The adaptive benefits of agricultural water markets in California

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Abstract

Climate change is expected to increase the scarcity and variability of fresh water supplies in some regions with important implications for irrigated agriculture. By allowing for increased flexibility in response to scarcity and by incentivizing the allocation of water to higher value use, markets can play an important role in limiting the economic losses associated with droughts. Using data on water demand, the seniority of water rights, county agricultural reports, high-resolution data on cropping patterns, and agronomic estimates of crop water requirements, we estimate the value of irrigation water and compare the agricultural costs of water shortages under the existing legal framework and under an alternate system that allows for trading of water. We find that a more efficient allocation of curtailments could reduce the costs of water shortages by as much as $362 million dollars per year or 4.4% of the net agricultural revenue in California in expectation, implying that institutional and market reform may offer important opportunities for adaptation.

1. Introduction

Rising temperatures and associated changes to the hydrologic cycle are expected to increase the frequency and intensity of droughts over many areas in the 21st century (Sheffield and Wood 2008, IPCC 2014). In turn, the economic and social consequences of water shortages during droughts will depend on how water supplies are curtailed and the flexibility with which those affected can adjust to water scarcity (Qin et al 2019). By allowing individuals to coordinate and allocate scarce resources to highest-value uses, well-functioning water markets can play an important adaptive role in limiting the damages of droughts, particularly for water-intensive activities like irrigated agriculture. The theoretical role of water markets has been widely discussed (Haddad 2000, Hanak and Lund 2012, Loch et al 2013, Libecap 2018) and efforts have been made to estimate the potential gains from water trading (Hearne and Easter 1997, Pujol et al 2006, Hagerty 2019) and to incorporate the nature of an uncertain water supply (Calatrava and Garrido 2005, Bruno and Jessoe 2019). Although it has been suggested that the benefits of agricultural water markets should increase with climate change, little work has been done to quantify these adaptive benefits or to estimate how these gains evolve over the 21st century.

Here we quantify the potential adaptive benefits of markets for surface irrigation water in the Central Valley of California. The valley is one of the highest-value irrigated agricultural systems in the world, producing roughly two-thirds of US fruit and nuts, including essentially all the country’s peaches, plums, figs, raisins, olives, almonds, walnuts, and dates (CDFA 2018). Agriculture in the region (herein defined as crop but not livestock production) is reliant on snowmelt from the Sierra Nevada mountains during the summer (Schlenker et al 2007), which provides 61% of irrigation water, with the remainder supplied by groundwater pumping (CDWR 2015a).
Summer surface water availability is likely to diminish as climate change decreases the fraction of precipitation falling as snow and melts the snowpack earlier in spring (Huning and Aghakouchak 2018, Mallakpour et al 2018).

As with other western US states, California law allocates water primarily on the basis of seniority so that water rights that were established most recently (junior rights) are curtailed first when water is scarce. California recognizes two types of water rights: riparian rights which are considered the most senior, and appropriative rights, for which seniority is on a “first in time, first in right” basis. Rights holders with the oldest claim have higher priority to water allocation during droughts (Tweet 2016, Nelson and Burchfield 2017, Sugg 2018). If senior rights holders do not have the highest value uses of water and are unable to trade, this allocation results in unnecessary (i.e. deadweight) economic losses. Some water trading occurs in California, but complex regulations and a lack of easily accessible information on the quantity and price of water available (Escriva-Bou et al 2016, Hagerty 2019) mean that the volume of traded water amounts to 4% of all water used annually in California. This has increased little since the early 2000s, even during the severe 2011–2015 drought (Hanak et al 2019a, 2019b). The deadweight losses associated with the seniority system are likely to increase with climate change as summer irrigation water becomes scarcer and curtailments more frequent (Cayan et al 2008, Macdonald 2010, Diffenbaugh et al 2015).

In years when surface water availability is less than total water withdrawals, water to some rights holders is curtailed. If no other source of water is available, agricultural production from those farms is lost. We calculate the costs of these curtailments, distributing available water either based on seniority (simulating the current system), or on the value of irrigation water (simulating the equilibrium outcome of a market for surface irrigation water). The difference in the cost of curtailment under these two allocation mechanisms is equivalent to the deadweight loss associated with the inability to trade or to the benefits of a more liberalized water market. In turn, the evolution of this deadweight loss with climate change reflects the adaptive benefits of an agricultural water market. This analysis should therefore be understood as a comparison between a strict application of California’s seniority rights system (within the agricultural sector) and a more liberalized water market. While there are legal, economic, and hydrologic reasons why the reality of drought curtailments may be more complicated than a simple seniority system, a statistical analysis of reductions in water use over the severe 2011–2015 drought shows evidence that, at the watershed scale, seniority but not water value was predictive of smaller cuts in water use (table S1). Therefore, evidence from recent history suggests that seniority still plays an important role in the allocation of scarce water supplies during droughts.

The Central Valley is composed of two main river basins, the water-rich Sacramento basin in the north and the drier San Joaquin basin in central California. The Sacramento and San Joaquin rivers meet at the Sacramento-San Joaquin Delta after flowing for more than 350 miles and collecting water from upstream tributary rivers. We analyze the two main river basins separately because of the legal, environmental, and economic barriers to transferring water across the Sacramento-San Joaquin Delta, with the (relatively small) withdrawals within the Delta assigned to the Sacramento basin. This effectively assumes that water trades occur only between irrigators within each river basin, a constraint that limits transport and transaction costs. To the extent water markets would allow trades over longer geographic distances or between agriculture and other sectors, our estimates will thus understate the value of this more expansive water market.

2. Methods

2.1. Data sources

We estimate the value of a market for surface irrigation water by combining data on surface water use and availability, the seniority of water rights, spatially-explicit cropping patterns, county agricultural reports, and agronomic estimates of crop water requirements obtained from the following sources:

2.1.1. Water demand and seniority data

Data on the monthly surface water withdrawals and seniority of all 9951 water rights holders in the Central Valley and its upstream tributaries (figures S1–S3 available online at stacks.iop.org/ERL/16/044036/mmedia) in 2010 was obtained from the Electronic Water Rights Information Management System (eWRIMS, www.waterboards.ca.gov/waterrights/water_issues/programs/ewrims/). Rights to withdraw water are held both by individual farms and by larger irrigation districts that distribute water to their members.

This analysis uses data for 2010 because it is the first year for which this data is available and it is the only normal water year (CDWR 2019) prior to the 2011–2015 drought. We take these water withdrawals in a relatively normal water year to be each right holder’s effective water endowment (i.e. the amount they would be able to trade in a theoretical water market, figures S2–S3). The face-value of water rights in California greatly exceeds available water. For example, Grantham and Viers (2014) find that water right allocations are approximately five times...

8 Between 2010 and 2015, the number of water rights holders reporting withdrawals in eWRIMS does not change systematically, implying 2010 gives a good approximation of the overall universe of water rights holders in the Central Valley of California.
the state’s annual mean runoff and that in the Sacramento and San Joaquin river basins, water rights account for up to 1000% of natural surface water supplies. Thus, equating observed water withdrawals to each right holder’s de-facto, rather than de-jure, water endowment is required for a meaningful analysis and is common practice in modeling water rights in California (Tweet et al, Hagerty 2019). Therefore we use the reported 2010 withdrawals as the closest available representation of the true, de-facto endowment of each rights holder.

We use data from the severe drought of 2011–2015 to examine factors determining the distribution of water use reductions of this period. Table S1 shows the results of a regression of the % reduction in water use from the 2010–2011 period to the 2014–2015 period on two explanatory variables: seniority and water value. Dummy variables by watershed control for the average effect for users within the same watershed, meaning coefficients are estimated only using variation between water users in the same water shed. Results show an association with seniority (i.e. junior water users reduced water use more) but not with water value, providing evidence that seniority is an important factor currently determining water allocation during droughts.

2.1.2. Current and projected surface water availability
The baseline availability of surface water during the irrigation season is based on 1980–2009 streamflow data of the Central Valley tributary system (CDWR 2016). Projected surface water availability is derived from ten downscaled and bias-corrected general circulation models (GCMs) under RCP 4.5 and RCP8.5 (figures S1 and S4) (Liang et al 1994, Pierce et al 2014, 2015, 2016, CDWR 2015b, Bedworth et al 2018, CCTAG 2018, Mallakpour et al 2018, 2019). The ten GCMs used in this study were selected from a set of 32 models as part of California’s Fourth Climate Change Assessment by the California Department of Water Resources based on their performance against historical observations and their ability to simulate drivers of water availability in the central valley (Pierce et al 2016, Bedworth et al 2018). The variable infiltration capacity (VIC) model, a process-based hydrologic model is forced with high-resolution Localized Constructed Analogs based on GCM output (Pierce et al 2014, 2015). Both VIC and the climate model simulations account for snow variability and change, which is critical to understanding changing water supplies in California. In particular, VIC models ground snow pack, snow on lake ice, and snow on the vegetation canopy (Andreadis et al 2009). The upper portion of the snowpack is used for solving energy balance which is important for snowmelt and runoff estimation. The model also includes a module for partial snow coverage and sublimation (Bowling et al 2004).

Projected surface water availability is constructed by adding the projected change given by the climate models to the baseline availability of surface water. These calculations are made at the sub-basin level first and then aggregated at the river basin level weighting each sub-basin by its contributions to the total surface water available in the river basin. Water available for agriculture during the March–October irrigation season (figure S5) is computed as the residual water available after subtracting water demand from other sectors, including urban water use, consumptive use by the energy sector, and environmental flow requirements9 (figures S6 and S7, tables S2 and S3) (Gartrell et al 2017, Hanak et al 2017, Qin et al 2019).

2.1.3. Agricultural output value
Average output value per acre $y$ in watershed $w$ is calculated as:

$$
y_w = \sum_{i=1}^{N} s_{iw} Y_i c
$$

with $s_{iw} = \frac{s_i}{s_{iw}}$. Here, average output value per acre $Y$ of crop $i$ in county $c$ is weighted by the share $s$ that farmland $a$ of crop $i$ in watershed $w$ represents in the total farmland $A$ of watershed $w$. $s_{iw}$ is obtained by intersecting the high resolution ($30 \times 30 m$) land cover from the 2010 USDA’s Crop Data Layer (Hang et al 2012) with the geographic boundaries of watersheds defined at 12 digits (see figures S1 and S8). A county is assigned to a watershed whenever the centroid of the watershed falls within the boundaries of the county. $Y_i c$ is obtained from county agricultural reports (USDA, 2011).

2.1.4. Potential evapotranspiration (PET) or crop water demand
Our location-specific estimates of PET (an upper bound on crop water demand) were obtained using a daily 2 km resolution reference ET dataset (Hart et al 2009), which provides a measure of PET over a reference land cover (i.e. well-watered grass), multiplied by standard land cover-specific crop coefficients (Allen et al 1998), a spatial representation of which we derived using annual 30 m resolution land cover classifications from the USDA’s Cropland Data Layer (Boryan et al 2011). Specifically, reference

9 Water use was classified as Irrigation, Domestic, Power Generation and Other (Mining, Stockwatering, Fire Suppression etc) using the description of the beneficial uses of the right. Estimates of the volumes required to meet minimum flow requirements to support fish and wildlife (environmental or ecosystem water) are based on Gartrell et al (2017) (table S3). These volumes are primarily determined under the federal Clean Water Act, the Endangered Species Act (ESA) and their state law counterparts. In our analysis, environmental water is re-allocated between the two river basins by first accounting for the water required to meet newly-adopted February–June minimum flow requirement for the San Joaquin basin of 1000 cubic feet/s⁻¹ (State Water Resources Control Board, Resolution No 2018-0059), with the remainder of Delta flow requirements subtracted from the supply in the Sacramento basin (figure S6).
PET (Hart et al 2009) at a given grid cell was multiplied by tabulated crop coefficient values (Allen et al 1998; see ‘Kc-mid’ values provided in table 12 at: www.fao.org/3/x0490e/x0490e0b.htm#tabulated%20kc%20values) according to the land cover classification (Boryan et al 2011) of that grid cell. We also subtracted daily 4 km resolution precipitation (PRISM 2018) from the PET estimates to generate daily potential vegetation water demand (PET-P) at the 30 m resolution of the land cover data. We calculated PET and PET-P at the watershed level and over the irrigation season (March–October) by taking the spatial mean of daily 30 m PET over agricultural land only. PET and PET-P volumes were calculated by multiplying PET depths (total mm) by the area of agricultural land in each watershed and converting those volumes to units of gallons.

2.1.5. Irrigation water values

To calculate irrigation water values, we scaled agricultural output value per acre ($/A) in a watershed by the relative importance of the irrigation required in that watershed using the following formula:

\[ \text{Irrigation Water Value}_{w} = \begin{cases} \frac{P_{w}}{\text{PET}_{w} - P_{w}} \cdot [1 - f(P_{w}/\text{PET}_{w})], & \text{PET}_{w} - P_{w} \geq 0 \\ 0, & \text{PET}_{w} - P_{w} < 0 \end{cases} \]

With \( f(P_{w}/\text{PET}_{w}) = 2 \cdot (\frac{P_{w}}{\text{PET}_{w}})^2 - \frac{P_{w}}{\text{PET}_{w}} \) is a concave non-linear function bounded between 0 (when \( P = 0 \)) and 1 (when \( P = \text{PET} \)). The concave shape of the function allows for larger benefits of additional irrigation water for crop growth at low levels of rainfall, with diminishing marginal benefits as available rainfall approaches crop water requirements (i.e. as \( P \sim \text{PET} \)). The relative importance of irrigation (given by \( 1 - f(P_{w}/\text{PET}_{w}) \)) is high when \( f() \) is low, i.e. when precipitation represents a small fraction of crop water demand. Locations where local rainfall exceeds crop water requirements (PET-P < 0) were assigned an irrigation water value of zero.

2.1.6. Simulating droughts and curtailment

Data on water withdrawals and crop water value is used to create two alternate cumulative demand curves, one ordered by water right seniority and one by crop water value. Droughts occur when the surface water available to the agricultural sector is insufficient to meet the full cumulative demand and water supply to agriculture is curtailed. Curtailments are based either on seniority (most junior rights holders curtailed first) or on crop water value (lowest-value users curtailed first). The latter simulates the equilibrium outcome of an agricultural water market where lower value users sell their allocation to higher value users during periods of scarcity. The potential benefit of agricultural water markets is estimated by comparing crop production lost under seniority-based curtailments to that from value-based curtailments. This estimate therefore implicitly keeps the crop mix, spatial distribution, water requirements, and water endowments of California fixed at 2010 levels, varying only timing and amount of surface water supply and the method of curtailment allocations and results should be understood in this ‘ceteris paribus’ context. Simulations were done separately for the Sacramento and San Joaquin basins, reflecting the difficulty of transporting water between these two basins through the Delta (Hanak et al 2019b).

An implicit assumption of this simulation method is that the availability of groundwater does not affect the adaptive benefits of surface water markets (discussed further in the section 4). In order to test the sensitivity of our findings to uncertainty about future groundwater availability and regulation in California, we also perform a set of simulations that re-estimate the benefits of water markets under RCP 8.5 and alternate assumptions regarding the availability (quantity) and extraction cost (price) of groundwater in the two Central Valley basins. These simulations are performed by changing the curtailment algorithm described in the previous paragraph: if farmers are unable to obtain surface water during droughts, groundwater acts as a ‘backstop’, available at a price \( p \), up to a total quantity \( q \). Producers with water value above the backstop price \( p \) are able to use groundwater rather than foregoing production altogether, up to the total quantity \( q \), reducing the total costs of surface water curtailments. Because both the quantity and extraction cost of future groundwater in these basins are uncertain, we obtain ranges for both \( p \) and \( q \) from Escriva-Bou (2019) allowing \( p \) to vary between 0–400 $/AF and \( q \) between 0–400 TAF.

3. Results

Figure 1 shows the heterogeneity across the Central Valley in the value of agricultural production (figure 1(A)), PET or crop water demand (figure 1(B)), irrigation water value (figure 1(C)), and the seniority of water rights (figure 1(D)). In figure 1(A), we observe watersheds with high estimates of agricultural value falling along the Central Valley floor. The highest values tend to concentrate in the southern part of the region made up of Madera, Fresno, Kings, Tulare and Kern
Figure 1. Estimates of agricultural value per acre (A), PET per acre (B), irrigation water value per acre (C) and average year of seniority (D) at the watershed level. The current system of water allocation is based on seniority (D) while an efficient allocation would be based on irrigation water values (C). Grey colors in panel D identify watersheds in which we do not observe individual water rights. Farmers in these locations receive water through the State Water Project (SWP) and the Central Valley Project (CVP). County boundaries are shown in black with boundaries of sub-basins in the study region shown in red.

counties, associated with intensive production of high-value specialty crops such as tree nuts, citrus, and grapes.

Figure 1(B) displays our estimates of PET for the Central Valley throughout the irrigation season. Dark blues indicate places where crop water demand is high, mostly the hottest inland areas along the floor of the valley. Figure 1(C) maps the value of irrigation water obtained by dividing production value per acre (figure 1(A)) by the crop water demand (figure 1(B)). High-value uses are seen both in areas of high-value production (figure 1(A)) such as the
southern part of the San Joaquin basin, and in areas with moderately-high production value and relatively low water demand (figure 1(B)) such as the northernmost part of the Sacramento basin. This is an upper bound on the average agricultural value of water; to the extent the yield response to irrigation is non-linear, the marginal value of water may be either smaller or larger than this average value. Similarly, to the extent farmers are irrigating at levels in excess of crop PET requirements, something we are not able to rule out given the available data, actual average water values may be lower than shown here. However, we note that the magnitudes in figure 1(C) match closely other estimates of farmer willingness to pay for irrigation water in the San Joaquin valley derived from agricultural production models (Hanak et al 2019b), as well as water prices observed at auction during the recent drought (Henry 2014).

Finally, figure 1(D) plots the average starting date of the water rights held by users within each watershed and shows a notable concentration of senior rights holders in and around the Sacramento-San Joaquin delta and junior rights holders in the inland Central Valley. A comparison between figures 1(C) and (D) shows the potential inefficiencies in water allocation based only on seniority. Efficient allocation would prioritize areas with the highest irrigation water values (figure 1(C)) rather than most seniority (figure 1(D)). Since there is not a strong correlation between seniority and the value of water use (figure S9), a market should provide gains over a system that allocates curtailment strictly on the basis of seniority.

Figures 2(A) and (B) show cumulative water withdrawals in the Sacramento and San Joaquin River basins respectively, ordered by seniority. Cumulative water withdrawals are constructed by aggregating reported surface water withdrawals during the 2010 irrigation season (March to October) for 4769 rights holders reporting irrigation as a principal water use in the study area (figures S2 and S3). Also shown in figures 2(A) and (B) are estimates of the availability of surface water after netting out non-agricultural uses and environmental flows (figure S6). These estimates are based on the average of the total streamflow during the irrigation season for the baseline period (1980–2009; blue horizontal lines) and the ensemble mean of streamflow projections for the end of the century (2070–2099; dashed orange horizontal lines for RCP 4.5 and dashed red horizontal lines for RCP 8.5). Since the inter-annual variability of water supply is very high (figure S4), we also plot the lower tail of the water supply distribution for the baseline (blue box-and-whisker plot) and the end of the century (orange and red box-and-whisker plots for RCP 4.5 and RCP 8.5, respectively) (see projected water supply distributions in figure S10).

Years of water scarcity occur when the available surface water intersects cumulative water withdrawals. These years occur more frequently in the San Joaquin basin, which is known to be a highly water stressed basin in that almost all available supply is fully allocated among users (Grantham and Viers 2014, Mekonnen and Hoekstra 2016, Mankin et al 2017, Qin et al 2019). In both basins, curtailments occur more frequently in the future as climate change reduces water available during the March–October irrigation season, with the anthropogenic signal most pronounced in the Sacramento basin (as seen in figure S4).

During years of water scarcity, some irrigators will lose access to water. Under a strict seniority system without transactions, curtailments will fall on the most junior rights holders (those to the right of the intersection between water availability and water withdrawals). With the same allocation of property rights but a more flexible water market, curtailments will still accrue to junior rights holders, but those with high value of water use will be able to purchase water from senior rights holders with lower value uses. The actual cuts in water use under such a market will thus come from lower-value producers who forgo production in favor of selling their water endowment. The difference in lost agricultural value under the two curtailment allocations gives the deadweight loss from a strict seniority system and, correspondingly, the benefits of a more flexible allocation of curtailments.

The Lorenz curves in figure 3 show the agricultural value lost by water curtailments of varying severity in each basin under two alternative allocation mechanisms: seniority-based (purple and green lines) and market-based (blue lines), created by matching our individual observations of water withdrawals and seniority data with our estimates of the irrigation water value (figure 1(C)) adjusting observations associated with the SWP and the CVP, two major aqueduct projects that transfer water from the Sacramento to the San Joaquin basin. Since seniority of rights

The valuation of the water diverted by these projects must correspond with the water value at the locations where it is delivered. We adjusted the water value of the eWRISM observations associated to the SWP and CVP with the following procedure. First, we calculate an average water value at the county level using our estimated water values from figure 1(C). Then, we associated these average water values to each project’s water contractor based on the contractor’s location. Each water contractor is in a specific area for which monthly information of water delivery exists. The SWP defines six areas of delivery, while the CVP defines eleven. We use the share that each water contractor represents in the total water withdrawn (figure S1) to weight the average water value of water delivered to the area during the irrigation season to calculate a weighted average of the value of water in every area. In turn, this weighted average is associated to the SWP and CVP observations in eWRIMS based on the point of diversion of each observation. We designated the area of delivery for each point of diversion as the end point of the stream weirs that were water diverted from. For all other observations, we assume that water is used in the watershed in which it is diverted. This procedure aggregates across some large delivery areas encompassing several irrigation districts associated with deliveries from the same diversion points for the SWP and CVP. This may mask significant heterogeneity in the value of irrigation water used by recipient
Figure 2. Irrigation surface water withdrawals and availability in 2010 (millions of acre-feet). The figure shows cumulative water withdrawals for irrigation (vertical axis) ordered by water right seniority (horizontal axis) according to California’s current allocation mechanism. Riparian rights (single purple bar) have the highest priority and thus are plotted before appropriative rights (turquoise bars). Water availability in the baseline period (1980–2009, blue line) is represented by the mean total streamflow during the irrigation season. Water availability for the projected period (2070–2099; dashed red line) is on the ensemble mean of the ten coupled climate-hydrological model projected flows shown in figure S4. Box-and-whisker plots show the lower end of the distribution of water availability within each period (see figure S10). Dots indicate the mean, black lines the median, bars the 25th–75th percentile range, and whiskers extend to the 1st and 99th percentiles. Note that the long upper tail of water availability in the Sacramento basin is cropped in order to provide sufficient resolution in the lower part of the distribution, which is most important for understanding the changing frequency of irrigation water curtailment.

Figure B. Irrigation surface water withdrawals and availability in 2010 (millions of acre-feet). The figure shows cumulative water withdrawals for irrigation (vertical axis) ordered by water right seniority (horizontal axis) according to California’s current allocation mechanism. Riparian rights (single purple bar) have the highest priority and thus are plotted before appropriative rights (turquoise bars). Water availability in the baseline period (1980–2009, blue line) is represented by the mean total streamflow during the irrigation season. Water availability for the projected period (2070–2099; dashed red line) is on the ensemble mean of the ten coupled climate-hydrological model projected flows shown in figure S4. Box-and-whisker plots show the lower end of the distribution of water availability within each period (see figure S10). Dots indicate the mean, black lines the median, bars the 25th–75th percentile range, and whiskers extend to the 1st and 99th percentiles. Note that the long upper tail of water availability in the Sacramento basin is cropped in order to provide sufficient resolution in the lower part of the distribution, which is most important for understanding the changing frequency of irrigation water curtailment.

does not correlate strongly with the value of water use (figure S9), curtailments under the green line lie close to the 1:1 line—in other words, each additional reduction in water availability results in similar economic losses from curtailment. In contrast, under a market allocation, low water value users cut production first, resulting in lower economic costs (i.e. the blue curve lies above the 1:1 line). The consequences of a hypothetical 25% reduction in water availability under both mechanisms is illustrated with the dashed red lines. In the Sacramento basin, a
Figure 3. The economic benefits of market-based water allocations. Lorenz curves showing cumulative agricultural water value (y axis) under two different systems of water assignment: (a) the existing system that assigns priority to the most senior rights holders (purple and green lines for riparian and appropriative rights, respectively) and, (b) a system in which priority is given to higher values uses of water (blue lines), for the Sacramento (A) and San Joaquin (B) basins. Water withdrawals (x axis) are reported by individual water rights holders in the Central Valley. During curtailment, the water value losses associated with the current seniority-based system are larger than in a market-based system (illustrated with a hypothetical 25% curtailment). The separation between the curves gives the deadweight losses associated with a strict appropriative scheme for any given level of water curtailment. Note that the 25% curtailment shown here is for illustrative purposes only—the adaptive benefits of water markets under climate change are calculated using projected surface water availability from the ensemble of GCM and hydrologic models (methods, figures S4 and S10).

25% curtailment would result in a loss of agricultural production equivalent to 29% of the 2010 total under the current seniority system, but only 8% if curtailments are allocated by water value, as would occur within a water market system (figure 3(A)). Therefore, the deadweight loss (the additional costs associated with inefficient allocations of curtailment under the seniority-based system), is approximately
Figure 4. Expected gains of a water market for surface irrigation water under climate change. Panel A graphs the expected gains from a market allocation of irrigation water, compared to the existing allocation mechanism based on seniority. Bars represent the expected percentage gain in years with curtailment obtained by intersecting annual projections from each climate-hydrologic model within each period with the Lorenz curves in figure 3. Panel B shows the expected years of water curtailments which occur whenever the availability of surface water for irrigation does not meet 100% of water withdrawals. Standard errors bars (in red) are derived from model uncertainty. Panel C graphs the expected gain per year within each 30-year period obtained from multiplying the average gain for each period, including years with and without curtailment, by the 2010 net farm revenue in the Central Valley.

21% (29% minus 8%) of the value of net agricultural revenue in the basin. The corresponding percentage for the San Joaquin River is 11% (figure 3(B)). In general, the benefits of surface water markets depend on the magnitude of the deadweight loss (i.e. the separation between the two Lorenz curves in figure 3) and how much water is available (i.e. the point at which surface water availability intersects cumulative withdrawals in figure 2).

The bars in figure 4 show the potential gains from trade in surface irrigation water, combining supply projections for three 30 year periods spanning the 21st century from the GCM ensemble, with the Lorenz curves in figure 3. The figure displays results
for both RCP 4.5 and RCP 8.5. In the Sacramento basin, the adaptive benefits of a more flexible water market during periods of scarcity range between 18% and 19% (figures 4(A) and (B)). In this basin, the percentage of year with shortages per 30 year period increases from about 25% to 33% by the end of the century (figures 4(C) and (D)). In the San Joaquin basin, surface water available is already very close to total withdrawals (see figure 2(B)). As a result, shortages occur in over 60% of years and this conditions persists over the XXI century (figures 4(C) and (D)). In this basin however, the climate change signal on water supply is less pronounced than in the Sacramento, and therefore the number of years of curtailment and the benefits of water markets do not change significantly over the century. Given these findings and the 2010 net farm revenue within counties in the study area of $5.6 billion (USDA 2014), we estimate that the expected value of allowing a more flexible water market ranges between $348 (RCP 8.5) and $362 (RCP 4.5) million per year (at 2010 prices) during the 2070–2099 period (figures 4(E) and (F)) with the water stressed San Joaquin basin accounting for the large majority of these gains. However, we note that in this specific California case, while the benefits of agricultural water markets are large, the adaptive benefits (i.e. the change in the benefits with climate change) are more limited, primarily due to the limited climate signal, relative to natural interannual variability, in the San Joaquin basin (figure S4). In addition, because limited surface water trades occur today, the gains from the current system to a more liberalized water market will be somewhat smaller than estimated here, which compare to a strict application of the seniority systems, without any additional trading. Increased groundwater extraction was an important margin of adjustment during California’s recent drought. But aquifers in the Central Valley are critically overdrawn (Famiglietti 2011) and new legislation stands to limit groundwater pumping, meaning it is unlikely to play the same role in future droughts (Murray and Lohman 2017, SGMA 2019). We therefore show the sensitivity of our estimates to various groundwater scenarios in figure S11 (see section 2). As expected, water availability increased by groundwater access lowers the benefits of agricultural water markets because farmers with a willingness to pay that exceeds the extraction cost are able to access groundwater rather than falling. This effect is particularly pronounced in the San Joaquin basin where, under scenarios of high groundwater availability, the benefits of surface water markets drop almost to zero. Such scenario is unlike given the critically overdraft of groundwater in this basin (Hanak et al 2019b). Estimated benefits in the Sacramento basin are more robust to groundwater availability. Regardless, improving farmers’ ability to access alternative supplies of surface water through a more flexible market structure would reduce pressure on groundwater resources during periods of scarcity, thereby reducing the costs of the constraints implied by new requirements for sustainable groundwater pumping.

4. Discussion and conclusion

Access to water in California is surrounded by complex legal, political, ethical, economic, and environmental issues, and there are a number of simplifications in this calculation that should be noted. Firstly, limiting the analysis to only the agricultural sector almost certainly underestimates the full benefits of a more liberalized water market. There is substantial evidence that potential gains from trade in water exist across sectors in California, particularly from agricultural to urban uses, which are not captured in our analysis (Medellin-Azuara et al 2008, Bruno and Jessoe 2019, Hagerty 2019). However, serious equity concerns surround the market-based transfer of water either across large distances or between very different competing uses. That is why we limit the analysis here only to transfers within a sub-sector (i.e. for crop production) and within relatively confined geographic areas (i.e. the Sacramento and San Joaquin basins). The quantity of water available for household use or for environmental protection would not be affected by these trades.

We note though that, although the market-based allocation mechanism examined here represents a potential Pareto improvement over the current seniority-based system, the resulting market equilibrium may not meet other standards of fairness or equity. In particular, in some years, lower value but junior water users will not receive any surface-water allocation and will also not be able to purchase water from more senior users. A more equitable distribution might reserve some allocation for these users. In addition, an expansion of water trading could lead to large gains for senior rights holders in dry years when surface water is scarce and highly valuable. These windfall profits may be perceived as unfair or inequitable and may warrant policy intervention in critically dry years.

We are also unable to consider the dynamics of perennial crops in estimating the costs of curtailment. We calculate costs as only the lost production for the year, but perennial crops involve large up-front establishment costs. If farmers are unable to irrigate for 1 year, they will lose not only the production for that year, but also the unamortized portion of the initial capital investment. For this reason, the average value of water to farmers of perennial crops is likely to be higher than estimated here (Arellano-Gonzalez and Moore 2020). The bias in terms of our gains from trade estimate depends on how the probability of growing perennial crops correlates with seniority: if perennial crops are disproportionately represented among junior rights holders then our calculation will be an underestimate. Moreover, some of
the high value perennial systems currently in place may become too risky to preserve or expand in the face of increasing water scarcity. A liquid water market in which surface water allocations could be traded freely would open up additional water supply options for perennial growers and maintain the viability of perennials in the future when access to groundwater will be more restricted and when climate change will put additional pressures on the hydrological cycle of the Central Valley.

We also note that we do not consider changes in PET driven by higher temperatures over the century (Scheff and Frierson 2014), increased crop water use efficiency (Lavergne et al 2019), land use change (Wilson et al 2016), or future price changes, independent and combined projections of which remain highly uncertain. While higher temperatures are likely to increase crop water requirements, improved water-use efficiency due to CO2 fertilization may have an off-setting effect. Finally, water value depends on crop prices as well as PET requirements. Because California is a major producer of particular specialty crops, lost production of these crops may be compensated by higher prices, thereby producing only a limited effect on revenue. For other crops where California is not a major producer, there will be no offsetting price increases and lost production will directly translate into lost revenue. Modeling these responses is beyond the scope of this paper.

Finally, our analysis does not consider the transport costs associated with a liberalized water market. This is potentially problematic since water is expensive to transport in large quantities, and our simulations imply that the amount of water exchanged by the end of the century would be equivalent to 30% of the irrigation water used in 2010. Therefore, these costs could substantially reduce benefits if the implied market transactions that would realize the gains we estimate require a net transport of water over long-distances (Ayres et al 2018, Hagerty 2019). This concern is partly addressed by separating the analysis by basin, thus limiting the transfer of water to areas within either the Sacramento or San Joaquin.

In order to determine the extent of the remaining problem, we map the volume-weighted centroid of water diversion points for buyers and sellers given a 50% curtailment in each basin. Figure S12 shows these points are close together in the Sacramento basin, suggesting the transactions required to realize the equilibrium market outcome there do not require a long-distance net transfer of water. These locations are more separated in the San Joaquin basin. We note however that the southern part of the San Joaquin basin has an extensive water conveyance infrastructure that regularly moves water between irrigation districts thus reducing the transactions costs associated with transporting water in this region (Arellano-Gonzalez and Moore 2020; Escriva-Bou et al 2019). Accounting for the network structure of hydrologic relationships in constraining potential market transactions is an area for future work. Other modeling techniques, such as an agent-based modeling approach, may be better able to model system dynamics arising from the interaction of heterogeneous agents such as the diffusion of new crops, the evolution of trading relationships, or spatial spillovers from groundwater extraction (Berger et al 2019, Nouri et al 2019).

Our results indicate that water scarcity will intensify over the course of the century due to decreased streamflow during the irrigation season. Water markets can give rights holders more flexibility in dealing with this scarcity, allowing water to flow towards higher value uses. We estimate that even the geographically and sectorally limited markets we examine here would generate substantial gains over the existing seniority system. Importantly, water market reforms to remove the deadweight losses associated with curtailment would produce gains that could be widely distributed among stakeholders. Senior rights holders would benefit from having the option to sell irrigation water rather than using it while junior rights holders benefit from more secure access to water. Taxes on transactions could also redistribute part of the gains to the wider public. Expanding market institutions where appropriate to increase the flexibility with which affected actors can respond to both increasing variability and absolute scarcity projected with climate change can be an important adaptation strategy.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

F M designed research. J A G analyzed data. A A provided streamflow projections for the Central Valley. Y Q and S J D contributed estimates of water consumption of power generating plants. J B and M L provided crop-specific estimates of PET and PET-P at
the watershed level. J A G and S J D created figures. All authors wrote the paper.

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**References**

Allen R G, Pereira L S, Raes D and Smith M 1998 Crop evapotranspiration—guidelines for computing crop water requirements, FAO Irrigation and drainage paper 56 (Rome: FAO—Food and Agriculture Organization of the United Nations)

Andreadis K, Storck P and Lettenmaier D P 2009 Modeling snow accumulation and ablation in forested environments Water Resour. Res. 45 W05429

Arellano-Gonzalez J and Moore F C 2020 Intertemporal arbitrage of water and long-term agricultural investments: drought, groundwater banking, and perennial cropping decisions in California Am. J. Agric. Econ. 1–15

Ayres A, Edwards E C and Libecap G D 2018 How transaction costs obstruct collective action: the case of California’s groundwater J. Environ. Econ. Manage. 91 46–65

Bedsworth L, Cayan D, Franco G, Fisher L and Ziaja S 2018 Statewide summary report California’s Fourth Climate Change Assessment Publication

Berger T 2001 Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis Agric. Econ. 25 245–60

Boryan C, Yang Z, Mueller R and Craig M 2011 Monitoring US agricultural statistics service, cropland data layer program Geospatial Int. 26 341–38

Bowling L, Pomeroy J W and Lettenmaier D P 2004 Parameterization of blowing snow sublimation in a macroscale hydrology model J. Hydrometeorol. 5 745–62

Bruno E M and Jessoe K 2019 Water markets and climate change adaptation: micro-level evidence on agricultural water demand Working paper (available at: https://ellenbrunonc.files.wordpress.com/2019/02/bruno_jessoe_watermarkets_20190118.pdf)

Calatrava J and Garrido A 2005 Modelling water markets under uncertain water supply Eur. Rev. Agric. Econ. 32 119–42

Cayan D R, Maurer E P, Dettinger M D, Tyree M and Hayhoe K 2008 Climate change scenarios for the California region Clim. Change 87 21–42

CCTAG 2018 Projected climate scenarios selected to represent a range of possible futures in California Climate Action Team Research Working Group, California Energy Commission (available at: https://elling.energy.ca.gov/Lists/DocketLog.aspx?docketnumber=26-IEPR-04)

CDFCA 2018 California agricultural statistics review, 2017–2018 (available at: www.cdfa.ca.gov/Statistics/PDFS/2017-18AgReport.pdf)

CDWR 2015a California’s groundwater update 2013 California Department of Water Resources, California Natural Resources Energy (https://water.ca.gov/~/media/DWR-Website/Web-Pages/Programs/Groundwater-Management/Data-and-Tools/Files/Statewide-Reports/California-Groundwater-Update-2013(California-Groundwater-Update-2013-Statewide).pdf)

CDWR 2015b Perspectives and guidance for climate change analysis California Department of Water Resources and Climate Change Technical Advisory Group (available at: https://water.ca.gov)
trends in the water-use efficiency of plants and ecosystems

Glob. Change Biol. 25 2242–57

Liang X, Lettenmaier D P, Wood E F and Burges S J 1994 A simple hydrologically based model of land surface water and energy fluxes for GMSs J. Geophys. Res. 99 14,415–14,428

Libecap D G 2018 Water markets as adaptation to climate change in the Western United States Water Econ. Policy 4 13

Loch A, Wheeler S, Bjornlund H, Beecham S, Edwards J, Zhao A and Shanahan M 2013 The Role of Water Markets in Climate Change Adaptation (Gold Coast: National Climate Change Adaptation Research Facility) pp 142

Macdonald G M 2010 Water, climate change, and sustainability in the southwest Proc. Natl Acad. Sci. 107 21256–62

Mallakpour I, Aghakouchak A and Sadegh M 2019 Climate-induced changes in the risk of hydrological failure of major dams in California Geophys. Res. Lett. 46 2130–9

Mallakpour I, Sadegh M and Aghakouchak A 2018 A new normal for streamflow in California in a warming climate: wetter wet seasons and drier dry seasons J. Hydrol. 567 203–11

Mankin J S, Viviroli D, Mekonnen M M, Hoekstra A Y, Horton R M, Smerdon J E and Diffenbaugh N S 2017 Influence of internal variability on population exposure to hydroclimatic changes Environ. Res. Lett. 12 044007

Medellín-Azuara J, Harou J J, Olivas-M A, Madani K, Lund J R, Howitt R E and Zhu T 2008 Adaptability and adaptations of California’s water supply system to dry climate warming Clim. Change 87 75–90

Mekonnen M M and Hoekstra A Y 2016 Four billion people facing severe water scarcity Sci. Adv. 2 2

Murphy J T, Altaweel M, Ozik J and Lammers R B 2019 Understanding institutions for water allocation and exchange: insights from dynamic agent-based modeling Wiley Interdiscip. Rev.: Water 6 e1384

Murray K D and Lohman R B 2017 Short-lived pause in Central California subsidence after heavy winter precipitation of 2017 Sci. Adv. 4 eaar8144

Nelson K S and Burchfield E K 2017 Effects of the structure of water rights on agricultural production during drought: a spatiotemporal analysis of California’s Central Valley Water Resour. Res. 53 8293–309

Nouri A, Saghaian B, Delavar M and Bazargan-Lari R 2019 Agent-based modeling for evaluation of crop pattern and water management policies Water Resour. Manage. 33 3707–20

Pierce D, Cayan D and Dehann L 2016 Creating climate projections to support the 4th California climate assessment Climate Assessment. Division of Climate, Atmospheric Sciences, and Physical Oceanography Scripps Institution of Oceanography (La Jolla, CA) (available at: http://loca.ucsd.edu/~pierce/IEPR_Clim_proj_using_LOCA_and_VIC_2016-06-13b.pdf)

PRISM 2018 Spatial climate datasets PRISM Climate Group (Corvallis, OR: Oregon State University) (available at: http://prism.oregonstate.edu) (Accessed 4 February 2004)

Pujol J, Raggi M and Viaggi D 2006 The potential impact of markets for irrigation water in Italy and Spain: a comparison of two study areas Aust. J. Agric. Resour. Econ. 50 361–80

Qin Y, Mueller N D, Siebert S, Jackson R B, Aghakouchak A, Zimmerman J B, Tong D, Hong C and Davis S J 2019 Flexibility and intensity of global water use Nat. Sustain. 2 515–23

Scheff J and Frierson D M W 2014 Scaling potential evapotranspiration with greenhouse warming J. Clim. 27 1539–58

Schlenker W, Hanemann W M and Fisher A C 2007 Water availability, degree days, and the potential impact of climate change on irrigated agriculture in California Clim. Change 81 19–38

Schmalensee R and Stavins R N 2017 Lessons learned from three decades of experience with cap and trade Res. Environ. Econ. Policy 11 59–79

SGMA 2019 Sustainable groundwater management act data viewer (available at: https://sgma.water.ca.gov/webgis/?appid=SGMADATAViewer)

Sheffield J and Wood E F 2008 Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations Clim. Dyn. 31 79–105

Sugg Z P 2018 An equity autopsy: exploring the role of water rights in water allocations and impacts for the central valley project during the 2012–2016 California drought Resources 7 12

Tweet A 2016 Water Right Curtailment Analysis for California’s Sacramento River: Effects of Return Flows (Davis, CA: University of California)

USDA 2011 County agricultural commissions’ data National Agricultural Statistics Service (Davis, CA: California Field Office) (available at: www.nass.usda.gov/Statistics_by_State/California/Publications/AgComm/2010/201010cactb00.pdf)

USDA 2014 2012 census of agriculture. California: state and county data (available at: www.nass.usda.gov/Publications/AgCensus/2012/Full_Report/Volume_1a,.../Chapter_2_County_Level/California/cav1.pdf)

Wilson T S, Sleet B M and Richard Cameron D 2016 Future land-use related water demand in California Environ. Res. Lett. 11 054018