A. APPENDIX

A1. Additional water transfer dataset description

The full nine-state water transactions sample from the *Water Strategist* includes 5,099 observations. The original data included 12 states (5,467 transactions); however, two of those states (Oregon and Wyoming) had no recorded permanent transfers and one state (Montana) had only one recorded permanent transfer. Both permanent transfers and one-year leases within a state-year are required to empirically estimate the asset pricing model; therefore, these three states were dropped from our sample.

Buyers and sellers are grouped into three main categories: agricultural, urban, and environmental sectors. Water rights transactions generally happen in one of three forms: permanent transfers, one-year leases and multi-year leases. Long–term leases vary greatly in length across observations (2 to 100 years) and represent the smallest number of transactions in this dataset. In this study, we focus on two types of market transactions: water rights permanent transfers and one-year leases. We omit observations associated with recycled effluent water, storage rights, and multi-year leases.[1] In order to provide a better understanding of quantities and prices in the market, we also omit observations with missing prices, prices lower than $1/acre-foot, and unidentified buyers.[2]

Water market issues related to environmental flows are unique, complex, and beyond the scope of this paper; we eliminate 529 transactions involving that sector. The agricultural sector is

[1] 154 (out of 5,099) observations are associated with reclaimed effluent water; 47 (out of 5,099) trades involve storage rights; 407 (out of 5,099) observations are leasing contracts for longer than 1-year period. (The groups of omitted observations are not mutually exclusive.)

[2] The actual price of the transaction was missing in 1,423 (out of 5,099) transactions, mostly for the following reasons: 1) the price was not provided; 2) the price was provided for a transaction that included both land and water; or 3) water rights were dedicated or exchanged for in-kind services. We dropped 32 transactions with a price lower than $1/af. We also dropped two outliers with one-year lease prices higher than $5,400/af, (the average one-year lease price is $109/af). We also dropped 419 transactions not reporting the sector of the buyer.

the largest water supplier in the western states; thus, we keep only those transactions that were associated with water coming from agricultural irrigators, eliminating the 702/5,099 water transactions where the urban sector was the seller or lessor.

A2. Irrigation Vulnerability Index

The Irrigation Vulnerability Index (IVI) is constructed as in Liu et al. (2017), using their data to construct our proxy for the risk premium (θ) in the asset pricing models. In this approach, irrigation vulnerability is defined as:

(water supply – water use) / irrigation water use

where *water supply* is the sum of surface water (including reservoir storage) and renewable groundwater sources. *Water use* is the sum of irrigation, domestic, industrial, and livestock water use. Lower values of the index indicate higher levels of water stress. An irrigation vulnerability < 0.2 is considered stressed. Irrigation vulnerability can have negative values, which occur where unsustainable water supplies are used to fulfill the *water use* category.

Water supply, water use, and irrigation water use are simulated by the University of New Hampshire's Water Balance Model (WBM) at the grid cell level and at a daily time step and provided here as state-level (and basin-level for the Mojave), annual aggregates. Where water supply is less than water use, unsustainable groundwater is used to fulfill the water use requirement.

WBM simulations for 2013 – 2099 are driven by the GISS-E2-R RCP 8.5 climate scenario, bias-corrected using the delta change method. The obtained annual IVI values were averaged over this long-run period for each state to show the mean projection for long-term water stress. Results suggest that Arizona is projected to be most stressed in irrigation water availability followed by California, Texas, and Colorado (Table A4).

Note the exceptionally high value of the index for the state of Nevada. While this is an unusual value, Nevada contributes a small number of transactions to our multi-state sample, and the main results are robust to dropping Nevada (along with all other states except California, Colorado and Texas), as noted in the discussion of Table 3 in the main paper. Thus, this value does not appear to substantially influence our results.

A.2.1. WBM methods and data for simulating water use and water supply

Note: these methods have been published before, and the relevant citations are: Wisser et al. (2010), Grogan (2016), and Liu et al. (2017).

Irrigation water use

Input data

Inputs to WBM for simulation irrigation water use are: crops maps, soil properties, crop parameters, daily mean temperature, and daily precipitation. Crop maps (i.e., the location, growing area, and growing season) are from the MIRCA2000 data base (Portmann et al 2000). Soil properties – namely, field capacity and soil available water capacity – are from the Harmonized World Soil Database v1.1 (FAO/IIASA/ISRIC/ISSCAS/JRC, 2009). Crop parameters k_c, CDF_c, and RD_c are from Siebert and Döll (2010). We use the GISS-E2-R global circulation model (Schmidt et al., 2014) representative concentration pathway (RCP) 8.5 to provide temperature and precipitation inputs.

Method

In WBM, crops extract water from the soil moisture each day of the crop’s growing season. Given sufficient water in the soil moisture pool, the amount of water used by each crop is the crop potential evapotranspiration, $PETc$ [mm]:

$$PET_c = k_c \cdot PET_0$$

where PET_0 [mm] is a reference evapotranspiration, and k_c [-] is a crop-specific, time-varying scalar. This method follows the FAO-recommended crop-modeling methodology outlined in Allen et al (1998). Here, we use the Penman-Monteith method for estimating PET_0 (Allen et al, 1998).

If soil moisture levels fall below a crop-specific threshold, SMT_c [mm], then irrigation water is called for. Soil moisture threshold SMT_c for crop c is:

$$SMT_c = CDF_c \cdot RD_c \cdot AW_{cap}$$

where CDF_c [-] is a crop depletion factor, RD_c [mm] is the crop's root depth, and $AWcap$ [-] is the soil's available water capacity.

When soil moisture is below SMT_c, then the time step's net irrigation water demand, $I_{net,t}$, is the difference between the current soil moisture and field capacity:

$$I_{net,t} = \begin{cases} Fcap - SM_t \text{ } if \text{ } SM_t \leq SMT_c \\ 0 \text{ } if \text{ } SM_T > SMT_c \end{cases}$$

where $Fcap$ [mm] is the soil's field capacity, and SM_t [mm] is the soil moisture at time t. Annual net irrigation water use is the sum of all daily net irrigation water uses through the year. We assume no shortage of water for irrigation; when water supply is insufficient to meet the crop's irrigation water requirement, then additional water is added to the soil moisture from an unlimited "unsustainable" water source.

Domestic and industrial water use

Input data

Data inputs for domestic and industrial water use are: domestic per capita water use, industrial per capita water use, and population density. Time series of domestic per capita water use, *DWpp* and industrial per capita water use, *IWpp,* are from Liu et al (2017). Annual population density projections are from the IIASA decadal projections (IIASA, 2007) under the B2 scenario.

Method

In WBM, the domestic and industrial sectors use water each day. Domestic water use, *Dw* [mm], is:

$$Dw = A \cdot DWpp \cdot D_{pop},$$

and industrial water use, *Iw* [mm] is:

$$Iw = A \cdot IWpp \cdot D_{pop},$$

where

A [km^2] is the area of the grid cell

DWpp [mm/d] is the domestic water use per capita

IWpp [mm/d] is the industrial water use per capita

D_{pop} [persons km^{-2}] is the population density.

Livestock water use

Input data

Input data for livestock water use are: average daily temperature, livestock density for each livestock category, service water per head, and two growth parameters. All livestock data and methods are from FAO (2006) and FAO employee Dominik Wisser (*personal communication*); the same temperature inputs are used here as in the irrigation water use section.

Method

Daily livestock water, L_w, for each livestock type is calculated each day as:

$$L_w = I_l + s_l \cdot T_m + SW_l \cdot D_l$$

where

I_l is an intercept parameter for livestock type l

s_l is a slope parameter for livestock type l [-]

T_m is the daily mean temperature, with a minimum value of 0 [°C]

SW_l is the daily service water volume required per animal

D_l is the density of livestock type l in the grid cell.

Livestock types represented are: buffalo, cattle, goats, pigs, poultry, and sheep.

Water supply

Input data

To simulate water supply, WBM requires inputs to represent rivers, reservoirs on those rivers, and the water budget of non-agricultural lands (including impervious areas). The river data is the STN-30p river network (Vörösmarty et al., 2000), and reservoir and dam inputs are from the GRanD database (Lehner et al., 2011). Soil properties of non-agricultural lands are from the Harmonized World Soil Database v1.1 (FAO/IIASA/ISRIC/ISSCAS/JRC, 2009), and impervious surface data is from the Global Distribution and Density of Constructed Impervious Surfaces database (Elvidge et al., 2007).

Method

Water supply is the sum of surface water (including reservoir storage) and renewable groundwater sources. Renewable groundwater is defined as the volume of water stored via percolation through soils, minus the volume of water exiting the groundwater stores as baseflow. Details for surface water and renewable groundwater methods are provided in Wisser et al (2010) and Grogan (2016).

A3. Australian water market results

At the suggestion of a referee, we estimated the basic asset pricing model (shown in equation (1)) using Australian water market transaction data.

$$\boldsymbol{p^{sale} = p^{lease}/r} \qquad (1)$$

Our empirical approach adapts equation (4) from the paper. Specifically, $\boldsymbol{lnp_{ijqt} = \gamma_0 + \gamma_1 ln\pi_{ijqt} + \gamma_2 r_{qt}} + \mu_t + \boldsymbol{\alpha_j + \varepsilon_{ijqt}}$, where $\boldsymbol{lnp}$ is the log price of entitlement transfer *i* (similar to permanent water rights transfer in the U.S.), in state $\boldsymbol{j}$, in quarter $\boldsymbol{q}$, and in year $\boldsymbol{t}$; $\boldsymbol{ln\pi}$ is the log price allocation transfer (similar to one year lease in the U.S.); $\boldsymbol{r}$ is the quarterly real Australian market interest rate; μ is a year fixed effect; $\boldsymbol{\alpha}$ is a state fixed effect or random effect; and $\boldsymbol{\varepsilon}$ is the error term. Note that we omit the growth rate and risk premium variables, lacking available data for this extra analysis outside of the United States, the site of our main analysis.

The Australian water transaction dataset was downloaded from the Australian Government Bureau of Meteorology. We obtained allocation and entitlement transfers from 2007-2018 for five states for which both transfer type data were available: New South Wales, South Australia, Tasmania, Victoria, and Western Australia. Similar to our approach for the U.S. markets, we omitted observations that lacked price information, were associated with bundled water and land transfers, or were described as temporary entitlement transfers.

Transaction prices ($/ML) were converted to 2009 Australian dollars using the consumer price index (CPI) obtained from the Australian Bureau of Statistics. The real interest rate was calculated by using Australian 90-day T-bill rate available via the Organization for Economic Co-operation and Development (OECD), and adjusting for inflation using CPI – similar to the U.S. models reported in the paper. The final quarterly averaged dataset comprised 165 observations.

Table A5 provides the results using two models: fixed effects (1), and random effects (2). Results using both approaches yield the expected coefficient signs: entitlement transfer prices are positively correlated with allocation transfer prices, and negatively correlated with real interest rates. Like our U.S. results, these results for Australia are consistent with asset pricing theory. However, given limits to data availability, we do not directly compare these results to those in the paper. A complete application of the asset pricing model to the Australian water market case would be an important extension of our analysis of the western U.S. water markets, and an excellent topic for further research.

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APPENDIX TABLES

Table A1. Asset Pricing Model IV Estimation Results for the Multi-State Sample (Dependent variable: Log Transfer Price)

	(1)	(2)	(3)	(4)	(5)	(6)
	(9 states)	(9 states)	(9 states)	(3 states)	(3 states)	(3 states)
Log lease price	0.009	0.007	0.224	0.134	0.134	0.308
	(0.543)	(0.596)	(0.283)	(0.434)	(0.554)	(0.226)
Growth rate: Acres irrigated	omitted	1.052	1.119**	omitted	-1.643***	-2.496***
		(0.678)	(0.546)		(0.334)	(0.074)
Risk premium: Irrigation vulnerability index	omitted	0.046***	0.053***	omitted	1.470***	1.418***
		(0.012)	(0.010)		(0.274)	(0.162)
Real interest rate	-20.650***	-20.685***	-9.214	-22.821***	-22.821**	-10.601
	(6.650)	(7.253)	(6.474)	(7.486)	(9.543)	(8.520)
Time trend	____	____	0.069***	____	____	0.069***
			(0.013)			(0.016)
State controls	FE	RE	RE	FE	RE	RE
N (obs)	66	66	66	53	53	53
R^2	0.176	0.053	0.096	0.268	0.724	0.772
Cragg-Donald Wald F statistic	3.404	3.683	3.670	3.789	3.789	3.702
Kleibergen-Paap rk.Wald F statistic	3.614	3.735	3.744	2.742	2.580	2.659
p-value of Kleibergen-Paap rk LM statistic	0.169	0.169	0.177	0.178	0.178	0.184
p-value of Endogeneity test	0.705	0.707	0.910	0.972	0.981	0.613

Note: *** Significance at 1%, ** Significance at 5%, *Significance at 10%; values in parentheses are robust standard errors clustered by state. *p*-value for Hansen J statistic not provided because the equation is exactly identified.

Table A2. Asset Pricing Model IV Estimation Results for the Mojave Market (Dependent variable: Log Transfer Price)

	(1) (5 areas)	(3) (5 areas)	(4) (5 areas)	(5) (2 areas)	(7) (2 areas)	(8) (2 areas)
Log lease price (qtr.avg)	-4.391	0.056	-0.975	-139.074	-139.074	-1.439
	(5.533)	(0.850)	(1.221)	(14970.4)	(21654.42)	(2.879)
Growth rate: Water consumption	omitted	1.989	2.914**	omitted	699.337	7.288
		(1.301)	(1.442)		(107992.7)	(7.125)
Risk premium: Irrigation vulnerability index	omitted	-0.063	-0.056	omitted	omitted	omitted
		(0.083)	(0.058)			
Real interest rate	-133.234	-22.906	-3.883	-4023.65	-4023.65	-9.847
	(177.974)	(20.906)	(8.775)	(431487.0)	(624138.1)	(17.927)
Yearly trend	____	____	0.111*	____	____	0.126
			(0.057)			(0.161)
Subarea controls	FE	RE	RE	FE	RE	RE
N (obs)	89	89	89	69	69	69
R^2	-21.405	0.552	0.528	-14000	0.147	0.704
Cragg-Donald Wald F statistic	0.593	11.538	5.238	0.000	0.000	4.240
Kleibergen-Paap rk.Wald F statistic	0.566	3.356	2.278	0.000	0.000	0.437
p-value of Kleibergen-Paap rk LM statistic	0.498	0.141	0.224	0.993	0.993	0.530
p-value of Endogeneity test	0.396	0.131	0.131	0.771	0.000	0.000

Note: *** Significance at 1%, ** Significance at 5%, *Significance at 10%; values in parentheses are robust standard errors clustered by state. *p*-value for Hansen J statistic not provided because the equation is exactly identified.

Table A3. Robustness Check: Asset Pricing Model Results for the Nine-State Sample with Different Growth Rate Proxy (Dependent Variable: Log Transfer Price)

	(1) (9 states)	(2) (9 states)	(3) (9 states)	(4) (3 states)	(5) (3 states)	(6) (3 states)
Log lease price	0.154*	0.162**	0.166***	0.146	0.146**	0.153**
	(0.070)	(0.072)	(0.061)	(0.071)	(0.072)	(0.063)
Growth rate: Irrigated crop price	____	1.215	0.754	____	-6.847***	-9.940***
		(2.740)	(2.732)		(0.255)	(0.585)
Risk premium: Irrigation	____	0.042***	0.047***	____	1.523***	1.417***
vulnerability index		(0.014)	(0.015)		(0.071)	(0.089)
Real interest rate	-20.061**	-20.026***	-9.341	-22.767	-22.767***	-11.437
	(7.320)	(7.440)	(6.534)	(8.306)	(8.477)	(7.851)
Time trend	____	____	0.070***	____	____	0.068***
			(0.013)			(0.017)
State controls	FE	RE	RE	FE	RE	RE
N (obs)	66	66	66	53	53	53
R^2	0.212	0.154	0.199	0.269	0.724	0.788

Note: *** Significance at 1%, ** Significance at 5%, *Significance at 10%; values in parentheses are robust standard errors clustered by state. All models include a constant. Growth rate proxy in this model is constructed for each state based on prices of the type of crop which uses a significant amount of irrigation water in its production. The major crops were determined based on analyzing the values for irrigated area harvested, irrigated crop/acre yield, and average AF of water applied for acre provided in the USDA Water Management and Irrigation Survey. Specifically, we used annual prices from 1990-2018 available at USDA for alfalfa (AZ), corn (CO, NM, TX, WA), rice (CA), and wheat (ID, NV, UT), and constructed the time invariant growth rate variable using the AR(1) approach (where we included the natural log of water price, year, and a constant).

Table A4: Average long-term Irrigation Vulnerability Index by state

State	Irrigation Vulnerability Index
Arizona	-2.408
California	-1.325
Colorado	-0.101
Idaho	0.501
Nevada	59.465
New Mexico	2.253
Texas	-1.021
Utah	4.326
Washington	1.650

Table A5: Asset Pricing Model Estimation Results for Australian Water Transfers, 2007-2018 (Dependent Variable: Log Entitlement Transfer Price)

	(1) (5 states)	(2) (5states)
Log lease price	0.026	0.225***
	(0.046)	(0.076)
Real interest rate	-10.298	-10.008
	(10.613)	(11.772)
Year Controls	Yes	Yes
State Controls	FE	RE
N (obs)	165	165
R^2	0.155	0.223

Note: *** Significance at 1%, ** Significance at 5%, *Significance at 10%; values in parentheses are standard errors clustered by state, which have been corrected for heteroskedasticity. All models include a constant. Observations are from five states: New South Wales, South Australia, Tasmania, Victoria, and Western Australia.