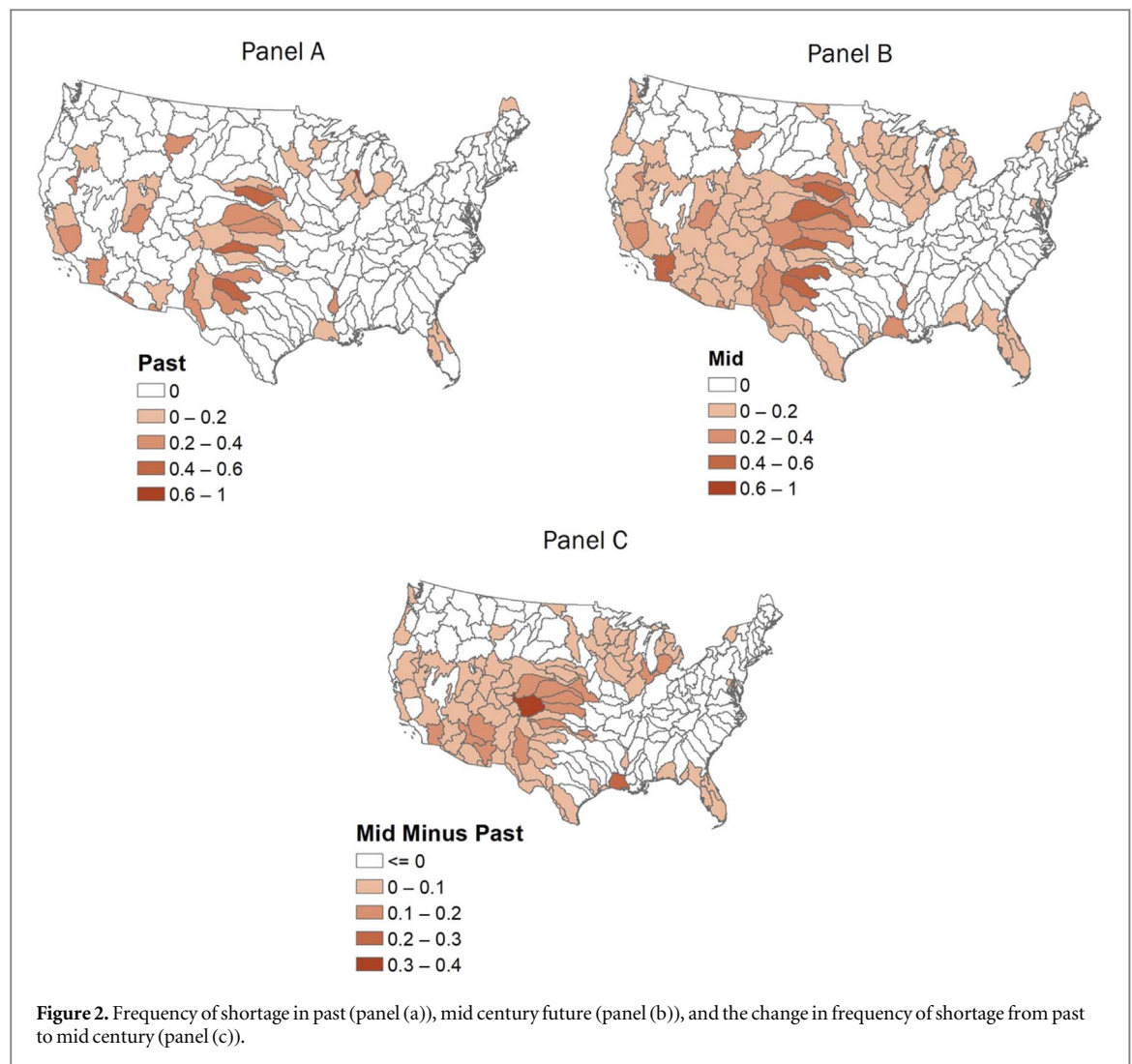
^a Shortage frequency increase >1%.

likely to be covered by long-term conservation measures or transfers from agriculture.

Figure 2 shows shortage frequencies of the past and mid-century periods, and changes in frequency of shortage between the two periods (if relying on only renewable water sources). We find that more than 45.8 million people, primarily in the Southwest, central Great Plains, and southern California, currently live in basins where water demand exceeds renewable water supply. In these basins, shortages are often covered by mining groundwater. By 2060, the number of people living in shortage basins will grow to over 136.2 million people. The increase in exposure to shortage may occur because of decreasing water yield or increasing water demand, and is especially likely where these two forces combine, as in the drier areas of the West.

Supply versus demand forces

To examine the relative importance of supply and demand forces in increasing future shortages, we separate the basins into four groups based on the directions of the average (over the 14 climate change futures) changes in demand and yield (table 5, figure 3). Looking at changes from the past period to the mid-century period, 132 of the 204 basins endure the most challenging change combination—an increase in demand and decrease in yield (table 5, figure 4 upper left quadrant). However, only 37 of those 132 basins



are projected to incur a shortage frequency increase. Although 78 of the 132 basins are in the East, only 10 of the 37 shortage-increase basins are, largely because yields tend to be ample in the East. The remaining 27 shortage-increase basins are in the West, most notably in the Missouri, Arkansas-White-Red, Rio Grande, and Upper Colorado River basins (WRRs 10, 11, 13, and 14, figure 3).

An additional 13 basins are projected to incur decreasing water yield but also a decrease in demand, and 11 of these basins are projected to incur a shortage frequency increase (table 5, figure 4 lower left quadrant). All 11 basins are in the Southwest (in or near the Rio Grande and Lower Colorado River basins, WRRs 13 and 15, figure 2) where yields are already limited relative to demand. Clearly, for these 11 basins the

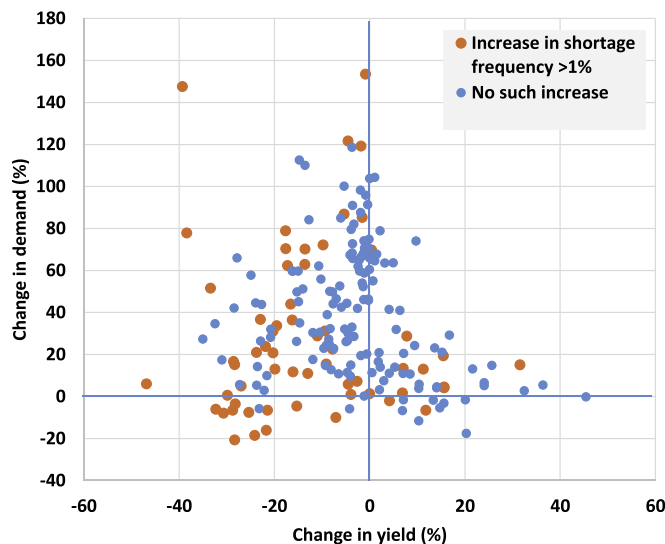


Figure 4. Basin-level percent change in mean annual yield and demand from the past period to the mid-future period (average over the 14 climate futures), distinguishing between basins incurring a >1% shortage increase and those that do not.

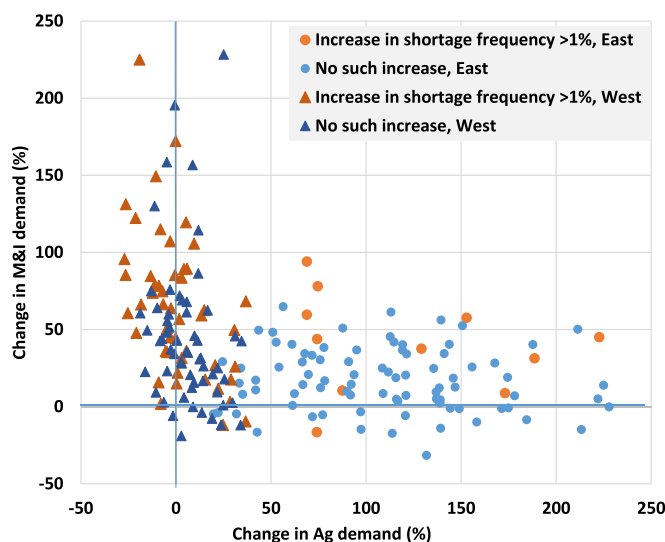


Figure 5. Relation of change in M&I demand to change in agricultural demand for changes from the past period to the mid-future period by basin (average over 14 climate futures).

decrease in yield is of more consequence than the decrease in demand.

The remaining 59 basins (table 5) are projected to receive an increase in mean annual yield, with 12 of those basins projected to incur a shortage frequency increase. In 10 of those 12 basins demand is projected to increase, with that demand increase having greater impact than the yield increase. Nine of these 10 basins are in the West and, in most cases, see M&I demand more than double while agricultural demand decreases or stays about the same. In the remaining 2 basins with a projected increase in shortage, demand is projected to decrease. This counter-intuitive result—an increase in shortage frequency despite favorable changes in demand and yield—occurs in the Great Basin

and in California (WRRs 16 and 18) (figure 4, lower right quadrant). The unexpected result occurs because of the projected increasing variance of monthly yields (Mahat *et al* 2017). When high yields become even higher they have little or no effect on shortages, but when low yields become even lower they can substantially affect shortages.

Relation of changes in M&I and Ag demands to changes in shortage

Figure 5 shows the projected percent changes (from the past to the mid-century period) in M&I and agricultural demands of the 204 basins, and distinguishes between those where increases in shortages are

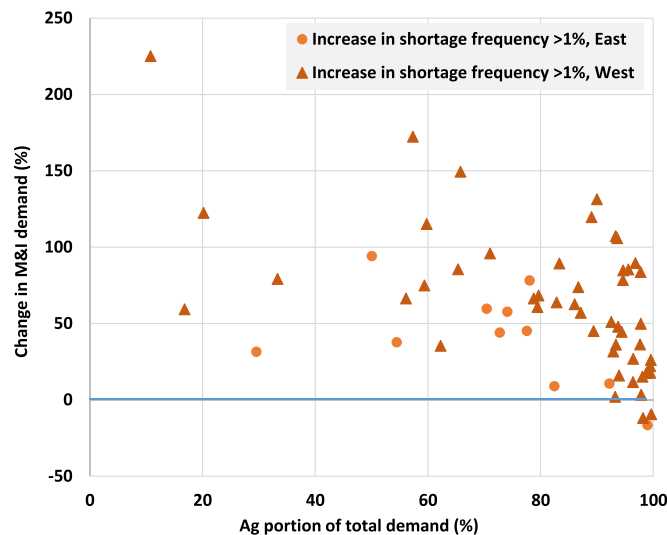


Figure 6. Relation of change in M&I demand from the past period to the mid-future period to the portion of total demand that goes to the agricultural sector in the mid-future period, for basins of projected shortage increase >1% (average over 14 climate futures).

projected to occur and those where they are not, and between eastern and western basins. As seen in figure 5, the eastern basins are expecting a large percentage increase in agricultural demands, but a relatively modest increase in M&I demands. Historically, irrigation was not widely used by eastern farmers, and agricultural demands for water tended to be smaller in both areal extent per basin and use per hectare than those in the West. More recently, eastern farmers are turning to irrigation for larger and more reliable production. Even with the expansions in agricultural water use, however, few eastern basins are expecting an increase in shortages. Noticeable exceptions occur in Florida, where rapid population growth and expansion of irrigated agriculture is already placing strains on water supply (Florida Department of Agriculture and Consumer Services 2016).

In the West, basins are rather evenly divided between those where agricultural demands are expected to increase and those where they are expected to decrease, but most basins are expecting a large percentage increase in M&I demands. Nearly half of the western basins are projected to see an increase in shortages. The western basins that see an increase in shortages span the range in percent change in M&I demand, as do basins where no shortage increase is projected (of the 99 basins with a projected increase in M&I demand, 47 have a projected increase in shortages); thus M&I increases alone are not decisive in leading to shortage increases. Rather, in most cases where shortages are projected to increase in the West, water yield is projected to decrease. For example, of the 47 basins expecting an increase in shortage and M&I demand, 36 also have a projected decrease in yield (of those 36, 16 also have a projected increase in agriculture demand).

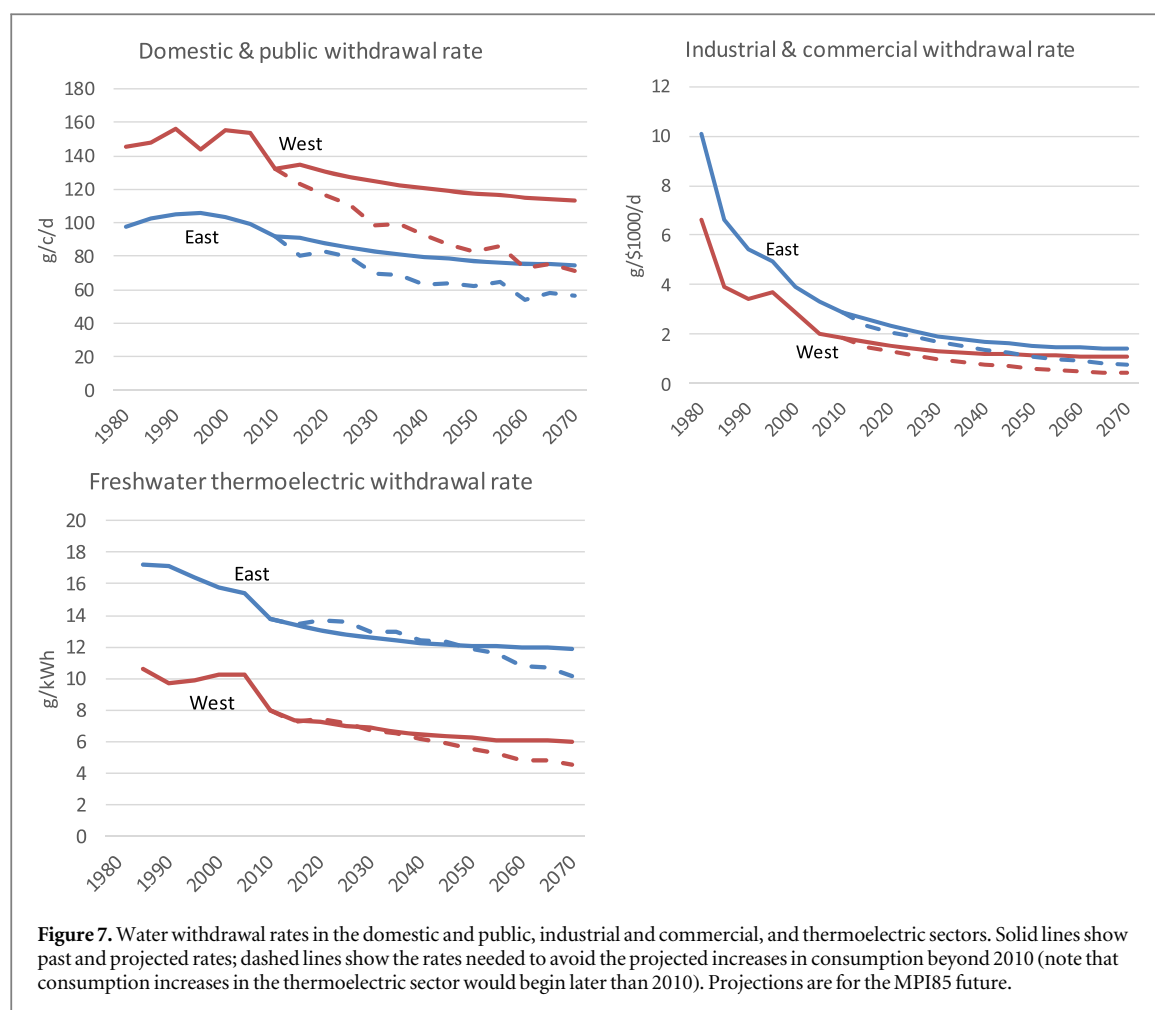
Figure 6 shows the projected percent change in M&I demand on the vertical axis and the percent of

total demand going to agriculture on the horizontal axis, and includes only the 60 basins where shortages are projected to increase from the past to the mid-century period. Here we see that in all but six of those basins most of the water demand is from agriculture, and in 36 of the basins over 80% of the water demand is from agriculture. We may hypothesize that in basins expecting future water shortages, if a large portion of total demand is from the agricultural sector, that sector is likely to bear the brunt of the cutbacks in water use.

Options for meeting future M&I demands: efficiency improvements or transfers?

As explained in the Methods section, projected future levels of water demand reflect ongoing changes in water use drivers (e.g. population, economic growth, climate) and in water withdrawal rates in the various water use sectors (e.g. domestic withdrawal per person, thermoelectric withdrawal per kWh produced). Withdrawals are converted to demands via consumptive use ratios. We now ask, how would projected withdrawal rates in the three M&I sectors need to change in the future to avoid the projected increases in consumption in those sectors?

As seen in figure 7, withdrawal rates in all three sectors would have to fall substantially more than projected. Looking first at the domestic and public sector, western water withdrawals would need to fall to 73 gallons per capita per day (g/c/d) by 2060, which is substantially below the projected 114 g/c/d (and is a 45% decrease from the 2010 level of 132 g/c/d). In terms of annual rate of change, the western domestic and public withdrawal rate would have to fall by 1.2% annually to keep withdrawals at their 2010 level, compared with a 0.83% annual rate of decline in the recent past (table 4). In the East, withdrawals would have to fall to



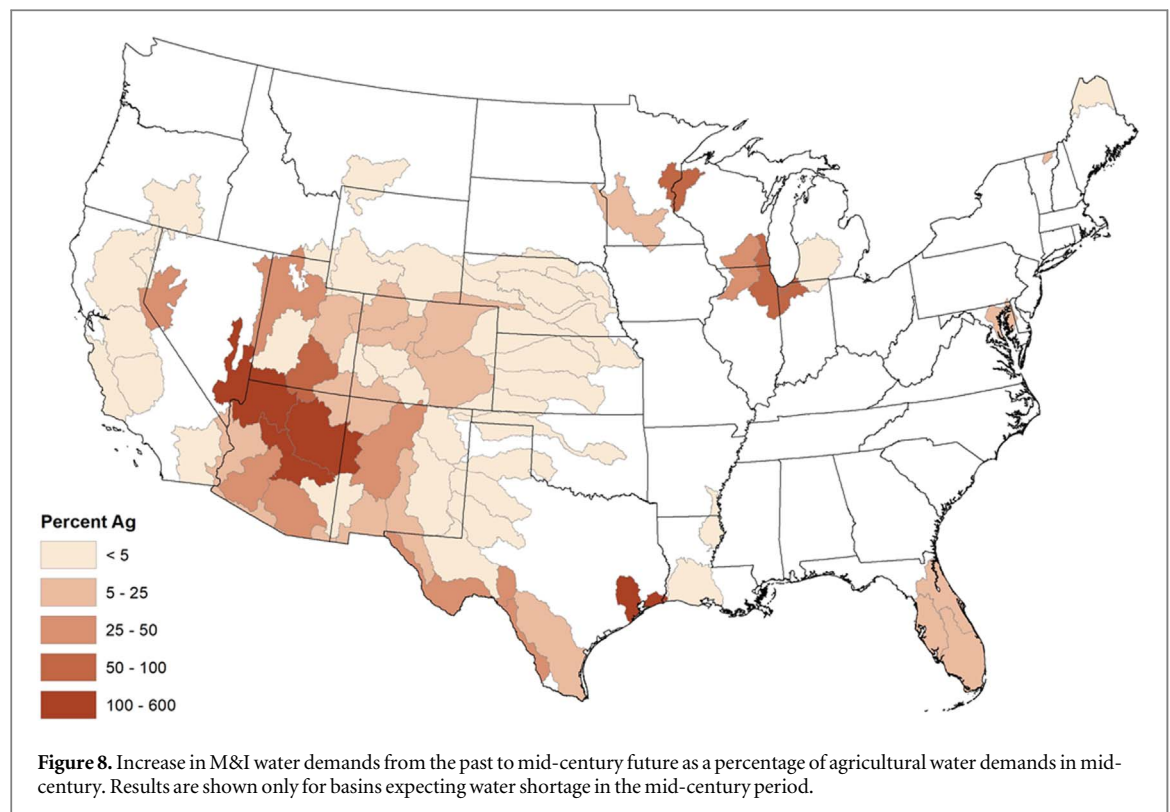
54 g/c/d (71% of the projected amount), and the withdrawal rate would have to fall annually by 1.1%, compared with a 0.95% annual rate of decline in the recent past.

In the industrial and commercial sector, western water withdrawals would need to fall to 0.5 gallons per \$1000 of income per day (g/\$1000/d) by 2060, which is below the projected 1.1 g/\$1000/d (and is a 40% decrease from the 2010 level of 1.8 g/\$1000/d) (figure 7). This amounts to an annual rate of decrease of 2.5%. Eastern water withdrawals in the sector would have to fall to 0.9 g/\$1000/d (61% of the projected amount), with a required annual rate of decrease of 2.2%.

In the freshwater thermoelectric sector, western water withdrawals would need to fall to 4.8 gallons per kWh produced (g kWh^{-1}), which is below the projected 6.1 g kWh^{-1} (and 24% below the 2010 level of 8.0 g kWh^{-1}). This amounts to an annual rate of decrease of 1.02%. Eastern water withdrawals in the sector would have to fall to 10.8 g kWh^{-1} (90% of the projected amount), with an implied annual rate of decrease of 1.0%.

If efficiency gains cannot be realized in the M&I sectors, transfers from agriculture may be an option. Here we look at the percentage of agriculture's water that would be required to meet growing M&I

demands, presumably either by applying less water per hectare or irrigating fewer hectares. Figure 8 shows the percentage of projected levels of basin agricultural water demand by mid-century needed to cover the increase in M&I demands. In the Central Great Plains, M&I demands are small relative to agricultural demands, so the required transfers from agriculture may not cause much disruption to the sector. In central Nebraska the amount needed to cover new municipal water demands is less than 1% of total agricultural withdrawals. The picture changes as one moves west. Agricultural demands in northeastern Colorado are comparable to those in central Nebraska, but northeastern Colorado is expected to see much more population growth, and thus a greater increase in M&I demands. A larger share of agriculture's future water withdrawals, therefore, would be needed to cover the new M&I demands. In northern New Mexico, parts of Utah, Nevada, and Washington, M&I demands are projected to grow to 25%–50% of agricultural water use. Here, the transfers would likely cause significant impacts on the agricultural sector. The situation is more extreme in northern Arizona and eastern Texas, where strong population growth and relatively small agricultural sectors make additional M&I demands six times the amount used by agriculture.



Discussion

Our projections of water demand and supply in the absence of groundwater mining show that 60 of the 204 basins in the conterminous United States will see an increase in frequency of water shortage from the past to the mid-century period. Over four-fifths of those 60 basins are in the West. Among the reasons we find for increased likelihood of water shortages, reduced water yield is the most consistent, affecting 48 of the 60 shortage-increase basins. In the Great Plains and Southwest, yields are already low relative to demand, and unsustainable groundwater mining has been used to overcome would-be shortages. Further declines in yield expected by mid-century spread those shortages more broadly, as seen in figure 2.

Short of avoiding future climate change, there is little that can be done to affect yield. Other options for increasing fresh water supply, such as expanding reservoir storage capacity or increasing drawdown of groundwater aquifers, are limited or unsustainable in many places (Brown *et al* 2019). Solutions like desalination and reuse of municipal wastewater are becoming more common and offer potential to increase the amount of water available (National Research Council 2012). These two options seem most viable in coastal areas. Desalination of seawater clearly adds new fresh water to the system. Water reuse can create new water supply in a water supply system if it does not reduce return flow that downstream users rely on (thus water reuse is most useful in cases where the return flow would not be used, such as in the case of a coastal city). If an upstream basin reuses its effluent, it

reduces withdrawal but also reduces return flow, such that there is little or no net effect on water supply within the system of linked basins. Because we model demand as consumption (essentially equal to withdrawal minus return flow), water reuse in an upstream basin would have no effect on our results, just as it would have no net effect on the aggregate water supply of a system of linked basins. However, water reuse in a coastal basin, or in a basin that is otherwise at the bottom of the water supply system, would increase supply beyond our supply estimates.

As shown in table 4, the annual rates of reduction in water use rates needed to keep sector demand at 2010 levels in the industrial and commercial and thermoelectric sectors are lower than those seen in recent decades, and projected water demand in these sectors is not too far from 2010 levels (table 3). In fact, the projected water use rates of the thermoelectric sector are below those needed to maintain 2010 levels of withdrawal until 2030 in the West and 2050 in the East (figure 7). These trends are attributed to declines in manufacturing, a shift to a more service-oriented economy, plant-level reuse of water and improved energy efficiency within manufacturing plants, increased use of renewable energy, and by switching from once-through cooling systems to recirculating cooling systems in thermoelectric plants (Dieter *et al* 2018). A more detailed look at implications in these trends, particularly with respect to water reuse, is outside the scope of this paper but worth exploring in future work.

Some of the needed efficiency gains in the domestic and public sector are comparable to reductions that

have occurred in recent decades or that may be possible with current technology. The US Environmental Protection Agency estimates that complete adoption of their Watersense high efficiency fixtures and appliances, without leaks, would reduce withdrawals for indoor use in an average US home to 36.7 gallons per capita per day (USEPA 2008), which is less than half of our estimate for 2010 of 88 gallons per capita per day. For the western US in 2060, we estimate that 73 gallons per capita per day would keep total withdrawal for domestic and public water use at its current level (figure 7), implying complete adoption of Watersense practices would leave 36 gallons per capita per day available for outdoor water use (compared to an estimated 45 gallons per capita per day withdrawn for use outdoors in 2010). According to DeOreo *et al* (2016), half of US homes already have high efficiency clothes washers, and over a third have high efficiency toilets (DeOreo *et al* 2016). The key to achieving these rates of withdrawal will be wider adoption of high efficiency technologies (Millock and Nauges 2010), especially in the Colorado River and Rio Grande regions that contain many of the basins with the largest percentage increases in projected domestic and public water use as well as the greatest percentage decreases in projected water yield.

In light of these challenges, water transfers and water markets will play an important role in adaptation efforts. We are already seeing increasing numbers of water transfers in the West where the prior appropriation doctrine facilitates movement of water between sectors (Brewer *et al* 2006, Ghosh 2018). Water markets work by changing water from a sector-specific input to a tradeable commodity between sectors. In times of water shortage, water markets not only reallocate water to higher value uses (Hewitt and Hanemann 1995, Espey *et al* 1997, Freeman 2003, Griffin 2006, Young and Loomis 2014), they also encourage conservation (Goodman 2000, Gleick 2003, Gomez *et al* 2004, Pulido-Velazquez *et al* 2004, Brown 2006)⁵. The economics literature largely finds water markets are welfare improving, or at least that allocating water through markets during times of shortage leads to smaller welfare losses than mandatory use restrictions and technology requirements (Grafton and Ward 2008, Olmstead and Stavins 2009). In some cases, transferring water out of agriculture also accelerates the removal of irrigated land from production. Such 'buy and dry' practices may have adverse effects on rural communities (Pritchett *et al* 2008). More work is needed to investigate the feasibility and economic impacts of these markets in a future with climate change, especially in regions that

are not only likely to be drier, but where weather is likely to be more variable.

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⁵ Conversely, beneficial use doctrines can discourage conservation, as any water not put to use potentially represents a lost water right. The Colorado Supreme Court ruled that any water conserved goes back into the appropriation system, rather than being able to be sold. California, on the other hand, has ruled that water conserved may be sold or leased.

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