# Institutions, Climate Change, and the Heterogeneous Cost of Snowpack Decline

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**Abstract**

Climate change is expected to reduce mountain snowpack across the western United States. The cost of this decline depends critically on how water allocation institutions distribute scarcity across users with different property rights to water. Under the prior-appropriation doctrine, junior water right holders face a higher risk of losing access to water, i.e., curtailment, when river supplies are scarce. This paper estimates the economic cost of snowpack decline in Colorado and examines how water allocation institutions shape the distribution of these costs across farmers with heterogeneous water rights. We first estimate the relationship between basin-level snowpack and annual curtailment of water rights. We see that lower snowpack levels significantly increase curtailments, and junior rights are substantially more sensitive to this variability. We then use a hedonic pricing model of irrigated farmland transactions to estimate how land markets capitalize long-run curtailment risk into property values. We find that a one–percentage-point increase in average water right curtailment reduces irrigated land values by 0.8 percent. We integrate these estimates with climate projections to simulate welfare losses from future snowpack decline. Under a moderate emissions scenario (SSP2–4.5), projected mid-century snowpack declines of roughly 22 percent generate irrigated land value losses of 4.6–6.5 percent across the South Platte and Arkansas River Basins, corresponding to a total loss of $976 million across our study area.

**Keywords:** Snowpack, Climate change, Non-market valuation, Water security, Prior appropriation, Water rights, Colorado
**JEL Codes:** Q15, Q25, Q51

> As the angel melts in the summer heat, her tears flow down to the valley as life-giving water.
>
> —*The Angel of Shavano, Jon Pinnow, Colorado Public Radio*

# 1 Introduction

Mountain snowpacks are the planet's natural water storage. They store winter precipitation and release it gradually as meltwater in spring and summer. This water then feeds rivers, fills reservoirs, recharges aquifers, and supports both human and ecological demands downstream. The hydrological pattern of snow accumulation and melting, however, has been disrupted by climate change (Marshall et al., 2026). Warmer winters are causing more precipitation to fall as rain rather than snow, and earlier melting has shifted the timing of streamflows by moving water availability away from summer months to earlier in the year (Barnett et al., 2005; Immerzeel et al., 2020; Hale et al., 2023). Snowpack levels in the western U.S., which accounts for over half of total water flows in the region (Li et al., 2017), reached among the lowest levels observed in decades in 2026 (Figure 1; NRCS, 2026). Projections indicate that the region could lose up to 25% of its snowpack by 2100 (Siirila-Woodburn et al., 2021; Cho et al., 2021). These changes are specifically consequential for irrigated agriculture in snow-dependent regions, where minimal growing-season rainfall leaves snowmelt-fed rivers the primary source of irrigation water (Qin et al., 2020; Mankin et al., 2015).

Institutional settings that govern surface water allocation can redistribute the economic cost of snowpack decline among users with different property rights to water. In most of the western U.S., water rights follow the prior appropriation doctrine, under which water is allocated based on the date it was first put to beneficial use. When streamflow is insufficient to satisfy all claims, junior rights are curtailed first before senior rights. Curtailments impose costs by constraining farmers' production and cropping decisions (Li et al., 2019; Cobourn et al., 2022), and by inducing costly investments to mitigate water supply risk (Blumberg et al., 2021). The prior appropriation doctrine therefore makes the costs of water scarcity depend on the seniority of users' water rights. Ex ante, the cost of future snowpack decline, and the extent to which the prior appropriation doctrine mediates its distribution among water users, are unquantified empirical questions.

In this paper, we estimate the economic cost of snowpack decline for irrigated agriculture in Colorado, with particular attention to how prior appropriation generates heterogeneous exposure to water scarcity. We first estimate the relationship between basin-level annual snowpack and the curtailment of individual water rights with different attributes, which allows us to quantify how changes in snowpack translate into changes in water curtailment risk. We then use a hedonic pricing model to estimate how the long-run curtailment risk of a parcel's water right portfolio is capitalized into irrigated land values. Our identification relies on variation in curtailment risk across properties with similar water right seniority within the same geographic settings, where remaining differences in curtailment exposure are primarily driven by exogenous streamflow and downstream water demand. Combining these estimates, we simulate irrigated land values under alternative climate and snowpack trajectories to measure the heterogeneous welfare losses from snowpack decline across irrigated properties.

Colorado is an ideal setting for this study. As the nation's highest-elevation state, it stores much of its water as snowpack concentrated in the Rocky Mountains. The state's economy depends on snowpack for winter recreation and on its spring melt for irrigation, drinking water, and power generation. Colorado also operates one of the country's clearest and most strictly enforced prior appropriation systems, where seniority of water rights governs allocation of water during shortages. Our analysis focuses on the South Platte and Arkansas River Basins, which together contain 94% of the state's population and account for roughly 58% of its total irrigated acreage.

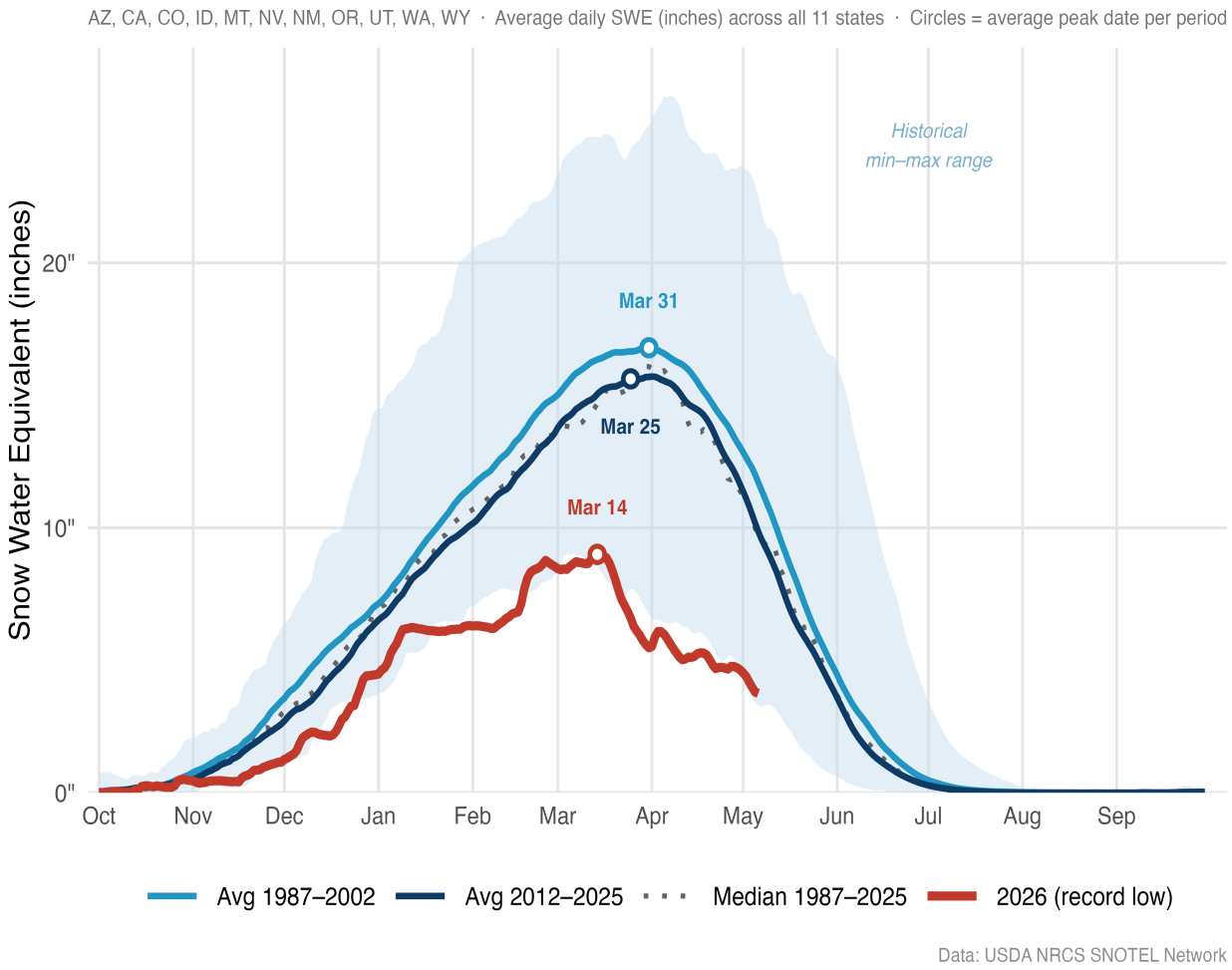



Figure 1: Daily Snow Water Equivalent in the Western U.S

Our results indicate that a decline in snowpack levels increases curtailment risk disproportionately for junior right holders relative to senior ones. Specifically, under a moderate emissions scenario, the projected increase in curtailments for water rights in the most junior quartile of the seniority distribution is 53% higher than for rights in the most senior quartile. Furthermore, we find that land markets capitalize the curtailment risk associated with a parcel's water right portfolio. Specifically, a 1 percentage point increase in the long-run

risk of water rights curtailment discounts irrigated land values by 0.8 percent. In 2022 dollars, this amounts to $106 per acre of irrigated land, on average. Applying our estimates to CMIP6 SSP2-4.5 climate projections, under which Colorado snowpack is predicted to decline by 21–22 percent by mid-century, we predict a 4.6%–6.5% loss in irrigated farmland market value, amounting to approximately $976 million in reduced irrigated agricultural land value by mid-century in our study area.

Our analysis makes three major contributions. First, we add to the research on how institutions mediate exposure to climate change. Across many settings, climate risk is filtered through institutions before it becomes an economic cost (Edwards et al., 2024). For instance, flood insurance zone designation affects how flood risk is capitalized into property values (Hino and Burke, 2021), fisheries quota systems affect the distribution of gains and losses from climate-driven shifts in fish stocks (Pinsky et al., 2018), and the underlying institutions of crop insurance programs determine how climate-driven agricultural losses are distributed (Annan and Schlenker, 2015). Under the prior appropriation doctrine, identical hydrological shocks do not translate into uniform water shortages across farms. Instead, the system generates heterogeneous curtailment risks based on the seniority and specific attributes of individual water rights. A growing literature shows that water right seniority affects agricultural decisions and outcomes, including crop choice, irrigation behavior (Cobourn et al., 2022), and land values (Edwards et al., 2025; Brent, 2017; Bahrami et al., 2026). We provide some of the first empirical evidence linking climate-driven variation in water supply to observed curtailments at the water-right level and, subsequently, to the capitalization of this risk in agricultural land markets. By explicitly modeling scarcity as an institutional outcome rather than a purely hydrological one, we show that institutional settings determine the distribution of climate-driven economic losses across users with different water rights.

Second, we contribute to climate economic literature by shifting the focus from local weather shocks to remote, climate-related, hydrological constraints. A large body of literature has estimated the impact of various climate change measures on agricultural production and the costs they impose. Most of these studies focus on the rainfed Eastern U.S, and relate different specifications of temperature and precipitation to agricultural outcomes such as yield, profit, and land values (Mendelsohn et al., 1994; Deschênes and Greenstone, 2007; Schlenker and Roberts, 2009). The main objective of these studies is to predict future economic outcomes with climate change using the underlying, estimated relationship between climate and economic outcomes. A common finding in these studies is that precipitation has a negligible effect compared with the dominant influence of temperature. While a smaller literature accounts for irrigation (Schlenker et al., 2005; Kurukulasuriya et al., 2011), existing work largely treats water scarcity as a local constraint driven by rainfall shortfalls or groundwater depletion (Perez-Quesada et al., 2024). In snow-fed regions, however, surface water availability is neither local nor farm- or county-specific; it is determined by snowpack accumulation at upstream headwaters, often far from farm fields. Our study exploits this setting to examine a form of climate-driven water scarcity that operates through non-local hydrological processes rather than local weather conditions. By linking snowpack accumulation at basin headwaters to downstream water availability, we identify a climate channel that affects irrigated agriculture even in the absence of changes in on-farm temperature or precipitation.

Third, our work relates to the literature on the economic value of snowpack. Similar to other ecosystems and environmental amenities, snowpack generates services that can be economically measured, such as ski resort revenues (Parthum and Christensen, 2022). We contribute to this literature by estimating the value of snowpack for agriculture. In doing so, our analysis treats snowpack as an upstream natural asset whose economic value extends beyond recreation and is mediated by legal and institutional water allocation rules.

# 2 Background

Access to reliable water resources has long supported social welfare and economic development. Many early societies emerged along rivers fed by snowmelt, where coordinating the distribution of variable water supplies required institutional arrangements. For instance, the challenges of managing river flows in ancient Mesopotamia have been linked to the emergence of very early forms of government (Allen et al., 2023). Similar challenges remain relevant today, and new institutional setups have emerged to govern the provision of water in modern societies.

Property rights are one of the most fundamental forms of institutions that have been used to allocate natural resources such as water (Burness and Quirk, 1979), land (Hornbeck, 2010; Galiani and Schargrodsky, 2011), fisheries (Grainger and Costello, 2011) and minerals (Libecap, 2024). In much of the western U.S., property rights to water are regulated under the prior appropriation doctrine, under which "first in time" means "first in right". Users with earlier (senior) priority dates retain access to water during periods of shortage, while later (junior) users are curtailed when streamflows fall below the total allocated decreed water. Unlike the riparian system of the eastern U.S., which links water access to landownership along waterways (Ciriacy-Wantrup, 1955), prior appropriation assigns rights based on the temporal sequence of water claims. The system emerged to protect established water claimants against newcomers, secure their investments, and enable off-stream water use. While appropriation rights vary across different margins, priority ranks are the most defining characteristic determining the security of water access under variable supply.

Appropriation rights meet the three fundamental criteria of well-defined property rights. First, they are established as perpetual property rights, contingent only upon continued beneficial use. Under the "use it or lose it" doctrine (Shupe et al., 1989), these rights remain secure as long as they are exercised, and they are strictly exclusive such that only those with an adjudicated decree may legally reap the benefits of the water. Second, they are transferable and can be sold either with or without the land. While the original priority date remains fixed during such transactions, any modifications to the place of use, type of use, or point of diversion must undergo court approval to ensure that downstream holders are not affected. Third, appropriation rights are enforceable (Milliman, 1959), and priority ranks explicitly determine which rights receive what portion of their allocated water when the supply is short.

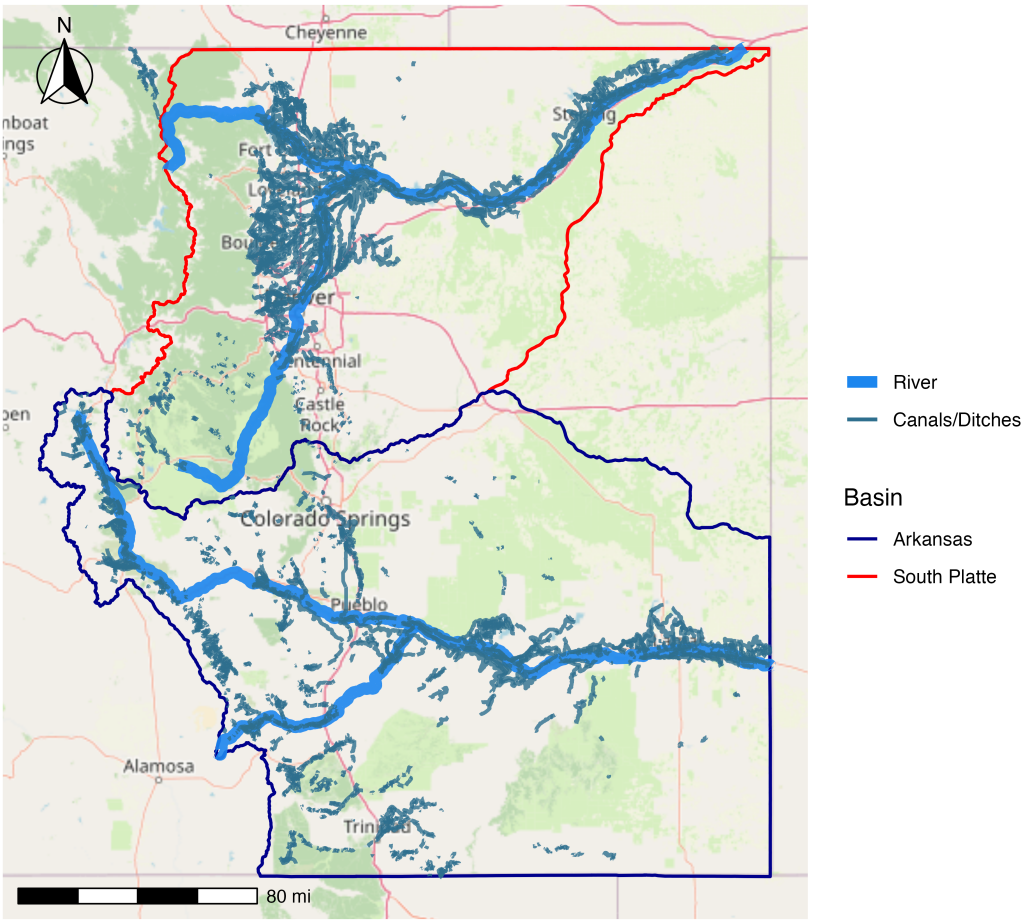



Figure 2: Study area, South Platte and Arkansas River Basins in Colorado

## Study area

Colorado is a critical headwaters state, supplying water to downstream users across 18 other states and Mexico. An average of 13.7 million acre-feet of streamflow originates within the state each year, roughly 60% of which ultimately flows beyond Colorado's borders under the terms of at least eleven interstate compacts (Colorado Water Conservation Board, 2023). Within the state, surface water meets approximately 83% of consumptive water use, with groundwater supplying the remainder. Agriculture is by far the largest consumptive user, accounting for roughly 89% of statewide consumptive use (Colorado Water Conservation Board, 2023).

Our analysis focuses on the South Platte and Arkansas River Basins, which drain the eastern slope of the Rocky Mountains and contain a substantial share of Colorado's population and irrigated agriculture. Surface water in these basins reaches farms through an extensive network of canals and ditches exceeding 8,000 miles in length (Figure 2).

### Snowpack and Hydrology in Colorado

Colorado's surface water supply is derived predominantly from mountain snowpack, with snowmelt contributing approximately 80% of the state's surface water supply and direct rainfall contributing comparatively little to streamflow (Water Education Colorado, 2013). Snow begins accumulating in the mountains in the fall, and sustained below-freezing temperatures allow subsequent winter precipitation to be stored as snowpack. Snowpack typically reaches its seasonal maximum in early to mid-April, after which rising temperatures initiate the spring melt.

Because streamflow is so closely tied to snow accumulation and melt, the timing and volume of runoff each year are largely set by winter snowpack. Flows typically rise through spring, peak in May or June, and decline over the summer as the snowpack is depleted. Reservoirs and dams modify this natural hydrograph by storing a portion of runoff for release later in the irrigation season, but the total volume available for storage and diversion remains fundamentally constrained by snow accumulation and subsequent runoff.

### Prior Appropriation in Colorado

Colorado's water rights system has developed through a series of legislative and judicial actions that formalized the allocation and administration of water supplies. The Adjudication Acts of 1879 and 1881 established the legal foundation for defining water rights and enforcing priority-based administration. The administration and enforcement of water rights are carried out by the State Engineer's Office and the Division Engineer's Offices, which oversee priority calls, regulate diversions, and ensure compliance with interstate compact obligations. Water rights are adjudicated through a specialized system of water courts that determine priority dates, quantify decreed uses, and issue enforceable rights to divert and apply water to beneficial uses (Jones and Cech, 2009).

Water rights can be transferred or modified, but changes to their place of use, type of use, or point of diversion generally require approval through the water court process. Such changes can involve substantial legal, hydrologic, and administrative costs because existing right holders must be protected from injury (Colby, 1990; Womble and Hanemann, 2020). In Colorado, surface water rights are commonly held and managed through diversion structures such as ditches and canals. Many of these structures are operated by irrigation companies, with farmers holding shares that entitle them to a proportional interest in the company's portfolio of water rights.[1] These shares commonly accompany the irrigated land when agricultural properties are transferred.

Priority of water rights is enforced through administrative calls initiated by downstream senior rights holders and administered by the division engineer. When available water supplies are insufficient to satisfy all decreed rights, a senior user places a call on the stream, which the division engineer verifies and enforces by establishing a controlling priority date, referred to as the call priority. All upstream water right holders with priorities junior to the call priority are required to temporarily cease diversions, allowing water to pass downstream to senior rights holders who are receiving less than their decreed entitlement. Administrative calls typically extend across the entire upstream reach of the river system, including

[1] Most structures hold portfolios of rights with different appropriation dates and decreed amounts

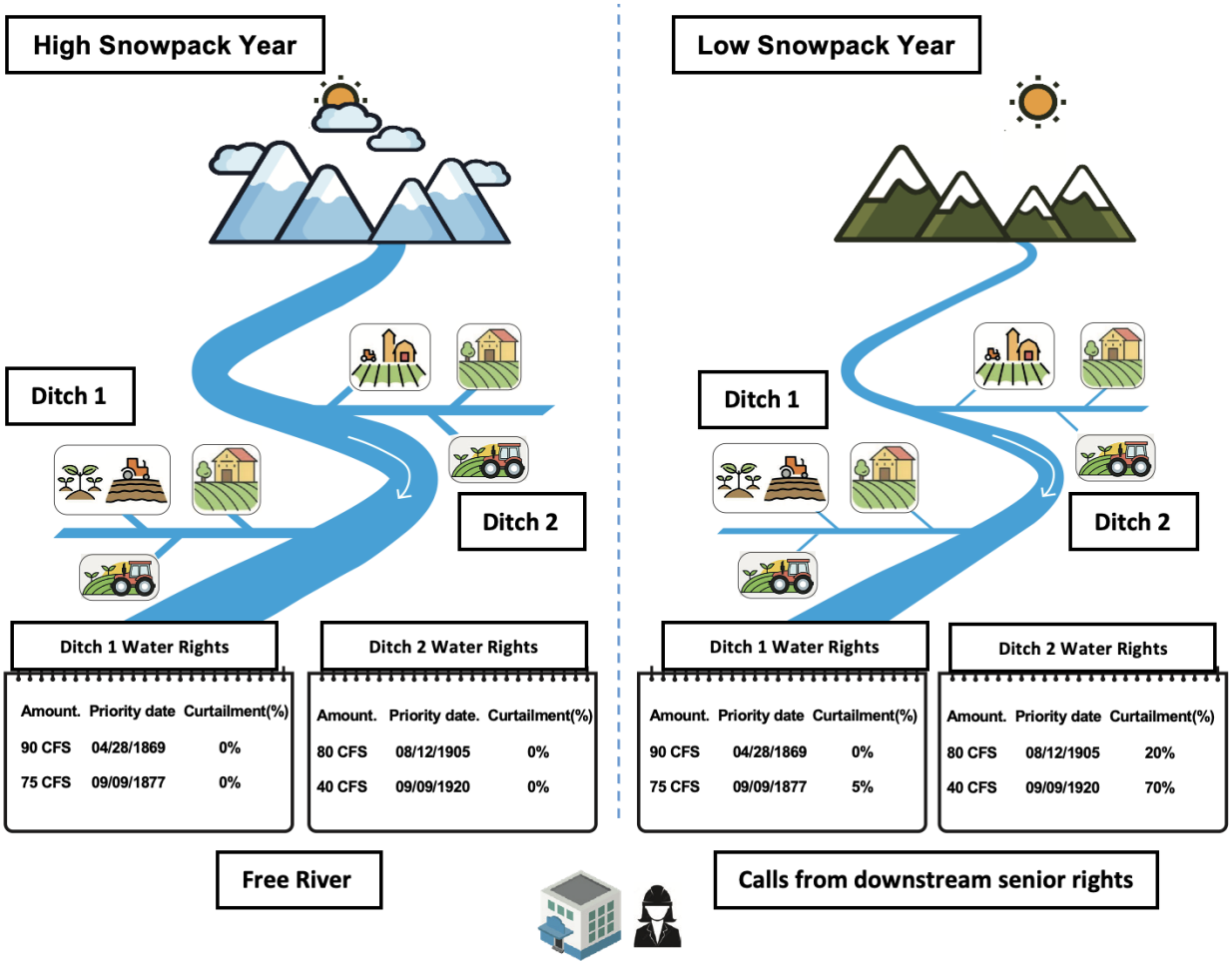



Figure 3: Illustration of how snowpack conditions translate into heterogeneous curtailment risk under prior appropriation.

all tributaries that contribute to the affected stream. Information on active calls is disseminated through the state's HydroBase system, where water users can monitor current calls and receive updates on changes in call status.

Figure 3 illustrates how variation in snowpack translates into heterogeneous curtailment risk across water right portfolios under the prior appropriation. In a high-snowpack year (left panel), the basin operates under "free river" conditions where streamflows are abundant enough to satisfy the entire hierarchy of claims, and the risk of curtailment is minimal. In contrast, in a low-snowpack year (right panel), reduced runoff lowers available streamflow and increases the frequency of administrative calls placed by senior rights downstream. These calls curtail upstream junior rights while senior rights remain largely protected. Consequently, although Ditch 1 holds relatively senior rights and experiences little to no curtailment, Ditch 2, whose portfolio consists of more junior rights, faces substantial reductions in allowable diversions.

# 3 Conceptual framework

Estimating the welfare cost of snowpack decline requires understanding how hydrological shifts in streamflow operate through the institutional setting under the prior appropriation to affect water users. We organize this process around four motivating assumptions about the relationship between snowpack, curtailment risk, and the present value of agricultural profits. Taken together, these assumptions imply that snowpack declines impose welfare losses on irrigated agriculture and that these losses are distributed unevenly across users with different water right seniority.

Let $W$ denote annual basin-level snowpack (e.g., Snow Water Equivalent[2]). Snowpack is stochastic, and climate change is modeled as a structural shift in its long-run distribution. Unlike standard production models where inputs such as precipitation enter the profit function directly, in the snowfed prior appropriation setting, the physical availability of water is mediated by appropriation rules. Consider a parcel endowed with surface-water rights characterized by seniority $s$, with higher values indicating more senior rights. Under the prior appropriation doctrine, the realized water access depends on both snowpack and seniority. Let $z(s, W) \in [0, 1]$ denote the curtailment risk, or the portion of the irrigation season during which the right is out of priority, when the snowpack level is $W$. We explore the following motivating assumptions (MA) that inform our analysis of the welfare loss from snowpack decline:

**MA1: Less senior rights experience higher curtailment.** Under the prior appropriation doctrine, water is allocated in order of priority during shortages. Less senior (more junior) rights therefore face higher curtailment risk. Figure 4 provides descriptive evidence consistent with this prediction by plotting average curtailment against priority year in our study area. The magnitude of the institutional gradient is given by $\partial z/\partial s < 0$, which measures how curtailment changes with a marginal increase in seniority holding hydrologic conditions fixed.

**MA2: Higher snowpack reduces average curtailment.** Snowpack determines basin-level water supply. Higher snowpack increases runoff and reduces the likelihood of administrative calls on average. Figure 5 plots annual basin-level snowpack and average curtailment rates. Across both river basins, lower snowpack years correspond to higher curtailment rates. The magnitude of this relationship is captured by $\partial z/\partial W < 0$, which measures how a marginal increase in snowpack translates into changes in curtailment risk.

**MA3: Seniority mitigates sensitivity of curtailment to snowpack.** Under prior appropriation, the effect of basin-level water availability conditions on individual water right curtailments depends on seniority. Junior rights are curtailed first during shortages, while some sufficiently senior rights may remain in priority even in low-snowpack years. Formally, this implies that $\frac{\partial^2 z(s,W)}{\partial s\, \partial W}$ is positive. Since $\frac{\partial z}{\partial W} < 0$, a positive cross-derivative implies that the marginal effect of snowpack on curtailment becomes smaller (in absolute value) as rights

[2]Snow Water Equivalent (SWE) measures the amount of liquid water contained in the snowpack, expressed as the depth of water that would result if the snowpack completely melted.

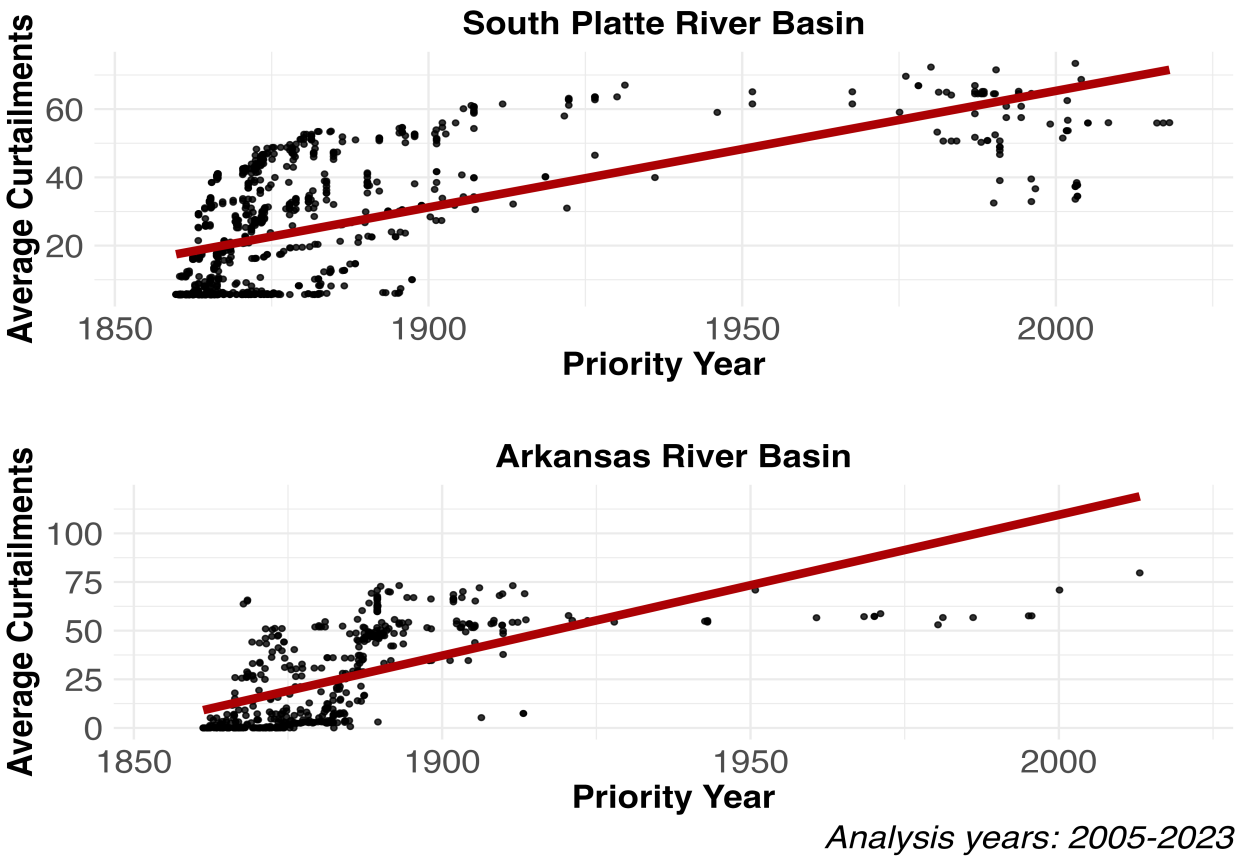



Figure 4: Relationship between seniority (year) and average curtailment (% of growing season)

become more senior. In times of scarcity (low snowpack), highly senior rights are largely protected from hydrologic fluctuations, whereas junior rights remain strongly exposed.

**MA4: Land markets capitalize curtailment risk.** Annual profits from irrigated agriculture depend on realized water access. Let $\pi(z(s, W))$ denote profits when curtailment risk is $z(s, W)$. Under Ricardian rent theory, land value equals the discounted present value of expected future returns:

$$V(S, w|\mathbf{X}) = \int_0^\infty e^{-rt} \left[ \int_0^\infty \pi(z(s, W))\, g(W)\, dW \right] dt, \tag{1}$$

where $r$ is the discount rate and $g(W)$ is the long-run density of snowpack.

If higher curtailment reduces expected profits or annual rents $\frac{\partial \pi}{\partial z} < 0$, then land markets capitalize this cost through $\frac{\partial V}{\partial z} < 0$. Agricultural land markets are expected to capture long-run adaptation possibilities that are important for estimating the cost of snowpack decline.

Taken together, these assumptions characterize the pathway through which changes in snowpack translate into welfare changes that are capitalized in agricultural land values. We next use this framework to derive the welfare implications of snowpack decline.

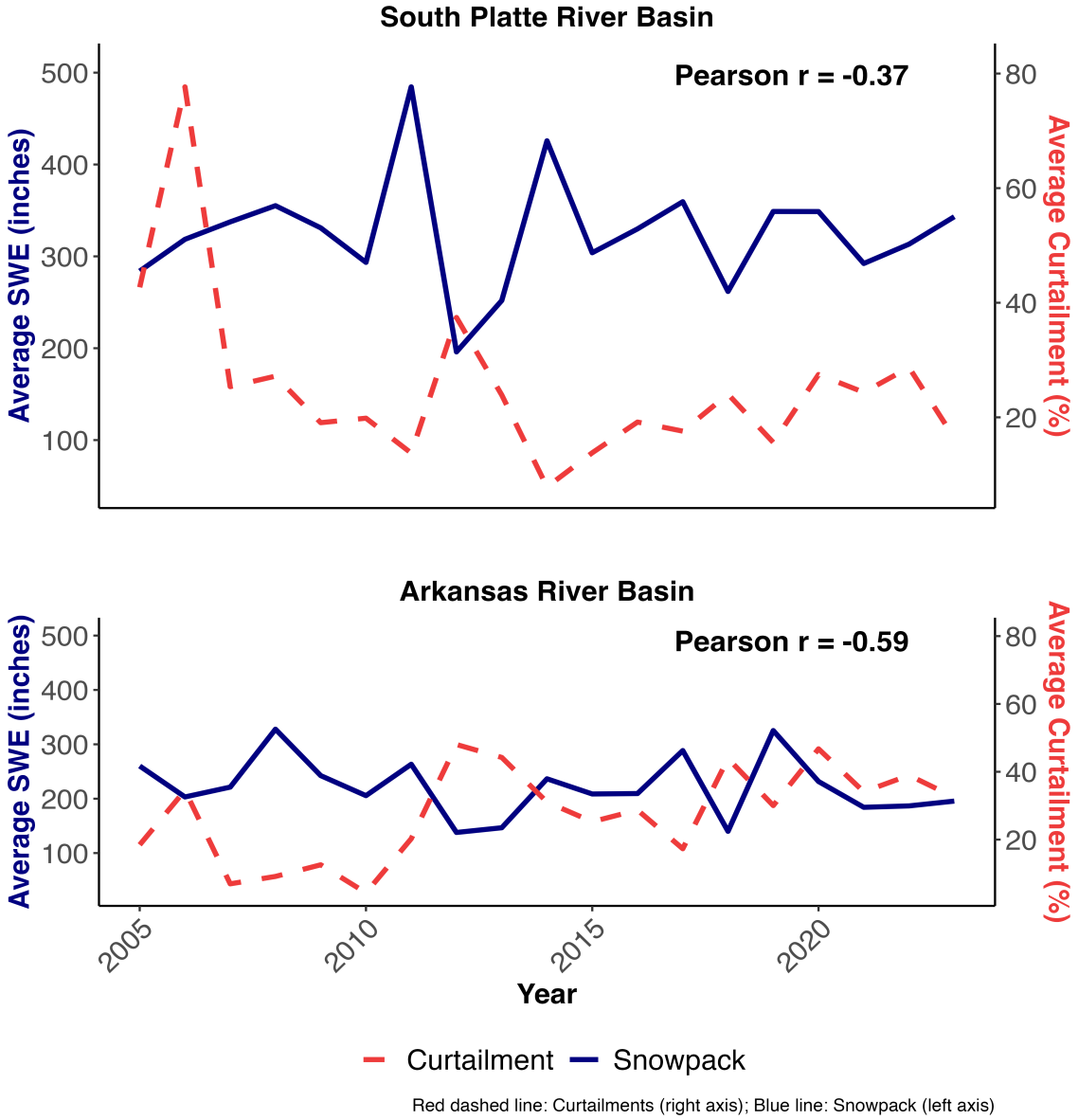



Figure 5: Snowpack and curtailment trends

## Welfare loss from snowpack decline

The marginal impact of changes in snowpack on land value can be written as

$$\underbrace{\frac{\partial V}{\partial W}}_{\substack{\text{welfare cost of} \\ \text{snowpack decline}}} = \underbrace{\frac{\partial V}{\partial z}}_{\substack{\text{market valuation} \\ \text{of curtailment risk}}} \times \underbrace{\frac{\partial z(s,W)}{\partial W}}_{\substack{\text{institutional mediation} \\ \text{of hydrological shift}}} . \tag{2}$$

Since $\partial V/\partial z < 0$ and $\partial z/\partial W < 0$, lower snowpack levels decrease land values. The distributional effect of climate change depends on seniority. Differentiating with respect to

$s$ yields: $\frac{\partial}{\partial s}\left(\frac{\partial V}{\partial W}\right) = \frac{\partial V}{\partial z} \cdot \frac{\partial^2 z(s,W)}{\partial s \partial W}$. Given $\partial V/\partial z < 0$ and $\partial^2 z/(\partial s \partial W) > 0$, it follows that $\frac{\partial}{\partial s}\left(\frac{\partial V}{\partial W}\right) < 0$. Therefore, projected declines in snowpack generate larger proportional welfare losses for less senior rights.

Our framework measures the welfare cost of snowpack decline through the channel of reduced water availability and increased curtailment risk. It is worth noting that increased water scarcity may simultaneously raise the marginal value of water, potentially increasing the market value of senior water rights that retain reliable access. This appreciation, however, largely reflects the capitalization of scarcity rents rather than new value creation. It represents a redistribution from junior right holders who lose access to senior right holders who retain it. Our approach instead focuses on reduced agricultural land rents due to more uncertain water supplies.

# 4 Data

We gather a dataset that links agricultural land transactions to the water access security associated with each property. Table (1) presents summary statistics for the variables used in our study. Our final sample consists of 3819 irrigated transactions representing 2877 unique properties. Of these transactions, 2397 are located within the South Platte, and 1422 are located within the Arkansas River Basin.

## Transaction data and property basics

We use transaction data of agricultural properties in Colorado from CoreLogic. We restrict the analysis to irrigated properties with arm's-length sales data and those that are not between family members. We impose additional restrictions to construct the estimation sample. Parcels below 10 acres and above 5,000 acres are excluded, as are sales with real prices exceeding $100,000 per acre and those below $100. Properties with improvement values greater than $500,000 are removed to limit the influence of residential or commercial structures on sale prices. We further require complete information on the land, soil, and water rights characteristics used in the analysis and restrict transactions to 1990 onward because the number of observations before that period is limited.

## Irrigated land

We determine whether a property is irrigated and identify its associated water diversion structure using spatial data from the Colorado Decision Support System (CDSS). The data identify each parcel's source of irrigation water and the structures through which water is delivered, including ditches, wells, and reservoirs.

Since our analysis concerns surface water allocation under prior appropriation, we exclude farms supplied exclusively by groundwater and retain parcels receiving surface water either alone or in combination with groundwater. Irrigated transactions are identified by matching CoreLogic sales locations to the 2020 CDSS irrigated-parcel layer. This linkage allows us to determine whether a property is irrigated and to associate it with the relevant water-delivery structure. For sales happening before 2020, the presence of irrigation in the CDSS

Table 1: Summary statistics

| Variable | Description | Mean | SD |
|---|---|---|---|
| Price | Real price per acre | 13831 | 17418 |
| **Water Rights Attributes** | | | |
| Curtailment | Weighted average curtailment of rights (2005–2022) | 31.6 | 15.2 |
| Groundwater | Dummy variable for groundwater | 0.36 | 0.48 |
| Storage | Dummy for storage reservoirs | 0.68 | 0.46 |
| Seniority | Weighted mean of water rights seniority | 1896.8 | 24.1 |
| **Other variables** | | | |
| Improvements | Dollar value of improvements ($1000) | 77.4 | 136 |
| Building area | Area of buildings on property (square feet) | 1343 | 6310 |
| Pastureland | Dummy for pastureland | 0.012 | 0.14 |
| Clay | Average clay | 25.7 | 9.7 |
| Sand | Average sand | 37.6 | 19.6 |
| Silt | Average silt | 35.4 | 14 |
| Slope | Average slope | 2.1 | 2.1 |
| Soil hydraulic conductivity | Average Ksat | 14.3 | 25.7 |
| Erodability | K-factor | 0.28 | 0.08 |
| Growing season precip | Mean growing season precipitation (mm) | 44.7 | 6.3 |
| Growing season temp | Mean growing season temperature (°C) | 17.7 | 1.4 |
| Distance to small city | Distance to nearest small city | 29.2 | 35.8 |
| Distance to big city | Distance to nearest big city | 41.6 | 38.5 |
| Observations | | 3,819 | |

*Notes:* All nominal prices are adjusted to constant 2022 dollars using the Consumer Price Index.

layer provides evidence that the land continued to be irrigated under that structure at the time of sale, supporting the interpretation that the associated water rights were part of the agricultural property transaction. Figure 6 shows the transactions included in the analysis.

## Water rights and curtailments

We obtain water right records from CDSS and link them to the diversion structures serving the irrigated parcels in our sample. Each water right contains information on the source and authorized use of water, the point of diversion, decreed quantity, appropriation date, and adjudication date.[3] The administrative ordering of these rights is summarized by the Priority Administration Number (PAN), which provides a common ranking of water rights for administration.[4]

[3]The adjudication date identifies when the water right was formally recognized through the water court process.

[4]The PAN is calculated as the number of days between the legally relevant priority date and December 31, 1849. For rights subject to the postponement doctrine, the previous adjudication date rather than the original appropriation date determines this ranking. We convert PAN from days to years for ease of interpretation.

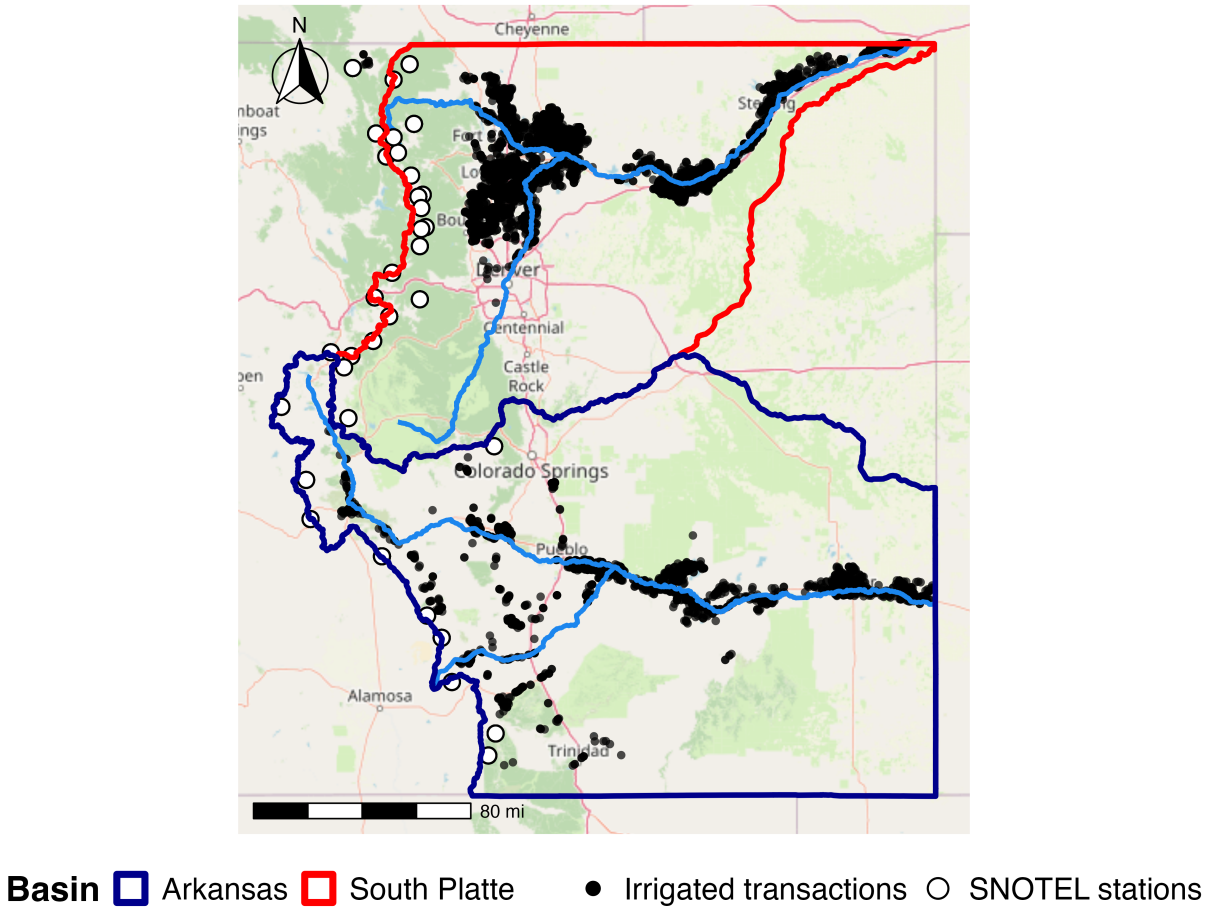



Figure 6: Location of snotel stations and irrigated transactions

A diversion structure or an irrigation company generally possesses multiple rights rather than a single one. We therefore characterize each structure using its entire irrigation right portfolio. To summarize its position in the priority system, we calculate a flow-weighted average of the PANs associated with the structure, weighting individual rights by their decreed cfs amounts. This aggregation places greater weight on rights representing larger shares of the structure's direct-flow water rights.

Our analysis uses net absolute irrigation rights associated with each structure. We exclude conditional rights, which have been decreed but have not yet been perfected through beneficial use. Rights recorded in cubic feet per second are treated as direct-flow rights, whereas decrees expressed in acre-feet are classified as storage rights. Because some direct-flow decrees also authorize storage, we additionally use the beneficial use information contained in the water right records to identify structures with access to storage. The amount legally available at a structure reflects its net absolute decree at the primary diversion point together with applicable alternate point and exchange rights.

After identifying the surface water rights portfolio for each property, we construct a curtailment exposure measure based on historical records of administrative calls during the irrigation season. Using daily curtailment records from CDSS, we first compute, for each

water right, the mean share of each day that the right is out of priority during the growing season (April 1–November 1) in each year. We then aggregate across all rights associated with a given diversion structure using a cfs-weighted average, so that rights with larger decreed or decreed flow receive higher weight.

Because hedonic land values reflect forward-looking assessments of water access security, we summarize curtailment exposure using a long-run average rather than a single year observation. Specifically, we average growing-season curtailment rates over 2005–2022, the period of daily curtailment data availability across both river basins.

## Snowpack

Data on snowpack are sourced from the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Snow Telemetry (SNOTEL) network. The SNOTEL system provides high-frequency, daily observations of snow water equivalent (SWE), precipitation, and temperature at high-elevation sites across the country. For this analysis, we utilize daily SWE observations from all active stations located within our study area. Figure Appendix 8.1 illustrates a SNOTEL site in the Rocky Mountains of Colorado. To capture the hydrological conditions most relevant to water availability during the irrigation season, we restrict the sample to the months of January through May, the period during which peak snowpack typically accumulates before spring runoff begins.

The raw daily data are processed through a two-stage aggregation to ensure compatibility with the curtailments data. First, we compute the annual mean SWE for each station based on the January–May observation window. Second, we spatially assign each station to its respective Colorado water division using official administrative boundaries. These station-level means are then aggregated to the division-year level by calculating the average across all stations within a given water division. This division-level SWE metric serves as our primary proxy for basin-wide water supply, capturing the interannual hydrologic variability that determines the frequency and severity of administrative calls within the prior appropriation system. Formally, the annual snowpack for division d in year t is calculated as:

$$\text{SWE}_{dt} = \frac{1}{N_d} \sum_{s=1}^{N_d} \left( \frac{1}{M} \sum_{m=1}^{M} \text{SWE}_{smt} \right), \tag{3}$$

where $\text{SWE}_{smt}$ denotes daily snow water equivalent at station s on day in year t, M is the number of daily observations between January and May, $\text{N}_d$is the total number of SNOTEL stations located within water division d, and $\text{SWE}_{dt}$ represents the division-level annual mean snowpack used in the analysis.

## Other control variables

Our hedonic model accounts for several characteristics of agricultural property that may independently affect prices. These include whether the property is pastureland, the value of improvements, the presence and size of permanent buildings, soil quality, and proximity to major urban areas. CoreLogic provides parcel acreage, improvement value, building square footage, and land-use information. We obtain soil characteristics from the NRCS Soil Survey

Geographic Database (SSURGO). These controls include slope, clay, sand, and silt shares; saturated hydraulic conductivity ($K_{sat}$); soil erodibility; organic matter; and available water storage to a depth of 100 centimeters.

We account for urban influences on agricultural land values by controlling for proximity to nearby population centers. Using population and location data from the U.S. Census Bureau, we calculate each parcel's distance to the nearest city with more than 50,000 residents and to the nearest city with between 10,000 and 50,000 residents. These measures control for spatial differences in market access and the potential influence of nearby urban development on agricultural land prices.

Climate projections are pulled from the U.S. Geological Survey's National Climate Change Viewer (NCCV) CMIP6–LOCA2 dataset (Alder and Hostetler, 2013). The LOCA2 projections are based on statistically downscaled CMIP6 global climate model outputs using the Localized Constructed Analogs method and include bias correction following Pierce et al. (2023). We use the weighted multi-model mean for the South Platte (HUC 1019) and the Upper Arkansas (HUC 1102) watersheds. Historical conditions (1950–2014) are drawn from the CMIP6 historical experiment, and future projections (2015–2100) correspond to SSP2-4.5, SSP3-7.0, and SSP5-8.5. We extract basin-level snow water equivalent (SWE) from the gridded monthly water balance projections.

# 5 Empirical model

Our objective is to estimate the economic cost of climate-driven reductions in snowpack for irrigated agriculture. We do so by connecting two sets of empirical relationships. We first investigate how snowpack levels affect water right curtailments. We then estimate how long-run curtailment risk is capitalized into irrigated land values.

## Snowpack and Curtailments

We first estimate how basin-level snowpack translates into annual curtailment outcomes across diversion structures with differing water-right portfolios. Annual average snow water equivalent (SWE) from the SNOTEL network is aggregated to the river-basin level and matched to the annual curtailment measure for each diversion structure.The empirical model is specified as:

$$\begin{aligned} Curtailment_{ibt} = {} & \alpha_1 \text{Snowpack}_{bt} + \alpha_2 \text{Seniority}_i + \alpha_3 (\text{Snowpack}_{bt} \times \text{Seniority}_i) \\ & + \alpha_4 (\text{Snowpack}_{bt} \times Basin_b) + \alpha_5 (\text{Seniority}_i \times Basin_b) \\ & + \alpha_6 (\text{Snowpack}_{bt} \times \text{Seniority}_i \times Basin_b) + \alpha_7 \text{Stream mile}_i \\ & + \lambda_s + \delta_t + \epsilon_{ibt}. \end{aligned} \tag{4}$$

Here, $\text{Curtailment}_{ibt}$ represents the cfs-weighted average share of the growing sesaon during which water rights associated with diversion structure $i$ in basin $b$ are curtailed in year $t$. $\text{Snowpack}_{bt}$ is the average SWE across SNOTEL stations in basin b and year t. and $\text{Seniority}_i$ is the weighted average appropriation year of water rights associated with

structure $i$. Stream fixed effects ($\lambda_s$) control for spatial variation within individual water stream, and year fixed effects ($\delta_t$) capture statewide shocks.

Because our model includes interactions between snowpack, seniority, and basin, the effect of snowpack on curtailment depends on both the seniority of the water right and the basin in which it is located. In the South Platte Basin, the marginal effect of snowpack is given by $(\alpha_1 + \alpha_3 \times \text{Seniority}_i)$, while in the Arkansas Basin it is given by $[(\alpha_1 + \alpha_4) + (\alpha_3 + \alpha_6) \times \text{Seniority}_i]$. We therefore interpret the snowpack effect using these basin-specific marginal effects rather than the coefficient on snowpack alone. The interaction coefficient $\alpha_3$ captures how the sensitivity of curtailment to snowpack varies with water-right seniority in the South Platte Basin, while $\alpha_6$ captures how the sensitivity of the snowpack effect to seniority differs in the Arkansas Basin. The coefficient $\alpha_4$ allows the snowpack–curtailment relationship to differ across basins, and $\alpha_5$ allows the relationship between seniority and curtailment to vary across basins. Finally, $\alpha_7$, together with stream fixed effects, captures upstream–downstream differences in curtailment among rights located along the same stream.

## Curtailments and Land Values

We next use a hedonic pricing framework to estimate the market valuation of long-run curtailment risk. Land prices reflect the discounted value of expected returns from the parcel, including the value of the water right portfolio associated with it. Properties facing a lower probability of curtailment are expected to trade at a premium relative to comparable parcels with higher curtailment risk. We estimate the following model:

$$Y_{it} = \beta_1 \text{Curtailment}_i + \beta_2 \text{Seniority}_i + \beta_3 X_i + \delta_c + \lambda_{bt} + \varepsilon_{it}, \tag{5}$$

where $Y_{it}$ is the natural log of real price per acre for property $i$ sold in year $t$, and $\text{Curtailment}_i$ is the long-run weighted average of the fraction of days in which any water right associated with property $i$ was out of priority between 2005 and 2022. Because land values reflect the present value of expected future returns (Section 3), we assume that forward-looking buyers primarily price curtailment risk based on expected future water availability, rather than on curtailment realized in the particular year of sale. We use each parcel's long-run average curtailment rate as a proxy for this expectation, which requires that the current distribution of long-run curtailment risk provide a reasonable approximation of the distribution of future curtailment risk buyers anticipated at the time of purchase, even as realized curtailment fluctuated year to year with hydrologic conditions. $Seniority_i$ is the weighted average priority year of water rights corresponding to property $i$. The vector $X_{it}$ includes parcel-level characteristics such as groundwater and storage reservoir access, dummy for pastureland, dollar value of improvements on the property, area of buildings on property, distance to big and small cities, and soil quality measures. County fixed effects ($\delta_c$) absorb time-invariant unobserved heterogeneity in local land markets, and basin-year fixed effects ($\lambda_{bt}$) control for time-varying shocks specific to different years in different river basins. The coefficient $\beta_1$ captures the capitalization of curtailment risk into agricultural land values, with $(e^{\beta_1} - 1) \times 100$ representing the percentage change in land value associated with a one-percentage-point increase in long-run curtailment risk.

A potential identification concern arises because variation in curtailment risk is closely

related to water rights seniority. Under prior appropriation, senior rights are less likely to be curtailed, but senior appropriators may also have selected more productive land or settled in locations later found to be advantageous for reasons unrelated to water rights per se. If these land characteristics are not fully observed, curtailment risk will be correlated with unobserved determinants of land value. In that case, the estimated coefficient on curtailment risk would conflate both the effect of water access insecurity and differences in underlying land quality associated with seniority.

Our identification strategy addresses this by exploiting variation in curtailment exposure among parcels of similar seniority. Conditioning on seniority removes both the mechanical link between priority date and curtailment frequency and the potential, historical selection channel through which early appropriators may have obtained more productive land (Bahrami et al., 2026; Edwards et al., 2025). The remaining variation arises because parcels with similar priority dates do not necessarily face the same administrative calls. Whether a right is curtailed depends on its priority relative to a senior downstream calling right and on whether curtailing that right would deliver additional water to the caller.[5] Our identifying assumption is that, conditional on seniority, parcel characteristics, county fixed effects, and basin-by-year fixed effects, this residual variation in curtailment risk is not systematically correlated with unobserved determinants of agricultural land value.

# 6 Results

In this section, we first show the estimated relationship between snowpack and water right curtailments. We then present the marginal value of water access security through curtailment risk and examine producers' adaptation margins in response to curtailment. Finally, we estimate the loss of wealth resulting from the future decline in snowpack in the study area under different climate change scenarios.

## Relationship between snowpack and curtailments

Table 2 reports estimates of Equation 4, which models annual water-right curtailments as a function of basin-level snowpack, water right seniority, and the relative location of the diversion along a stream (stream mile).

Column (1) presents the baseline relationship between snowpack (SWE) and curtailment. Column (2) adds water-right seniority. Column (3) introduces stream fixed effects, ensuring that comparisons are made among rights located along the same stream system and controls for stream mile. Column (4) further includes year fixed effects to control for time-varying factors common to all water rights, such as basin-wide water demand.

Across all specifications, higher snowpack is associated with significantly lower curtailment rates, while more junior rights experience substantially higher curtailment, consistent with priority-based allocation under the prior appropriation doctrine. In column (4), the

[5] A downstream call is non-futile with respect to an upstream junior right when curtailing the junior diversion is expected to increase the amount of water available to the calling right. If the division engineer determines that hydrologic conditions prevent the curtailed water from reaching the caller, the call is considered futile with respect to that junior right, and the right is not curtailed.

Table 2: Regression results for the relationship between snowpack and curtailment

| | Curtailment | | | | |
|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) |
| SWE | −0.076*** | −0.085*** | −0.119*** | −0.123*** | 1.352*** |
| | (0.005) | (0.004) | (0.005) | (0.010) | (0.458) |
| Seniority | | 0.433*** | 0.511*** | 0.511*** | 0.613*** |
| | | (0.015) | (0.016) | (0.014) | (0.081) |
| Stream mile | | | 0.061*** | 0.061*** | 0.057*** |
| | | | (0.007) | (0.007) | (0.007) |
| SWE × Seniority | | | | | −0.001*** |
| | | | | | (0.0002) |
| SWE × Arkansas Basin | | | | | 2.170*** |
| | | | | | (0.733) |
| Seniority × Arkansas Basin | | | | | 0.568*** |
| | | | | | (0.107) |
| SWE × Seniority × Arkansas Basin | | | | | −0.001*** |
| | | | | | (0.0004) |
| Year FE | - | - | - | ✓ | ✓ |
| Stream FE | - | - | ✓ | ✓ | ✓ |
| $N$ | 6,346 | 6,346 | 6,346 | 6,346 | 6,346 |
| Adjusted $R^2$ | 0.042 | 0.158 | 0.415 | 0.518 | 0.539 |

*Notes:* ***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

coefficient of −0.123 on SWE implies that a one-millimeter increase in basin-level snowpack reduces annual curtailment by 0.123 percentage points on average. The positive coefficient on stream mile indicates that rights located further upstream experience higher curtailment rates relative to downstream rights, holding other factors constant.

Column (5) allows the effect of snowpack to vary flexibly with both seniority and basin through interaction terms. The estimated coefficients indicate substantial heterogeneity. The negative coefficient on the SWE × Seniority interaction implies that improvements in snowpack reduce curtailment disproportionately for junior rights. Moreover, the basin interaction terms indicate that curtailment sensitivity to snowpack differs between the South Platte and Arkansas Basins. The triple interaction confirms that the slope of the snowpack–curtailment relationship varies systematically along the seniority distribution across basins.

Figure 7 plots the estimated marginal effect of snowpack on curtailment across the seniority distribution for each basin. The effect is negative throughout most of the observed seniority range and becomes larger in magnitude for more junior rights, indicating that junior rights are more sensitive to changes in snowpack. The figure also shows that this relationship

differs across the South Platte and Arkansas River Basins.

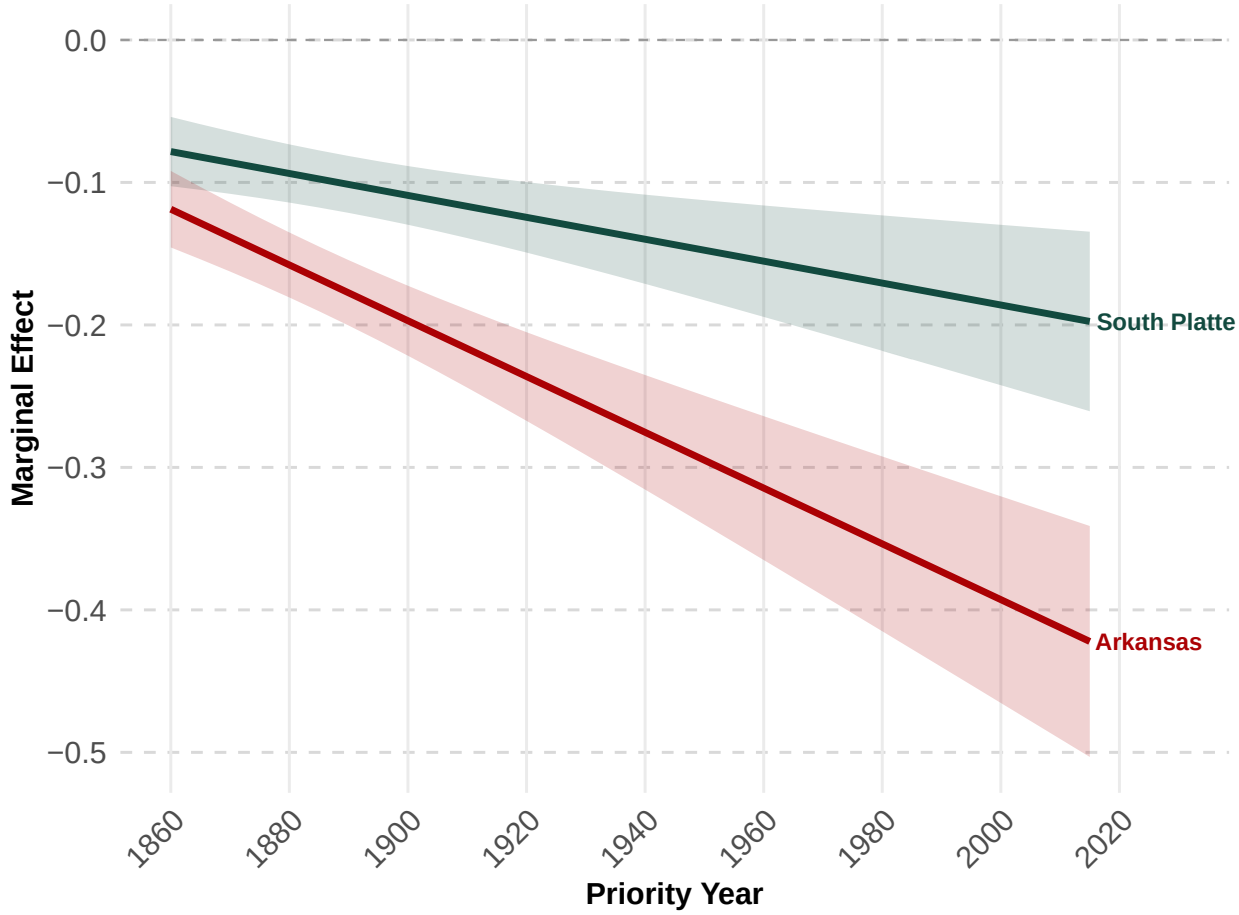



Figure 7: Marginal effect of snowpack on curtailments by seniority year

## Market valuation of curtailment risk

Table 3 presents hedonic regression estimates of the premium for higher security in water access. Column (1) reports the simplest specification that relates land values to average curtailment exposure, controlling for county and basin–year fixed effects. Column (2) extends this specification by including indicators for access to groundwater and storage reservoirs, along with a full set of parcel-level controls. In Column (3), which is our preferred specification, we further control for the seniority of water rights to identify the effect of variation in curtailment risk among parcels with rights of similar seniority.

Across all three specifications, the coefficient on curtailment exposure is negative and significant, and is stable in magnitude as controls are added and seniority is conditioned. The negative and significant relationship indicates that land markets capitalize the reliability of water access. Specifically, a one–percentage-point increase in average curtailment decreases irrigated land value by 0.8% or $106 per acre of irrigated land. Applying this coefficient to

one standard deviation of curtailment exposure in our sample (15 percentage points) implies a decline of approximately $1,590 per acre.

The negative coefficient on priority implies that parcels holding more senior rights are more valuable, although this relationship is imprecisely estimated after controlling for curtailments. Access to groundwater is associated with a significant premium of approximately 20%, while access to storage is associated with a premium of about 11%, although the estimate is not statistically significant at the 5% level. Including groundwater and storage variables in column 2 does not significantly change the coefficient of curtailments. We show the full set of coefficients in Table Appendix 8.1, and basin-specific estimates in Tables Appendix 8.2 and Appendix 8.3.

Table 3: Hedonic estimate of curtailment risk

| | Log real price per Acre | | |
|---|---|---|---|
| | (1) | (2) | (3) |
| Average growing season curtailments | −0.010*** | −0.009*** | −0.008*** |
| | (0.002) | (0.001) | (0.002) |
| Average Water rights seniority | | | −0.001 |
| | | | (0.001) |
| Groundwater | | 0.192** | 0.192** |
| | | (0.097) | (0.096) |
| Storage | | 0.103* | 0.109* |
| | | (0.062) | (0.063) |
| Division-Year FE | Yes | Yes | Yes |
| County FE | Yes | Yes | Yes |
| Controls | No | Yes | Yes |
| Seniority | No | No | Yes |
| *N* | 3,819 | 3,819 | 3,819 |
| Adjusted $R^2$ | 0.329 | 0.381 | 0.381 |

*Notes:* ***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

## Mechanisms: Crop Choice and Irrigation Technology

The capitalization results indicate that persistent curtailment risk is associated with lower agricultural land values. We examine two margins through which curtailment imposes costs on producers: crop choice and irrigation technology. Producers facing greater long-run curtailment exposure may respond by shifting toward less water-intensive crops (Cobourn et al., 2022) or investing in more efficient irrigation technology.

To examine these mechanisms, we link observed crop choice and irrigation technology in 2010, 2015, and 2020 to long-run curtailment exposure, measured as the average curtail-

ment rate over 2005–2022. We use long-run curtailment exposure as a proxy for farmers' expectations about future water availability. For each outcome, we estimate:

$$Y_i = \alpha + \theta \text{Curtailment}_i + \delta_d + \epsilon_i \tag{6}$$

where $Y_i$ is an indicator for the crop grown on parcel $i$ or for the use of sprinkler irrigation, $\text{Curtailment}_i$ is the parcel's long-run average curtailment rate over 2005–2022, and $\delta_d$ denotes water-district fixed effects. We estimate Equation 6 separately for each crop and also for sprinkler irrigation adoption. The coefficient $\theta$ represents the percentage-point change in the probability of observing a given outcome associated with a one-percentage-point increase in long-run curtailment risk.

Figure 8 presents estimates using the 2020 observations. Higher long-run curtailment exposure is associated with a higher probability of sprinkler irrigation, consistent with producers engaging in defensive investments to mitigate water supply risk. Curtailment exposure is also associated with changes in crop choice. In particular, parcels facing greater curtailment risk are less likely to be planted in corn and hay or pasture, while the probability of leaving land fallow increases substantially along with the probability of growing wheat, which is a less water-intensive crop.[6] For other crops, including alfalfa, sorghum, small grains, and beans, the estimated relationships are comparatively small.

## Simulating the Cost of Snowpack Decline

We combine the estimated relationship between snowpack and curtailment with the capitalization of long-run curtailment risk into agricultural land values to quantify the welfare loss from future snowpack decline. These estimates come from two separate sources of variation. The hedonic estimate (Equation 5) captures differences in long-run curtailment exposure across properties and therefore reflects how persistent water-supply risk is capitalized into land values. The Ricardian basis of this approach allows the capitalization estimate to incorporate farmers' long-run adaptation to curtailment risk (Mendelsohn et al., 1994). In contrast, the snowpack–curtailment estimates (Equation 4) are identified from interannual, short-run variation in snowpack and realized curtailments.

Our simulation therefore relies on the assumption that the marginal relationship between snowpack and curtailment observed from year-to-year variation provides a reasonable approximation to how a persistent shift in the mean of snowpack alters long-run curtailment risk. This assumption allows producers to adapt to water scarcity–the land value estimates incorporate such adaptation–but assumes that these responses do not fundamentally change the mapping from basin-level water availability to priority-based curtailment. We view this as a reasonable assumption since curtailment is triggered when available water is insufficient to satisfy senior claims, and water conserved through adaptation margins by junior users generally remains valuable to other appropriators within the river system rather than going unused. Long-run adaptation then changes how the economic costs of curtailment are absorbed across producers, but is unlikely to change the underlying hydrologic and institutional

[6]The fallow result is estimated using data from the Arkansas River basin only, where fallow land is identified in the crop data.

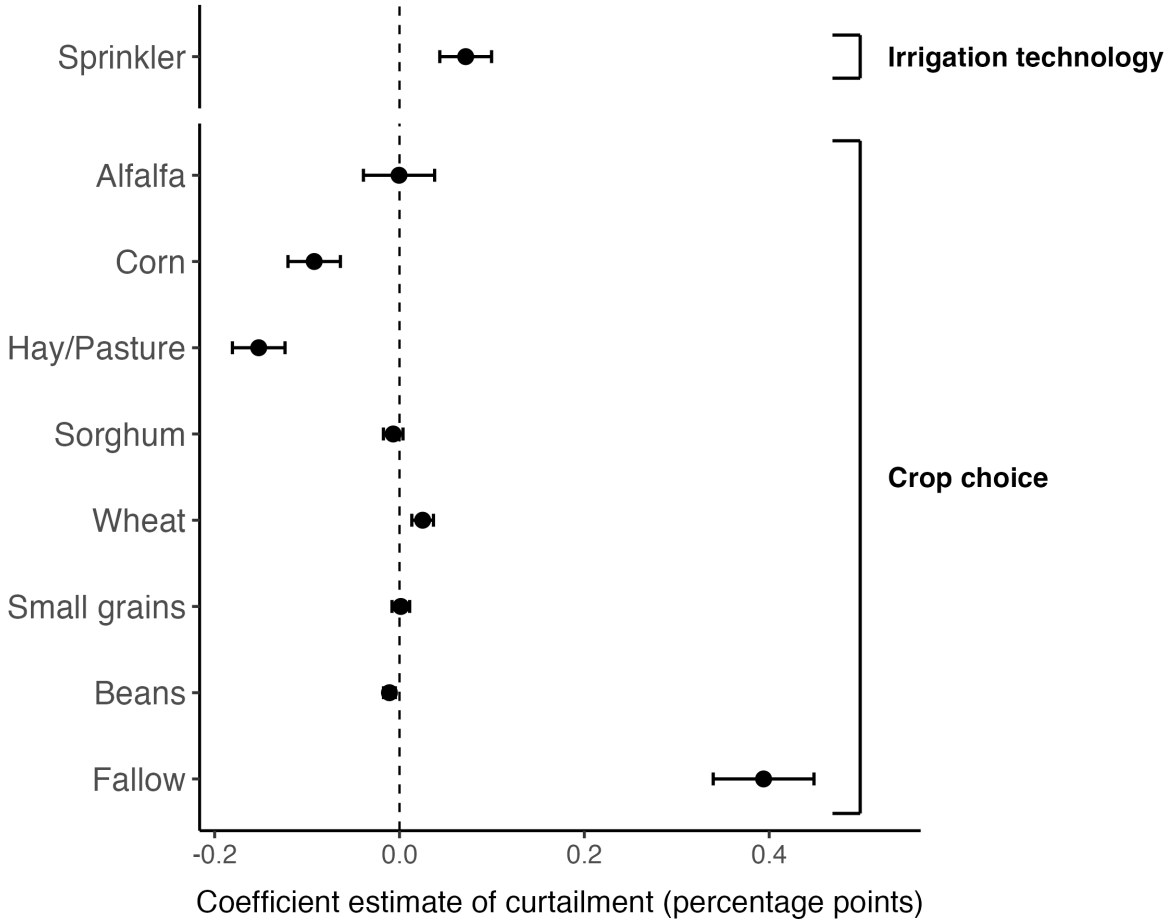



Figure 8: Effect of long-run curtailment exposure on irrigation technology adoption and crop choice. Points show estimated change in outcome probability (percentage points) associated with a one percentage-point increase in curtailment risk; bars show 95% confidence intervals. Sample restricted to 2020 outcomes, $N = 34{,}767$.

relationship between basin-level snowpack and the probability that a surface water right is curtailed, conditional on a relatively stable priority distribution.[7]

One limitation worth acknowledging is that over longer horizons, water rights transfers through markets or other institutional adjustments could alter the spatial distribution of demand and the set of rights exposed to curtailment. Our simulations do not incorporate these general-equilibrium adjustments and should therefore be interpreted as the cost of projected snowpack decline under the existing water-allocation regime and the historical relationship between snowpack and curtailment.

[7]Ditch companies may adapt by acquiring storage rights or by making their conditional storage rights absolute, upon completion of reservoir projects. However, storage rights are themselves administered under the prior appropriation system and generally hold priorities far junior to many existing direct-flow surface water rights. Such adjustments may improve the timing and reliability of water deliveries within the adapting ditch company, but they do not change the priority dates of other existing surface-water rights or the order in which those rights are curtailed.

## Simulation process

We use projections from the CMIP6 ensemble under three Shared Socioeconomic Pathways (SSP2–4.5, SSP3–7.0, and SSP5–8.5) to predict mid-century changes in basin-level snowpack. Figure 9 illustrates the projected evolution of snowpack in the South Platte and Arkansas River Basins across scenarios, while Table 4 reports the corresponding percentage changes over the 2025–2050, 2025–2075, and 2025–2100 horizons.

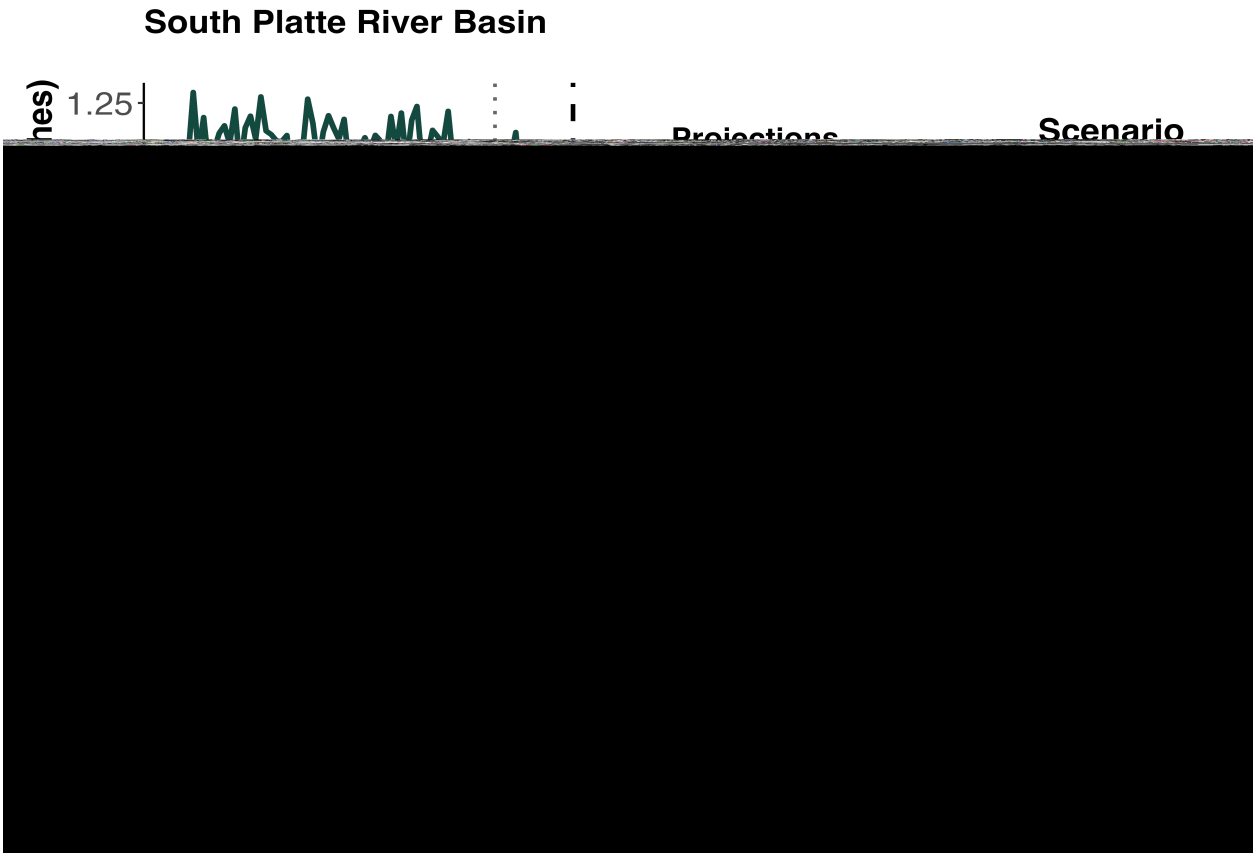



Figure 9: Historical and projected SWE trends

Table 4 shows that under SSP2–4.5, average January–May SWE declines by approximately 22 percent in both basins over the 2025–2050 period. Projected declines become larger over longer horizons and under higher-emissions scenarios.

Because the SNOTEL and LOCA2 SWE measures differ in their spatial aggregation and units, we use the LOCA2 projections only to obtain the percentage change in basin-level SWE. We then apply this percentage change to the historical SNOTEL mean used in the estimation sample to construct $\Delta \text{SWE}_b$ in the same units as Equation 4.

We next translate these projected changes in snowpack into changes in farm-level water availability. Using the estimated coefficients from Equation 4, we compute the implied change in curtailments for each water right as:

Table 4: Projected changes in average SWE relative to 1990–2015 baseline

| Basin | Scenario | Baseline (1990–2015) | %Δ 2025–2050 | %Δ 2025–2075 | %Δ 2025–2100 |
|---|---|---|---|---|---|
| South Platte | SSP2–4.5 | 1.030 | -21.7 | -26.7 | -33.8 |
| South Platte | SSP3–7.0 | 1.030 | -20.3 | -35.6 | -45.1 |
| South Platte | SSP5–8.5 | 1.030 | -25.9 | -39.3 | -55.7 |
| Arkansas | SSP2–4.5 | 0.841 | -22.5 | -26.3 | -32.3 |
| Arkansas | SSP3–7.0 | 0.841 | -20.3 | -34.7 | -44.8 |
| Arkansas | SSP5–8.5 | 0.839 | -25.2 | -38.5 | -54.6 |

Notes: Baseline values are average annual (January-May) snow water equivalent (SWE; inches) over 1990–2015. Percent changes are computed relative to the basin–scenario baseline.

$$\Delta\widehat{\text{Curtailment}}_{ib} = \Delta\text{SWE}_b \times \begin{cases} \alpha_1 + \alpha_3 \text{AppYear}_i, & \text{if } b = \text{South Platte}, \\ (\alpha_1 + \alpha_4) + (\alpha_3 + \alpha_6)\text{AppYear}_i, & \text{if } b = \text{Arkansas}. \end{cases} \tag{7}$$

where the marginal effect of snowpack varies with the seniority of the water right and the basin in which it is located. We then translate the predicted change in curtailment into a change in parcel value using the estimated capitalization coefficient $\beta_1$ from Equation 5. The resulting change in log land price for parcel $i$ is given by:

$$\Delta \log(\widehat{P}_i) = \beta_1 \times \Delta\widehat{\text{Curtailment}}_{ib}. \tag{8}$$

To aggregate these effects across the study area, we apply the parcel-specific proportional changes to the full sample of irrigated agricultural land in the South Platte and Arkansas River Basins rather than only to properties observed in the transaction sample. Because market transaction prices are observed only for a subsample of properties, we use county tax-assessed agricultural land values to construct baseline parcel values. Assessed values are systematically below observed transaction prices because agricultural assessments are based primarily on agricultural use rather than market valuation. We therefore compute basin-specific scaling factors equal to the median ratio of observed sale prices to assessed land values among transacted parcels and apply these multipliers to all irrigated parcels to construct market-consistent baseline values.

For each parcel, the dollar change in land value is

$$\Delta\widehat{V}_i = V_i^0 \left[\exp\left(\widehat{\beta}_{\text{curtail}}\Delta\widehat{\text{Curtailment}}_i\right) - 1\right], \tag{9}$$

where $V_i^0$ denotes the estimated baseline market value of parcel $i$. We then aggregate parcel-level changes within each basin:

$$\Delta\widehat{V}_b = \sum_{i \in b} \Delta\widehat{V}_i. \tag{10}$$

This aggregation preserves heterogeneity in both projected curtailment exposure and baseline agricultural land values across parcels. To characterize estimation uncertainty in these

projections, we draw 5,000 parameter vectors from the joint asymptotic distribution of the snowpack–curtailment coefficients and independently draw the curtailment-capitalization coefficient from its estimated sampling distribution. For each draw, we recompute parcel-level curtailment changes and aggregate land-value losses. We report the 2.5th and 97.5th percentiles of the resulting distribution of $\Delta\widehat{V}_b$ as the 95% confidence interval.

## Simulation Results

Figure 10 shows the distribution of predicted changes in curtailment risk obtained by applying the estimated snowpack–curtailment relationship in Equation 4 to the SSP2–4.5 projected change in basin-level snowpack over the 2025–2050 horizon. The same basin-level decline in snowpack generates considerably larger increases in curtailment risk for junior than for senior rights. On average, the increase in curtailment risk is 53% larger for rights in the most junior quartile of the seniority distribution than for those in the most senior quartile.

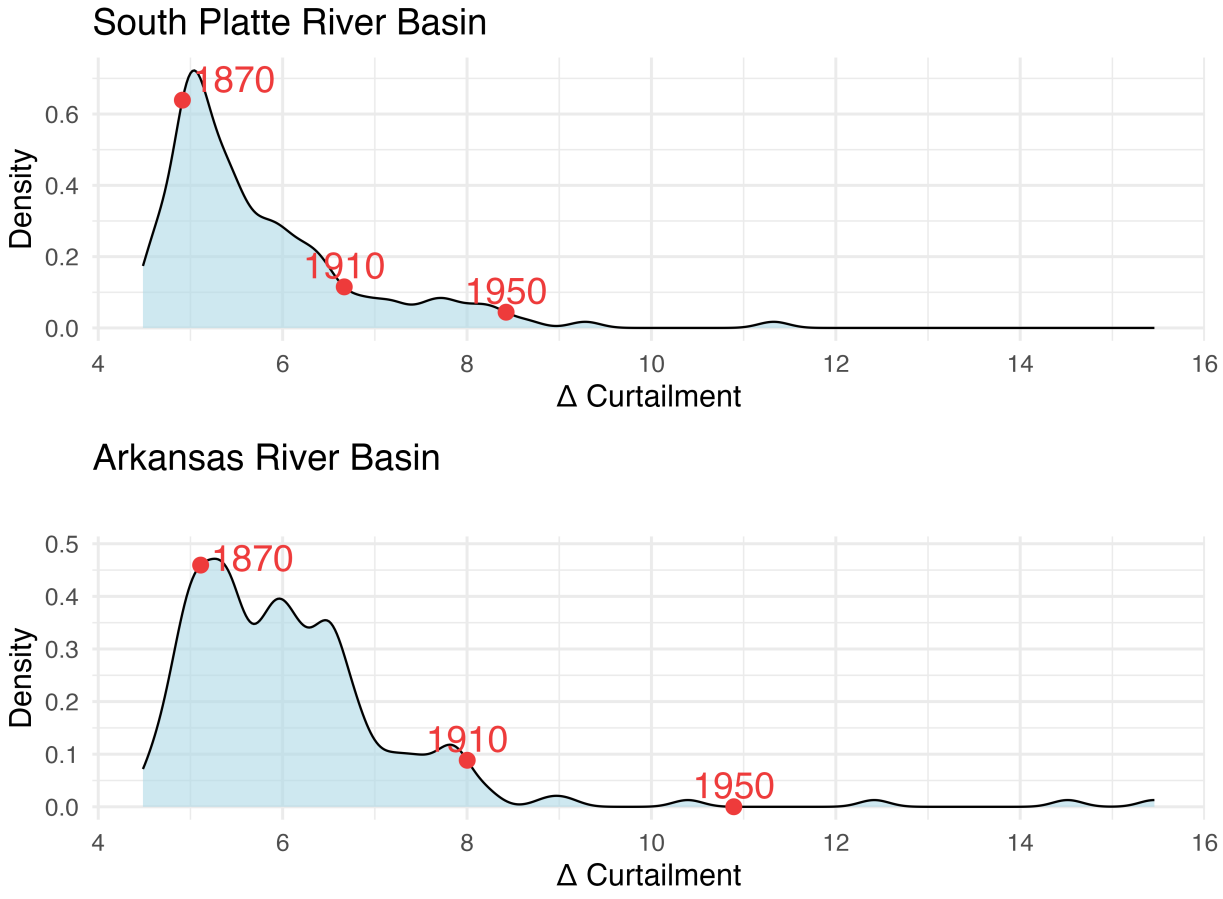



Figure 10: Predicted changes in curtailment risk under SSP2–4.5 for the 2025–2050 horizon.

Table 5 reports the projected losses in irrigated agricultural land value under SSP2–4.5. By mid-century, estimated losses amount to approximately $124 million in the Arkansas River Basin and $852 million in the South Platte River Basin, corresponding to declines

of 6.5 percent and 4.7 percent, respectively. Although the proportional decline is larger in the Arkansas Basin, the aggregate dollar loss is substantially greater in the South Platte because the total value of irrigated agricultural land is considerably larger. Projected losses increase over longer horizons as snowpack continues to decline, reaching approximately $176 million in the Arkansas Basin and $1.31 billion in the South Platte Basin by 2100 under SSP2–4.5. Results under SSP3–7.0 and SSP5–8.5, reported in Appendix Table Appendix 8.4, show larger late-century losses under more severe declines in snowpack.

Table 5: Projected losses in irrigated agricultural land value under SSP2–4.5

| Basin | Horizon | Loss ($ Billion) | % Loss |
|---|---|---|---|
| Arkansas River Basin | 2050 | 0.124 [CI: 0.067–0.181] | 6.54 [CI: 3.55–9.58] |
| | 2075 | 0.144 [CI: 0.079–0.211] | 7.61 [CI: 4.15–11.12] |
| | 2100 | 0.176 [CI: 0.096–0.256] | 9.28 [CI: 5.08–13.49] |
| South Platte River Basin | 2050 | 0.852 [CI: 0.451–1.295] | 4.66 [CI: 2.47–7.08] |
| | 2075 | 1.040 [CI: 0.552–1.576] | 5.68 [CI: 3.02–8.61] |
| | 2100 | 1.310 [CI: 0.698–1.977] | 7.16 [CI: 3.82–10.81] |

*Notes:* Dollar losses are expressed in billions of 2022 dollars. Bracketed values report 95% confidence intervals obtained from 5,000 parametric simulations that propagate estimation uncertainty in both the snowpack–curtailment and curtailment–land-value relationships.

The economic costs of snowpack decline presented above are also heterogeneous across the seniority distribution. Table 6 shows that, for instance, for the SSP2–4.5 mid-century projection, parcels in the most junior quartile experience a 5.7% decline in land value, compared with 3.8% for parcels in the most senior quartile, implying a roughly 51% larger proportional loss for junior rights. Despite this larger proportional effect, the most senior quartile accounts for 54% of aggregate dollar losses because it represents nearly 60% of baseline irrigated land value.

Table 6: Distribution of projected Land-value losses by water right seniority

| Seniority quartile | Share of baseline value (%) | Share of total loss (%) | Land-value loss (%) |
|---|---|---|---|
| Q1: Most senior | 59.59 | 53.56 | 3.77 |
| Q2 | 12.36 | 12.83 | 4.35 |
| Q3 | 16.50 | 17.96 | 4.57 |
| Q4: Most junior | 11.56 | 15.65 | 5.68 |

*Notes:* Results correspond to the SSP2–4.5 mid-century projection. Seniority quartiles are defined using the weighted appropriation year of surface-water rights, with Q1 representing the most senior rights and Q4 the most junior. Land-value loss is the aggregate projected loss within each quartile expressed as a percentage of that quartile's baseline irrigated agricultural land value.

# 7 Discussion

The unprecedented 2026 snow drought across the western United States was approximately 4.4 times more likely under current climate conditions than under preindustrial conditions

(Marshall et al., 2026). Under a moderately high emissions scenario, the annual probability of a similarly severe snow drought is projected to rise from roughly 10% in the 2020s to 32% by the 2050s (Marshall et al., 2026). These trends highlight the importance of understanding not only the economic cost of snowpack decline, but also how existing water allocation institutions distribute these losses among water users with different property rights to water. In this paper, we quantify these costs in the context of Colorado's prior appropriation system. We first estimate how long-run curtailment risk is capitalized into irrigated agricultural land values, and then estimate how changes in snowpack affect curtailment risk across water rights with different seniority. Combining these relationships with climate projections allows us to quantify both the aggregate cost of future snowpack decline and its distribution across agricultural landowners with different levels of water right security.

First, we show that declining snowpack does not generate a uniform increase in water scarcity across irrigators. The prior appropriation system mediates the effect of a common hydrologic shock by protecting relatively senior rights while exposing junior rights to larger increases in curtailment risk. Under the SSP2–4.5 mid-century projection, the increase in curtailment risk is approximately 53% larger for rights in the most junior quartile of the seniority distribution than for those in the most senior quartile.

Second, we find that long-run exposure to curtailment risk is capitalized into agricultural land values. A one-percentage-point increase in the long-run probability of curtailment reduces irrigated land values by approximately 0.8 percent, equivalent to about $106 per acre in 2022 dollars, on average. This result indicates that land markets internalize persistent differences in the reliability of surface water access. Because agricultural land values reflect the discounted stream of expected returns to land, the estimated capitalization effect captures the long-run economic consequences of water-supply risk, including producers' ability to adjust production and investment decisions in response to that risk.

Third, combining the estimated snowpack–curtailment and curtailment–land-value relationships with CMIP6 projections, we quantify the economic cost of future snowpack decline. Under SSP2–4.5 at mid-century, projected losses in irrigated agricultural land value total approximately $976 million across our study area, with $852 million occurring in the South Platte River Basin and $124 million in the Arkansas River Basin. These losses correspond to declines of 4.7% and 6.5% of baseline irrigated land value in the South Platte and Arkansas Basins, respectively. Importantly, these aggregate costs are distributed unevenly across the distribution of water rights with different priority year. Parcels in the most junior quartile experience a projected 5.7% decline in land value, compared with 3.8% for parcels in the most senior quartile, implying a roughly 51% larger proportional loss for junior rights.

Much of the empirical literature linking economic activity to weather and climate focuses on production systems in which contemporaneous temperature and precipitation directly affect agricultural productivity. This framework is less well suited to irrigated agriculture in some areas in the western United States, where water available during the growing season depends importantly on snow accumulated months earlier and on the institutions governing how the resulting runoff is allocated. In these settings, the economic effect of a climatic shock is therefore mediated by both hydrology and allocation institutions. Our results show that this institutional layer matters. Under prior appropriation, seniority provides protection against declining water availability, while junior rights absorb larger increases in curtailment risk. Consequently, producers facing the same basin-level decline in snowpack can experience

substantially different economic losses depending on the seniority of their water rights.

It is worth noting that our estimates focus on only one component of the economic cost of snowpack decline, which is the loss in irrigated agricultural land value from less secure water access. Snowpack decline may impose additional costs through other channels that are outside the scope of this study. Reduced snowmelt can affect municipal and residential water supplies, reservoir operations, recreational activities, hydropower generation, aquifer recharge, and environmental flows needed to support ecosystems and endangered species. Furthermore, because snowmelt originating in the Rocky Mountains supplies water well beyond Colorado, these effects may extend to downstream users in other states. The aggregate economic cost of declining snowpack is therefore likely to extend well beyond the agricultural land value effects estimated here. Future research could quantify these additional margins and examine how they vary across sectors, basins, and downstream regions.

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# 8 Appendix



Figure Appendix 8.1: Lake Irene SNOTEL station in the Rocky Mountains of Colorado. Photograph by the author.

Table Appendix 8.1: Hedonic estimate of curtailment risk with full set of controls

| | Log real price per Acre | | |
|---|---|---|---|
| | (1) | (2) | (3) |
| Average growing season curtailments | −0.010*** | −0.009*** | −0.008*** |
| | (0.002) | (0.001) | (0.002) |
| Average water rights seniority | | | −0.001 |
| | | | (0.001) |
| Groundwater | | 0.192** | 0.192** |
| | | (0.097) | (0.096) |
| Storage | | 0.103* | 0.109* |
| | | (0.062) | (0.063) |
| Parcel size | | −0.002*** | −0.002*** |
| | | (0.001) | (0.001) |
| Precipitation | | 0.018** | 0.018** |
| | | (0.008) | (0.008) |
| Temperature | | −0.027 | −0.020 |
| | | (0.049) | (0.051) |
| Pastureland | | −0.371*** | −0.371*** |
| | | (0.114) | (0.114) |
| Improvements | | 0.001** | 0.001*** |
| | | (0.0002) | (0.0002) |
| Building area | | 0.00000* | 0.00000* |
| | | (0.00000) | (0.00000) |
| Distance to nearest small city | | −0.002 | −0.002 |
| | | (0.009) | (0.009) |
| Distance to nearest big city | | −0.009 | −0.009 |
| | | (0.008) | (0.008) |
| Clay | | 0.001 | 0.0005 |
| | | (0.003) | (0.003) |
| Sand | | 0.0001 | −0.0001 |
| | | (0.002) | (0.002) |
| Slope | | 0.004 | 0.004 |
| | | (0.011) | (0.011) |
| Conductivity | | 0.004*** | 0.004*** |
| | | (0.001) | (0.001) |
| Erodability | | −0.391 | −0.380 |
| | | (0.367) | (0.363) |
| Silt | | 0.008*** | 0.008*** |
| | | (0.002) | (0.002) |
| Organic matter | | 0.036 | 0.038 |
| | | (0.039) | (0.039) |
| Soil water storage capacity | | −0.012 | −0.013 |
| | | (0.013) | (0.013) |
| Division-Year FE | Yes | Yes | Yes |
| County FE | Yes | Yes | Yes |
| Controls | No | Yes | Yes |
| Seniority | No | No | Yes |
| $N$ | 3,828 | 3,819 | 3,819 |
| Adjusted $R^2$ | 0.329 | 0.381 | 0.381 |

*Notes:* ***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

Table Appendix 8.2: Hedonic model results with full set of controls (South Platte Basin)

| | *Dependent variable:* | | |
|---|---|---|---|
| | log(real_price_acre) | | |
| | (1) | (2) | (3) |
| Curtailments | $-0.014^{***}$ | $-0.012^{***}$ | $-0.011^{***}$ |
| | (0.003) | (0.002) | (0.004) |
| Priority year | | | $-0.001$ |
| | | | (0.001) |
| Groundwater | | 0.016 | 0.016 |
| | | (0.050) | (0.059) |
| Storage | | 0.025 | 0.023 |
| | | (0.066) | (0.073) |
| Farm size | | $-0.003^{***}$ | $-0.003^{***}$ |
| | | (0.0003) | (0.001) |
| Growing-season precipitation | | $0.043^{***}$ | 0.042 |
| | | (0.013) | (0.029) |
| Growing-season temperature | | $-0.123^{**}$ | $-0.109$ |
| | | (0.058) | (0.149) |
| Pastureland | | $-0.324^{**}$ | $-0.320^{*}$ |
| | | (0.158) | (0.174) |
| Improvements | | $0.0004^{***}$ | $0.0004^{**}$ |
| | | (0.0001) | (0.0002) |
| Building area | | $0.00000^{*}$ | $0.00000^{**}$ |
| | | (0.00000) | (0.00000) |
| Distance to nearest small city | | $-0.005$ | $-0.004$ |
| | | (0.006) | (0.011) |
| Distance to nearest big city | | $-0.016^{***}$ | $-0.015^{*}$ |
| | | (0.005) | (0.009) |
| Clay | | 0.003 | 0.003 |
| | | (0.004) | (0.004) |
| Sand | | 0.001 | 0.001 |
| | | (0.003) | (0.002) |
| Slope | | 0.015 | 0.014 |
| | | (0.012) | (0.015) |
| Conductivity | | $0.005^{***}$ | $0.005^{***}$ |
| | | (0.001) | (0.001) |
| Erodability | | $-0.668$ | $-0.647^{**}$ |
| | | (0.505) | (0.266) |
| Silt | | 0.006 | $0.006^{**}$ |
| | | (0.004) | (0.002) |
| Organic matter | | 0.026 | 0.029 |
| | | (0.037) | (0.052) |
| Water storage capacity | | 0.011 | 0.011 |
| | | (0.013) | (0.013) |
| Division-Year FE | ✓ | ✓ | ✓ |
| County FE | ✓ | ✓ | ✓ |
| Controls | – | ✓ | ✓ |
| Seniority | – | – | ✓ |
| Observations | 2,397 | 2,397 | 2,397 |
| Adjusted $R^2$ | 0.338 | 0.398 | 0.398 |
| *Note:* | | | $^{*}$p<0.1; $^{**}$p<0.05; $^{***}$p<0.01 |

Table Appendix 8.3: Hedonic model results with full set of controls (Arkansas River Basin)

| | *Dependent variable:* | | |
|---|---|---|---|
| | log(real_price_acre) | | |
| | (1) | (2) | (3) |
| Curtailments | −0.003 | −0.003 | −0.004 |
| | (0.005) | (0.002) | (0.003) |
| Priority year | | | 0.001 |
| | | | (0.003) |
| Groundwater | | 0.637*** | 0.633*** |
| | | (0.076) | (0.076) |
| Storage | | 0.319*** | 0.293*** |
| | | (0.071) | (0.074) |
| Farm size | | −0.002*** | −0.002*** |
| | | (0.0002) | (0.0002) |
| Growing-season precipitation | | 0.015** | 0.018** |
| | | (0.007) | (0.007) |
| Growing-season temperature | | −0.022 | 0.018 |
| | | (0.057) | (0.057) |
| Pastureland | | −0.550** | −0.525** |
| | | (0.238) | (0.235) |
| Improvements | | 0.002*** | 0.002*** |
| | | (0.0004) | (0.0003) |
| Building area | | 0.00001 | 0.00000 |
| | | (0.00001) | (0.00001) |
| Distance to nearest small city | | −0.022 | −0.028* |
| | | (0.015) | (0.015) |
| Distance to nearest big city | | 0.023 | 0.027* |
| | | (0.015) | (0.015) |
| Clay | | −0.005 | −0.004 |
| | | (0.010) | (0.010) |
| Sand | | 0.001 | 0.002 |
| | | (0.009) | (0.009) |
| Slope | | −0.026 | −0.018 |
| | | (0.018) | (0.018) |
| Conductivity | | 0.0002 | 0.0003 |
| | | (0.003) | (0.003) |
| Erodability | | 0.296 | −0.115 |
| | | (0.991) | (0.983) |
| Silt | | 0.011 | 0.014 |
| | | (0.010) | (0.010) |
| Organic matter | | 0.051 | 0.064 |
| | | (0.054) | (0.054) |
| Water storage capacity | | −0.044*** | −0.046*** |
| | | (0.016) | (0.016) |
| Division-Year FE | ✓ | ✓ | ✓ |
| County FE | ✓ | ✓ | ✓ |
| Controls | – | ✓ | ✓ |
| Seniority | – | – | ✓ |
| Observations | 1,422 | 1,422 | 1,422 |
| Adjusted $R^2$ | 0.238 | 0.297 | 0.330 |
| *Note:* | | *p<0.1; **p<0.05; ***p<0.01 | |

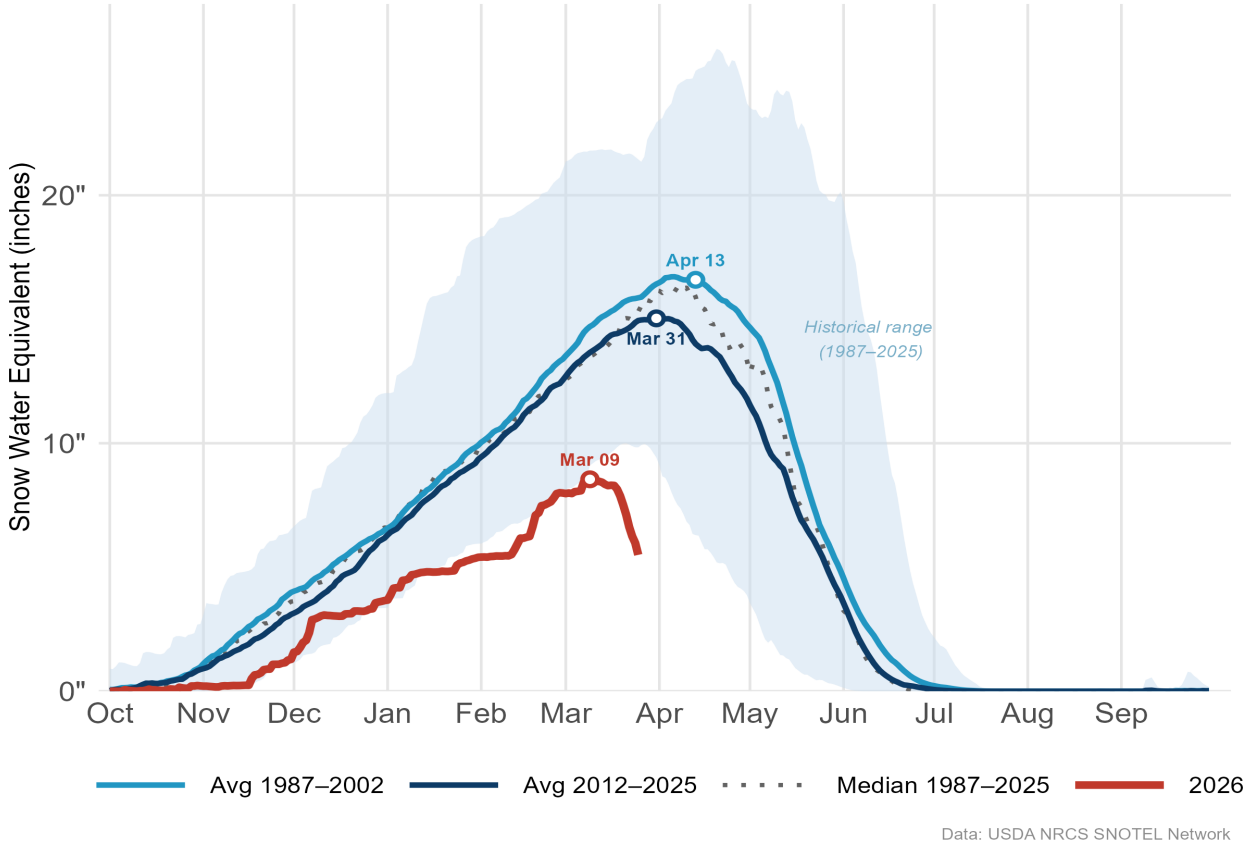



Figure Appendix 8.2: Daily Snow Water Equivalent in Colorado

Table Appendix 8.4: Projected losses in irrigated agricultural land value from snowpack decline

| Basin | Scenario | Horizon | Loss ($ Billion) | % Loss |
|---|---|---|---|---|
| *Arkansas River Basin* | | | | |
| | SSP2–4.5 | 2050 | 0.124 [CI: 0.067–0.181] | 6.54 [CI: 3.55–9.58] |
| | | 2075 | 0.144 [CI: 0.079–0.211] | 7.61 [CI: 4.15–11.12] |
| | | 2100 | 0.176 [CI: 0.096–0.256] | 9.28 [CI: 5.08–13.49] |
| | SSP3–7.0 | 2050 | 0.113 [CI: 0.061–0.165] | 5.94 [CI: 3.22–8.71] |
| | | 2075 | 0.188 [CI: 0.103–0.272] | 9.91 [CI: 5.43–14.38] |
| | | 2100 | 0.239 [CI: 0.132–0.344] | 12.60 [CI: 6.95–18.16] |
| | SSP5–8.5 | 2050 | 0.138 [CI: 0.075–0.202] | 7.30 [CI: 3.97–10.67] |
| | | 2075 | 0.207 [CI: 0.114–0.300] | 10.93 [CI: 6.00–15.81] |
| | | 2100 | 0.287 [CI: 0.159–0.410] | 15.13 [CI: 8.40–21.65] |
| *South Platte River Basin* | | | | |
| | SSP2–4.5 | 2050 | 0.852 [CI: 0.451–1.295] | 4.66 [CI: 2.47–7.08] |
| | | 2075 | 1.040 [CI: 0.552–1.576] | 5.68 [CI: 3.02–8.61] |
| | | 2100 | 1.310 [CI: 0.698–1.977] | 7.16 [CI: 3.82–10.81] |
| | SSP3–7.0 | 2050 | 0.799 [CI: 0.423–1.215] | 4.37 [CI: 2.31–6.64] |
| | | 2075 | 1.371 [CI: 0.732–2.068] | 7.49 [CI: 4.00–11.30] |
| | | 2100 | 1.730 [CI: 0.928–2.595] | 9.46 [CI: 5.07–14.18] |
| | SSP5–8.5 | 2050 | 1.011 [CI: 0.537–1.532] | 5.52 [CI: 2.93–8.38] |
| | | 2075 | 1.509 [CI: 0.807–2.271] | 8.25 [CI: 4.41–12.41] |
| | | 2100 | 2.109 [CI: 1.137–3.144] | 11.53 [CI: 6.22–17.18] |

*Notes:* Dollar losses are expressed in billions of 2022 dollars. Bracketed values report 95% confidence intervals obtained from 5,000 parametric simulations that propagate estimation uncertainty in both the snowpack–curtailment and curtailment–land-value relationships.