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RESEARCH ARTICLE

Conserving groundwater: Why irrigators chose to tax themselves

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At the turn of the century, irrigators in San Luis Valley (SLV), Colorado confronted a reality of precipitously dropping water levels of their shared groundwater resource stemming from their collective overextraction. Rather than continuing with business as usual—risking further declines and potential state intervention—they decided to self-organize and agreed to adopt a pumping fee, substantially increasing the cost of water—one of their key agricultural inputs. This innovative approach to conservation departs from those commonly championed by many groundwater stakeholders, who tend to favor conservation policies that decrease—not increase—costs, such as subsidizing more efficient irrigation technology or paying farmers to fallow their land. Despite few empirical examples of the introduction of a pumping fee, there are sound economic reasons to consider this approach. In this article, we review the adoption of this home-made policy, discussing the process and reasoning behind the stakeholders' choices, the economic theory that supports it, and some of the agricultural, hydrological, and social outcomes that have resulted from it. The case study illuminates the potential benefits of a groundwater fee but also highlights that policy choices are multifaceted and what works in one scenario does not imply it is a panacea. The article concludes with a discussion of a recent and surprising policy move: SLV farmers have decided to increase the primary groundwater pumping fee exponentially to $500 per acre-foot (10 times the original fee in 2009). We discuss how this new policy represents a shift from a Pigouvian tax structure to what resembles more of a cap-and-trade system. While the results of this latest policy innovation are still unknown, the eventual results promise to be instructive not only to SLV but also to other areas facing similar water scarcity issues.

Keywords: Groundwater, Economic incentives, Agriculture

1. Introduction

Irrigation has been a long-term adaptation strategy to increase yields in arid regions (Troy et al., 2015; Zhang et al., 2015; Tack et al., 2017; Zaveri and Lobell, 2019; Smith and Edwards, 2021). In the United States, despite irrigated acreage constituting just 14% of cropland (U.S. Department of Agriculture, 2024a), irrigated farms produce 50% of the nation's crops as measured by market value. Around 54% of the irrigated acreage in the United States relies on groundwater (U.S. Department of Agriculture, 2024b). Furthermore, the strategic importance of groundwater—the world's largest distributed store of freshwater—will continue to intensify with ongoing climatic changes (Taylor et al., 2013). Meanwhile, groundwater regulation has generally lagged that of surface water, leaving much groundwater to be an "open-access" resource, meaning that farmers who farm land over the aquifers are often free to install wells and then pump as they please (Edwards and Guilfoos, 2021). This has resulted in large drawdowns of aquifers worldwide (Rodell et al., 2018) and across the United States (Konikow, 2013). In efforts to move toward more sustainable extraction rates, many states in the United States now restrict the establishment of new wells and many regions have mandated (and sometimes subsidized) a variety of responses, such as the use of more efficient irrigation technology (Pfeiffer and Lin, 2014), subsidies to irrigators for fallowing their lands or retiring their water rights (Monger et al., 2018; Tsvetanov and Earnhart, 2020), or investments in groundwater recharge (Endo, 2015; Perrone and Rohde, 2016).

Irrigators in San Luis Valley (SLV), Colorado took a surprisingly different tack: Following a particularly dry period, punctuated by a severe drought in the 2002 (Pielke et al., 2005; Woodhouse and Lukas, 2006), they voluntarily increased their own costs to pump groundwater, roughly tripling the cost of one of their most critical inputs. The chosen approach defies much of the conventional wisdom when it comes to selecting policy instruments targeting farmers in the United States: Politicians and their farmer constituents prefer using soft economic incentives (subsidies) over hard cost increases (taxes). In this article, we unpack why the farmers decided to go against expectations and impose a tax on themselves.

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What were the political, economic, and hydrological factors that explain the self-taxation experiment? Since the implementation of the self-imposed pumping fee started in 2011, we also use 15-plus years of data to assess the effects of the policy and lessons learned so far.

Our 15-year analysis of the self-taxation experiment in the SLV offers 3 key insights into the local governance of shared resources. First, it identifies the main contextual factors driving farmers to self-regulate, highlighting the influence of irrigation associations and state officials. Second, it reveals why farmers favored self-taxation over less stringent alternatives. Finally, it examines the latest evolution of the experiment—a 10-fold tax increase—showing how it is increasingly mirroring a cap-and-trade system in both structure and function.

2. The challenge to govern groundwater commons

Groundwater use in the United States expanded immensely after 1940, thanks to advances in technology like centrifugal and submersible pumps, the advent of the center pivot irrigation systems, and lower energy costs. Tapping into previously inaccessible groundwater accounts for nearly 90% of the growth in crop production after 1950 in the Western United States (Edwards and Smith, 2018). Not only does groundwater increase yields on average, but it also provides resiliency to climate change—more so than surface water—and is now being deployed in the more humid Eastern United States as an adaptation to climate change (Smith and Edwards, 2021). Much of the historical development of groundwater occurred under unfettered open-access conditions.[1] Regulations have emerged to limit new entry, including by farmers, but it remains that only 36% of irrigation wells in the United States are even metered—a prerequisite for any pumping limitations—as of 2023 (U.S. Department of Agriculture, 2024b).

Shared aquifers are common-pool resources. By common-pool resources, we mean that the resource is rival in its consumption—namely, an irrigator's use of a unit of water precludes another from using the same unit[2]—and that the migratory nature of the water underground makes it difficult to exclude others from using the resource, even if new wells are no longer readily developed. In other words, an irrigator's claim to any specific unit of water is weak and they do not bear the full cost of extraction. For a group of profit-maximizing operations, this externality creates a system where the irrigators are prone to collectively draw more groundwater at any point in time than is collectively optimal. In the groundwater context, five related but distinct externalities of pumping groundwater are often discussed (Ayres et al., 2018): the pumping cost externality, or that one irrigator's pumping lowers the water table for others and increases their cost of extraction; the stock externality, or that the opportunity cost of future groundwater is undervalued as another irrigator may claim that unit; the risk externality, which is closely related to the stock externality but considers the quasi-option value of groundwater availability in unexpectedly dry or hot years; the strategic externality, or the behavior of irrigators knowingly pumping more to compete with other irrigators (not simply ignoring the costs imposed on them); and finally the physical changes, most often as land subsidence or, in coastal regions, saltwater intrusion. These all can lead to individual irrigators to extract more than we would consider optimal for society as a whole.

Generally, policies ignored these externalities for a long time. There were several reasons for such policy inaction. For one, it took time for researchers and policymakers to better understand the hydrologic behavior of different aquifers, including their connections to surface water (Sophocleous, 2002). Second, mischaracterization of aquifers led economists to assert that the gains from regulation were minimal and would barely justify the costs of imposing them (Gisser and Sanchez, 1980). Hydrologists continue to advance proper characterization of aquifers and economists are becoming more attentive, understanding that external effects can be more localized, making them more drastic and costly (Brozović et al., 2010). In short, rather than a "bathtub" of water, from which extraction would immediately drop the water level only slightly uniformly across the other users, groundwater extraction creates more localized cones of depression, leading to large externalities for other irrigators in the immediately surrounding area (see **Figure 1**). Furthermore, greater understanding of hydrology has also made it apparent that groundwater use often affects surface water availability due to interactions between the two, which economists are also more cognizant of (Kuwayama and Brozović, 2013). Still, social science research has shown that the political process and path dependency often stymie efficiency-enhancing changes (Libecap, 1993), leading to drawn out processes and incomplete solutions, even among groundwater users (Ayres et al., 2018).

Many regions have sought to intervene and move toward more sustainable groundwater use. Various policy tools can target different points in the production processes that use water, and **Figure 2** provides a general schematic of generalized options. Direct quotas on groundwater extraction can effectively reduce water use (Drysdale and Hendricks, 2018) and create value when the quotas are tradeable (Ayres et al., 2021). However, beyond the regulation of groundwater quantities themselves, policies can limit where wells can be placed (reducing overlapping cones of depression) as has been deployed in the state of Kansas (Edwards, 2016) or subsidies can be provided to induce some existing wells to cease irrigation as the U.S. federal government's Conservation Reserve

1. Water law, especially related to quantities, is primarily the domain of the individual states with the federal government overseeing "navigable" water and much of the water quality aspects. Therefore, the "open-access" characterization is a generality that over time has become less true in particular states and specific subregions.

2. Withdrawal is different than consumptive use, as some water applied will not be taken up by the crops and instead percolate back down as return flow, meaning some water extracted is not actually "used" and that water will return to the system for others to re-withdrawal but usually with a time lag.

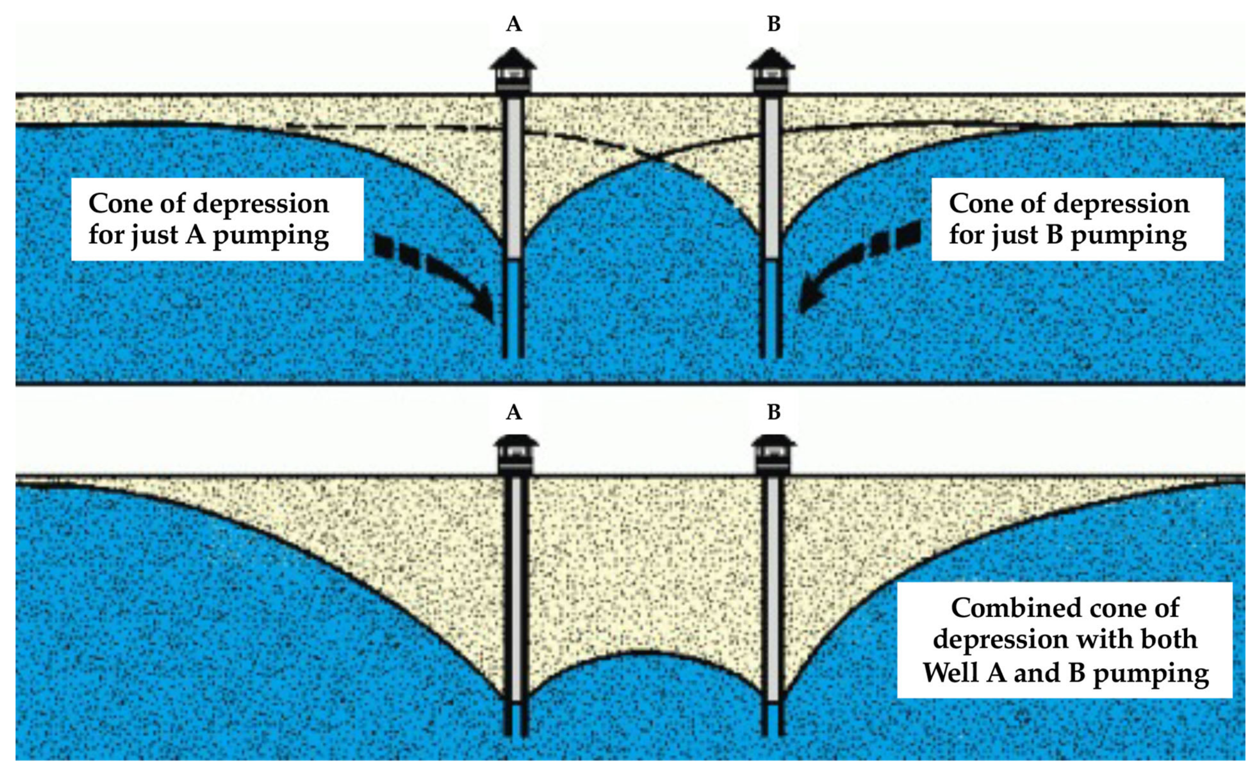


Figure 1. Groundwater pumping and cones of depression. This figure provides an overview of how overlapping cones of depression interact. Source: Oregon State University (2024).

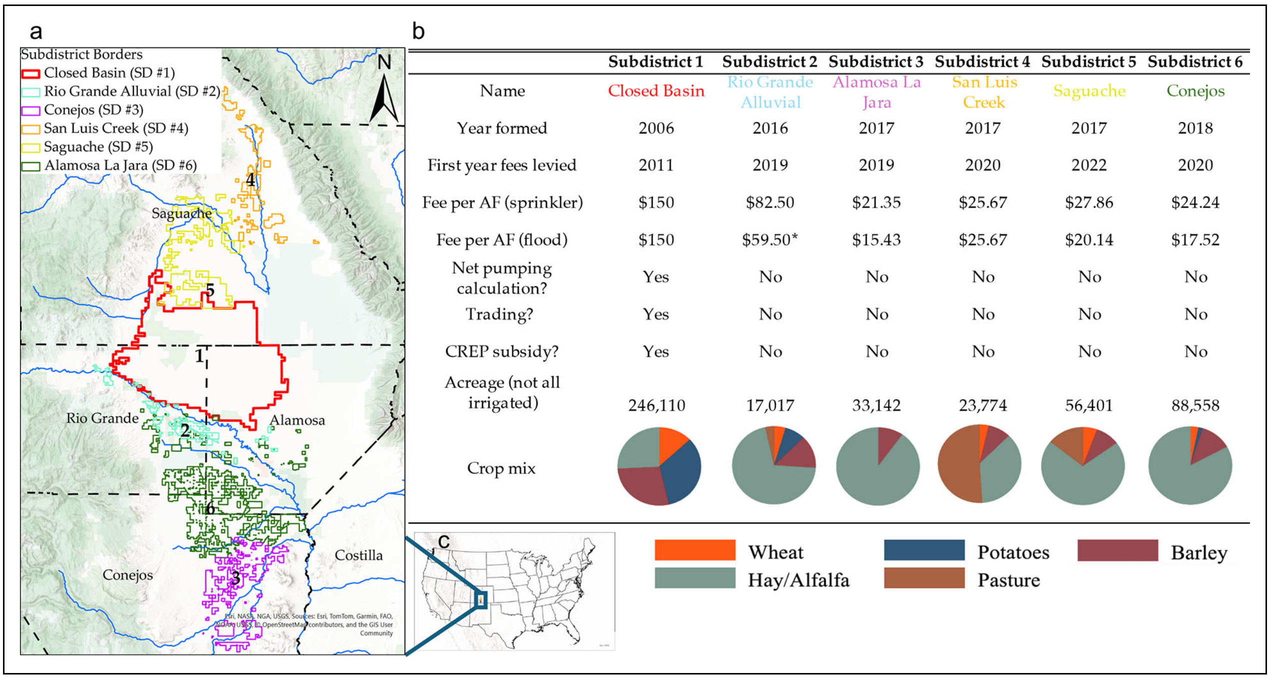
Targeted production step	Potential regulatory tools: Standards	Subsidies	Quotas	Fee
Output	Mandate a certain crop or seed variety	Subsidize reductions in water intensive crops	Maximum amount of a crop that can be grown	Charge a fee to sell units of water intensive crops
Technology used	Mandate specific efficient technology	Subsidize more efficient technology	Maximum number of inefficient systems	Charge a fee to use inefficient technology
Groundwater extracted	NA	Subsidize *reductions* in water extracted	Maximum units of water extracted	**Charge a fee for each unit extracted**
Location of extraction	Mandate minimum distances	Subsidize *specific* wells to exit	Maximum wells per area	Charge a fee for new wells based on spacing
Groundwater stock	NA	Subsidize irrigators whose water levels rise	Maximum allowable drop at wells	Charge a fee per unit of water level drop

Figure 2. Conceptual matrix of groundwater regulatory policies. This figure presents a matrix of groundwater used in agricultural production and broad types of potential regulatory tools. Groundwater stock in blue is the metric policymakers are caring about. Green highlights indicate those favored and historically more commonly adopted by irrigators. Bolded text is the option chosen by San Luis Valley (SLV) irrigators. Source: Authors' creation.

Enhancement Program supports in portions of the country like Colorado, Kansas, and Nebraska (Monger, 2016; Monger et al., 2018; Manning et al., 2020). More efficient irrigation technology can be mandated or subsidized, aiming to provide the same yield benefits with lower water withdrawals (Cameron-Harp and Hendricks, 2025; Pfeiffer and Lin, 2014). Most often, groundwater users lobby for the options that appear less costly to them, such as subsidies on technology or fallowing land, schemes to subsidize groundwater recharge, or, if pumping limitations seem inevitable, a more attractive option for groundwater users is the introduction of quotas or pumping permits which often do not have an explicit, financial cost. Given these widely held preferences among irrigators, one would expect the irrigators in SLV to follow a similar path. But this is not what happened. Why did the irrigators there push for a pumping fee? Was this a wise choice?

3. SLV and water policy

SLV is located in the south-central portion of Colorado. Nestled between the San Juan and Sangre de Cristo Mountain ranges, the broad valley floor sits at nearly 8,000 feet above sea level and spans some 3,200 square miles (see **Figure 3**). The high, semiarid desert contains fertile soil



	Subdistrict 1	Subdistrict 2	Subdistrict 3	Subdistrict 4	Subdistrict 5	Subdistrict 6
Name	Closed Basin	Rio Grande Alluvial	Alamosa La Jara	San Luis Creek	Saguache	Conejos
Year formed	2006	2016	2017	2017	2017	2018
First year fees levied	2011	2019	2019	2020	2022	2020
Fee per AF (sprinkler)	$150	$82.50	$21.35	$25.67	$27.86	$24.24
Fee per AF (flood)	$150	$59.50*	$15.43	$25.67	$20.14	$17.52
Net pumping calculation?	Yes	No	No	No	No	No
Trading?	Yes	No	No	No	No	No
CREP subsidy?	Yes	No	No	No	No	No
Acreage (not all irrigated)	246,110	17,017	33,142	23,774	56,401	88,558
Crop mix						

Figure 3. Overview of San Luis Valley groundwater management subdistricts. Panel (a) is a closeup map of the region and the subdistricts. Panel (b) provides details about the subdistricts and their rules. Panel (c) gives context of the San Luis Valley (SLV) within the broader United States. Source: Authors' creation, data from Allen and Smith (2023).

but receives just 6–9 inches of precipitation each year. Drawing on the Rio Grande and its tributaries, fed by snowmelt from the nearby mountains, settlers established agriculture in SLV via irrigation beginning in 1852. Initial efforts were by Hispanic irrigators expanding settlement north from Taos County, New Mexico, into modern-day Costilla County, Colorado, and bringing their irrigation institution (acequias) with them. Floods of Anglo-American settlers—and their water institutions—quickly followed in the 1870s and came to dominate most of the region (Cody, 2019; Smith, 2021, 2022). By 1890, over 350,000 acres had been brought under irrigation in the SLV (Carlson, 1973). Nearly 150 years later, in 1997,[3] the SLV had over 1,300 farms irrigating over 580,000 acres that produced some $340 million (2024 dollars) worth of crops, primarily potatoes, barley, alfalfa, and wheat (Haines et al., 2018).

Farms remain predominantly family owned (<1% non-family corporate), most farmers still reside on the farms (70%), and only 11% reported being tenants rather than owners. The farmers, like across the United States, tend to be older (53 years old), experienced (18 years farming), male (93%), and mostly white (93%) of which 15% identify as Hispanic. Farm size averages about 1,000 acres, of which 400 tend to be devoted to cropland; nearly all of which is irrigated in addition to irrigated pastureland, bringing the average farm to 550 irrigated acres. Just around 15% are smaller farms (<49 acres), 47% are medium sized (50–499 acres) and the balance, or 38%, make up the larger farms (>500 acres). The cropland in SLV is highly productive, producing about $690 per crop acre in market value (2024 dollars) compared to $250 per acre across the rest of Colorado; Alamosa, Rio Grande, and Saguache counties (counties with portions included in Subdistrict #1) ranked second, third, and seventh, respectively, out of the 63 counties in Colorado in terms of crop value per crop acre. Farms exhibit heterogeneity in their revenue. One-third reported sales below $10,000, another 40% reported between $10,000 and $100,000, and 26% reported revenues greater than $100,000 with some above $500,000. This heterogeneity tracks with farm size heterogeneity along with additional economies of scale effects.

Like other arid Western states, Colorado adopted the prior appropriation doctrine to allocate surface waters and encourage their development (Leonard and Libecap, 2019). Under this legal regime, a water user gains a usufruct right to a set quantity of water when they divert the water and apply the diverted water to beneficial use (Getches, 2009). Familiarly known as "first in time, first in right," the system applies a seniority ranking, and those with later priority dates are cut off first when less water is available. In practice today, this means that when there is not enough water for everyone, a water right established in 1861 can be cut off to ensure that one from 1859 receives its full share. During the severe droughts of the 1930s and 1950s, this rationing occurred and many of the 400 irrigation ditches in SLV found themselves short of water (Cody et al., 2015). When this occurred, many irrigators turned to an alternative source of water.

Not only had fertile soil piled up on the land in the valley over the ages, but groundwater had also been accumulating beneath the land's surface. Below the SLV sits

3. We draw on the 1997 census to capture pre-intervention farm and farmer characteristics. The 2002 census also precedes the 2006 subdistrict formation, but the data that year on crop value and irrigation are heavily affected by the drought that year.

two underground reservoirs, one unconfined that has a direct interconnection with the Rio Grande River and a second confined aquifer separated by a layer of blue clay ranging from 10 to 80 feet of thickness (Emery et al., 1969).[4] Following the droughts of the 1930s, there was modest development of the groundwater in SLV. By the droughts of the 1950s, however, the center pivot irrigation system had been invented, centrifugal pump technology had advanced, and farmers had access to cheaper energy sources, leading to massive expansion of groundwater use in the SLV and across the western United States (Hornbeck and Keskin, 2014; Edwards and Smith, 2018). From 1950 to 1959, the SLV increased from 800 wells to over 2,700 wells and expanded sprinkler irrigated acreage 10-fold (Cody et al., 2015). Initially, junior surface irrigators tapped the groundwater first with nearly 600 wells being developed on parcels with no surface water rights, but eventually, many of the more senior water right holders also installed wells and center pivot systems (Cody et al., 2015).

This groundwater development occurred outside of the scope of the prior appropriation doctrine. At the time, there were no firm limits or metering of the newly established wells at all, nor ways to govern the overlapping cones of depression. More importantly, because the drawdowns interacted with the surface waters, the senior surface water right holders were negatively impacted by the unconstrained pumping, making less surface water available to them than if no pumping had been allowed. The unconfined aquifer has direct connectivity to the streams, but even the confined aquifer is not completely separated (Bredehoest et al., 1982) and exhibits hydrologic connections with streams due to artesian pressure head feeding nearby rivers and faults in the clay layer. Formally recognizing this hydrologic truth, Colorado promised to bring groundwater wells into the prior appropriation system with the Water Rights Administration and Determination Act of 1969. However, beyond a moratorium on new wells, little was done in practice and few complaints occurred during the relatively wetter years of the 1980s and 1990s.

In the background, however, climatic conditions have evolved. Precipitation averages in the SLV have trended downward since 2000 and by 2012 the 30-year moving average flow of the Rio Grande was a mere 85% that of the 1930s.[5] Furthermore, average temperatures have risen 1°C since 1993, contributing to season-ending frost moving back 10 days (Mix et al., 2012) while peak snowmelt runoff is now 16 days earlier than in 1971 (Skiles et al., 2012), driving a larger gap between peak supply and peak demand. Groundwater provided a means of adapting to these changes and fluctuations (Edwards and Smith, 2018). In 2002, things came to a head. Snowpack and subsequent water flows were exceptionally low (6% and 24% of respective average levels; Cody et al., 2015) and the irrigators drew on the groundwater stock extensively: the unconfined aquifer storage was reduced by 740,000 acre-feet (AF) over the next 3 years after having netted just 270,000 AF reductions in total over the previous 26 years (Rio Grande Water Conservation District [RGWCD], 2025). The junior groundwater users continued their collective pumping as groundwater levels fell, and the more senior surface irrigators found no solace in their empty irrigation ditches. According to the 2002 USDA Census, only 905 of the farms in the valley could irrigate their land (two-thirds the number from 1997) and the reduced water supply allowed for only 330,000 acres to be irrigated, or 57% of the land irrigated in 1997 (Haines et al., 2018).

Faced with the reality of a falling water table and the real threat from the Colorado state government to start shutting down wells pumping out of priority—as they had already done in other parts of Colorado—farm values in the Valley fell nearly 20% during and after the 2002 growing season (Gebben and Smith, 2024a). It is at this point, however, where the SLV departed from the familiar groundwater narratives elsewhere—namely, subsidizing water efficiency technology, continuing over drafting, and/or having the out-of-priority wells shutdown—and turned to a seemingly less attractive way forward. Irrigators decided to impose a groundwater pumping fee on themselves to curb their own use of groundwater. A detailed theory and narrative as to why SLV successfully acted collectively in this case are provided in Cody et al. (2015) and Loos et al. (2022) and we highlight just three elements here. First, as discussed above, while there is heterogeneity in farm size and hence revenue, the irrigators are similar in age, race, gender, and dependence on irrigation. Second, many groundwater users also have surface water rights delivered through shared ditch infrastructure, providing years of experience cooperating and building trust among subgroups preceding the groundwater crisis. Third, in response to Rio Grande Compact issues in the 1960s, the state of Colorado supported the formation of the RGWCD, providing a broader regional governance structure with the capacity to provide a forum to discuss and execute rule changes.

Through the leadership and guidance of the RGWCD, irrigators were organized into the six subdistricts that roughly follow hydrologic connectivity and similar farming practices—reducing the number of irrigators and heterogeneity of those irrigators even further to reduce transaction costs of rule formation closer aligned to conditions of each group. From the outset, the irrigators wanted to rely on economic incentives rather than mandates, stating that:

> *[T]he overall objective of this Plan is to provide a water management alternative to state-imposed regulations that limits the use of irrigation wells within the Subdistrict, that is, a system of self-regulation using economic-based incentives that promote responsible irrigation water use and management and insure the protection of senior surface water rights.*
>
> —Proposed Plan of Water Management, Subdistrict #1 of RGWCD, June 2009, p. 8

4. Generally, unconfined aquifers have water tables at atmospheric pressures and more readily fluctuates, whereas a confined aquifer has impermeable layers below and above it, causing the aquifer to be under pressure.

5. This is based on the Rio Grande, using aggregate flows during the water year as measured at the USGS Del Norte Gauge (08220000) accessed at https://waterdata.usgs.gov/nwis/inventory/?site_no=08220000.

Figure 3 provides the resulting boundaries and the rules as of 2024. Subdistrict #1 (the pilot project area), also known as the Closed Basin due to its lower drainage elevation that limits its hydrologic connectivity to the Rio Grande drainage (Heide, 2005), was compelled to go first. It is the largest subdistrict (160,000 irrigated acres and 70% of the wells) and has the largest aggregate effect on the downstream surface water right holders. Meanwhile, the state government only had the resources to construct a detailed hydrologic model for one subdistrict initially, as well as the legal resources needed to shepherd through the rule changes.

Subdistrict #1 was officially formed in 2006 as a legal entity when a majority of landowners within the proposed boundary, by number and by acreage, signed the petition. As a group, they opted for a pumping fee—or what an economist might call a Pigouvian Tax (Pigou, 1920)—as the marquee policy tool to work toward their three goals. At the time, this was the first instance of a pumping fee being implemented, let alone a self-imposed fee, and few cases have emerged since. In part, their willingness to try a fee compared to other groundwater users in the United States, may be related to their experience with paying some financial amounts for collective surface water infrastructure and organizations.[6] Interviews with irrigators indicate that fees rose to the top because revenue was necessary to meet state required surface water payments and folks viewed it as fair that those that used more groundwater should pay more toward that effort (Allen and Smith, 2023). Beginning in 2011, the irrigators in Subdistrict #1 faced a \$45 fee per *net* acre-foot extracted, receiving credits for any surface water rights they put toward aquifer recharge.[7] The fee was then increased to \$75/AF in 2012, \$90/AF in 2015, and has sat at \$150/AF since 2017. Given that previous to the intervention, the upper range of pumping costs was \$55/AF (and as low as \$25/AF), the fees marked a substantial increase in groundwater costs (Smith et al., 2017). Meanwhile, the remaining subdistricts, as can be seen in **Figure 3**, have now formed and begun to also charge pumping fees, although much smaller in magnitude in large part because they do not receive the same surface-water credit as those in Subdistrict #1, meaning every AF of groundwater extracted is charged the per AF fee in the five other subdistricts. In the remainder of this article, we focus on the lessons learned from the first Subdistrict, where the taxation experiment first started and where there is now more than a decade-worth of data on outcomes.

4. Policy insights

4.1. Economic underpinnings

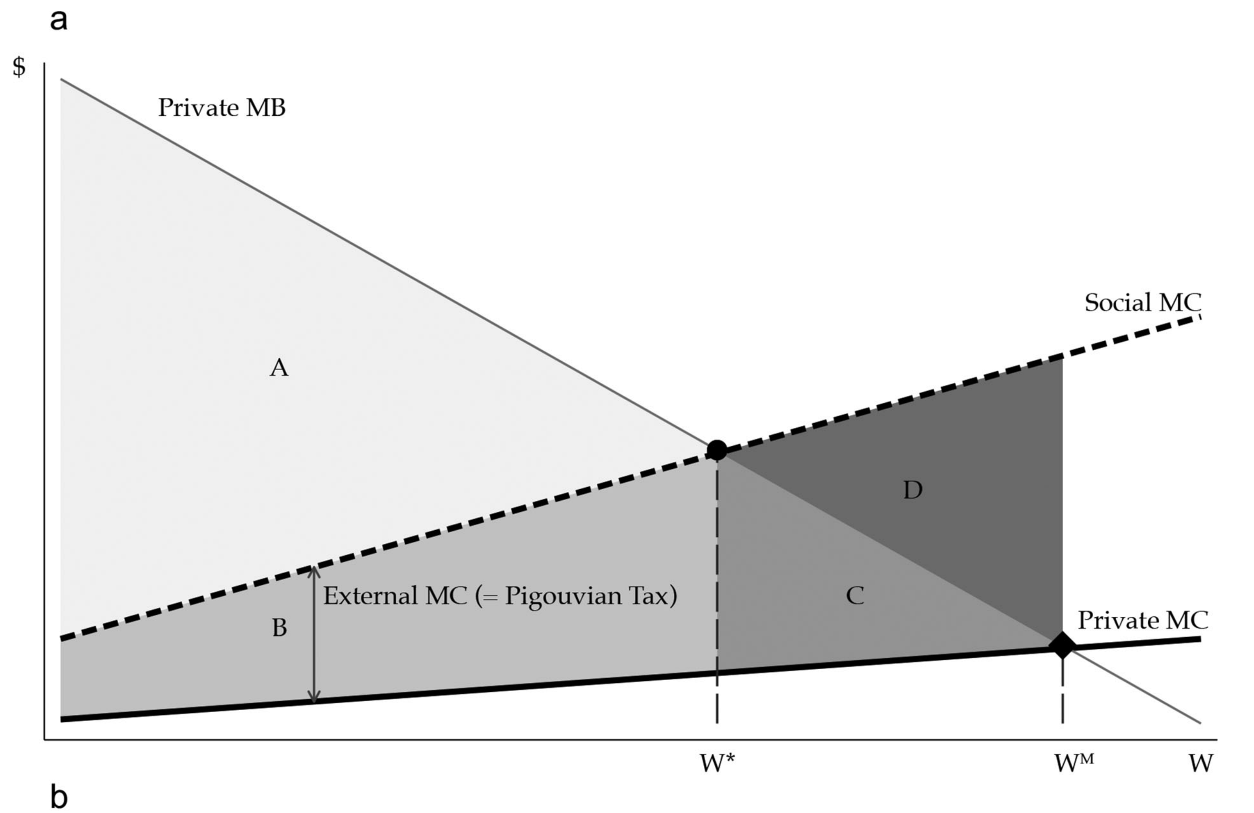
Although groundwater depletion is fundamentally a dynamic problem, a simplified model of a single-period, as we show here, is sufficient to illustrate the economic intuition behind a pumping fee. Consider a farmer who can utilize groundwater to enhance the yield of a crop. Taking their other inputs as fixed (e.g., land), the gains from more water will decline as a function of how much water the farmer has already applied to their crop. That is, the first units of water add more value than their last units of water. This produces the typical downward sloping demand curve, equivalent to the private marginal benefits, as shown in **Figure 4**, capturing the diminishing marginal benefits of water. Bringing this water up from the depths of the aquifer requires significant amounts of energy, which comes at a cost. Furthermore, as water is extracted and the cone of depression is formed, the water table drops under the well, necessitating even greater amounts of energy to lift the next unit at a farther distance from the aquifer (Kanazawa, 1992; Mieno and Brozović, 2017). Once the static water levels reach their drawdown levels at a given well, this lift will stabilize. The specifics of how this process unfolds—how much the water drops and over how long—at any given well will depend on the extraction rate and the aquifer's storativity and permeability. Additionally, many energy providers deploy increasing block-tiers, meaning the costs of the energy itself can also increase the more water that is extracted. Together, the marginal cost of extracting water will be nondecreasing as more water is taken out, represented by the slightly upward sloping private marginal cost curve in **Figure 4**.[8]

A farmer, then, will choose to extract W^m, where the marginal benefit is equal to their private marginal costs. This yields them an economic surplus of $A + B + C$. However, this is too much water from society's standpoint because there are external costs that the farmer is ignoring. Many externalities were discussed above, but for this context, it is sufficient to consider that nearby groundwater pumpers also have their water table lowered (increasing their pumping costs) or, as is the case in the SLV, senior surface right holders are not receiving their surface water and hence "costing" them output. For an empirical reference, on average, only 47% of annual declining water levels under a given well in SLV was attributable to its own pumping in the 2009–2013 period; the remaining 53% was due to neighbors' pumping within a quarter mile (Smith, 2018). Capturing this externality gives rise to the true cost of pumping the groundwater, represented by the

6. Many of the irrigators, not the shared ditches, own the water rights themselves. Based on surveys of surface water organizations in the area ($n = 45$), 66% of the organizations do not own the water rights. Only 57% of ditch organizations levied any sort of fees for operation and maintenance; none reported paying a marginal fee (per acre-foot) for surface water deliveries. In other words, though irrigators have experience cooperating and sharing expenses in this region, few if any were conditioned to pay an explicit marginal cost for surface water deliveries in the SLV.

7. Many in Subdistrict #1 receive surface water themselves and are able to earn credit for allowing it to seep into the aquifer under a special decree to recognize aquifer recharge as a beneficial use under the prior appropriation doctrine. If they receive 100 AF of surface water that they put toward recharge and then pump 110 AF, they only are taxed on the 10 AF above and beyond the surface inflow. If they pump less, they can sell the credits.

8. In a dynamic version of the model, there is the additional marginal *opportunity* cost, which represents the foregone use of that water (and associated net benefits) in the future periods.



b

	Changes from a pumping fee									
	GW User 1				GW User 2				Government	Net
	Production	Taxes	Loss due GW 2 (externality)	Net	Production	Taxes	Loss due GW 1 (externality)	Net	Tax revenue	Net
With pumping fee (W*)	A+B	-B	-B	**A-B**	A+B	-B	-B	**A-B**	2B	**2A**
No pumping fee (W^m)	A+B+C	0	-B-C-D	**A-D**	A+B+C	0	-B-C-D	**A-D**	0	**2(A-D)**
Difference with fee (column difference)	*-C*	*-B*	*C+D*	***D-B***	*-C*	*-B*	*C+D*	***D-B***	*2B*	***2D***

Figure 4. Theoretical ground for the pumping fee. This figure represents the basic economic theory behind a fee. Panel (a) provides an overview of the marginal costs and marginal benefits while panel (b) summarizes the total costs and benefits to different constituencies under different conditions that are indicated by the shaded areas in the graph. "MB" is marginal benefit and "MC" is marginal cost. Source: Authors' creation.

Social marginal cost curve, which we have shown as increasing in water use. The external marginal cost can be added to the curve to arrive at the higher social marginal cost of water extraction. At W^m, then, another irrigator is paying B + C + D in external costs. If the local farming economy is made up of only these two irrigators, then user 1's production has netted society A–D. When all costs, not just private costs, are considered the irrigator ought to be pumping W*, where society would be netting A (i.e., gain D back from not over pumping). This over pumping in this model is essentially the "tragedy of the commons" as set out by Garret Hardin in his famous 1968 paper. Because the resource is not wholly owned by the user and they are free to pump as they wish, they will use too much and "ruin is the destination toward which all men rush" (Hardin, 1968, p. 1244).

A possible solution to the issue is state government intervention, and the Pigouvian tax is one form of state intervention that has long been recognized in economics (Pigou, 1920). Often called a "sin tax," the notion is to levy a per unit tax equal to the external marginal cost, effectively internalizing those costs on the decision maker. In **Figure 4**, this would amount to enacting a tax equal to the gap between the social marginal cost and private marginal cost curves, specifically at W*. Notably, when there was a statewide initiative to do something like this in the 1990s, which was to impose a $40/AF pumping fee across SLV, the irrigators and residents of SLV rallied support across Colorado to defeat the ballot initiative nearly 3-to-1 (Cody et al., 2015). Led by Elinor Ostrom (1990, 2009), a lot of research has broadly shown that state intervention or privatization is not always necessary to avoid overuse of a collective resource because users can create self-governance regimes (and hence, the "tragedy" is not inevitable). And so, the question remains as to why, when the SLV irrigators did act collectively, they opted for a Pigouvian-like tax.

One important feature to recognize is the symmetric nature of the problem: those contributing to the external effect on their neighbors are also bearing the external cost imposed by their neighbors. Not only is this true due to the groundwater connection, but in the SLV case where surface water rights are also affected, many (though not all) utilize both sources. Therefore, unlike other scenarios of external costs, like carbon emissions, where the producer is only marginally affected by the damages, those sharing a common-pool resource have an incentive to correct the issue because all users stand to lose directly from inaction. Drawing on **Figure 4**, this is captured by the notion that not only is GW user 1 inflicting B + C + D on GW user 2, but GW user 1 is also being inflicted by B + C + D. This is why, absent the fee, they only net A–D themselves even though they are making profits of A + B + C. Accordingly, the irrigators themselves do have an incentive to collectively reduce pumping (reigning in their neighbors). Still, why increase their own costs? After imposing the fee, relative to without the fee, the irrigator is up D–B. If D is greater than B, then this is a gain and the pumping tax paid is less than the external costs they no longer face. Why not opt to subsidize more efficient irrigation technology or put in place pumping quotas like irrigators have in portions of Kansas (Perez-Quesada and Hendricks, 2021; Orduña Alegría et al., 2024) and California (Ayres et al., 2021)?

The appeal of technology upgrades is that irrigators would be able to apply less water and receive the same benefits, saving water and money, especially when subsidized. This, however, ignores the human and hydrologic responses. In **Figure 4**, the more efficient technology would pivot the marginal benefit curve upward from the *x*-axis. Without an increase in the marginal costs, though, this will lead to a rebound effect, where the more efficient technology incentivizes additional use of the resource, eroding at least a portion of the water saving technology. In the extreme, the rebound effect can be so large that it leads to Jevon's paradox; more water ends up being used than before the introduction of the more efficient technology. The extent to which this occurs in practice remains an area of empirical debate (Pfeiffer and Lin, 2014; Cameron-Harp and Hendricks, 2025). But other leakages can occur at the aquifer level through hydrology and other users (Grafton et al., 2018). For instance, if water tables are higher, neighbors will pump more due to the lower costs while the more efficient technology reduces return flow and aquifer recharge.

It is true, however, that irrigators could have opted for a quota of W^* for each irrigator. This would have equally led to the efficient reduction in water in **Figure 4**. The underlying economic logic suggests either the fee or the quota is efficient because the irrigators are incentivized to reduce water use using whatever margin is the least costly for them rather than being forced to make a specific change. In other words, for some it may be that installing more efficient irrigation systems is the best option, but others may find it more useful to reduce their irrigated acreage, change to a less water intensive crop, or reduce water applied to a given crop per acre. The equivalence of the outcome between the fee and the quotas, however, have their limitations. For one, while the outcomes in terms of adaptations and resulting water use may be the same, the distribution of wealth is not. When irrigators receive a quota, they will use W^*, but they do not have to pay for the water they do extract, keeping more money (area B in **Figure 4**) in their own pockets and making a quota more appealing, all else equal. Inverting this logic, however, is that a fee-based incentive will generate revenue to the group. To this point, we have ignored the "government," but under the self-imposed fee system, it is the collective of farmers themselves who receive B from the irrigator (i.e., it is a transfer). For the SLV irrigators, this was a critical point because they needed revenue to help pay for water to compensate for the "injuries" to downstream senior surface water appropriators. The collected revenues may also be utilized to subsidize some irrigators to completely fallow their lands (Gebben and Smith, 2024b). In contrast to the defeated state-level initiative in the 1990s, this self-imposed fee kept the revenues local rather than going to support state initiatives elsewhere. In other words, a portion of B is redistributed back to the irrigators themselves under the local collective-action fee, whereas it was likely to flow to other members of society when it was a state-level government tax being proposed. Under these circumstances, there was a clear economic incentive for SLV farmers to self-regulate and self-tax, rather than relying on the state-government to do so.

There are also other potential advantages of a fee compared to a quota. First, in a world of high levels of uncertainty, when it comes to how people will respond to policy interventions one should not overlook the cost of being wrong. Specifically, when policies are set based on bad information, the costs of being wrong are not equal between the two tools (Weitzman, 1974). The steeper the marginal benefit curve (relative to the steepness of the social marginal cost curve), in **Figure 4**, the more appealing the fee is because when that fee is set wrong, the differential change in water use will not be too great. In contrast, a quota makes certain a maximum amount water can be used but may be wrong on the costs (captured as *reduction* in net benefits) imposed on the irrigators, while a fee provides flexibility to conditions but leaves the total water withdrawn unknown from the start. Second, when the regulated irrigators have heterogeneous cost and benefit curves, all else equal, fees become an increasingly attractive option, especially under extreme levels of uncertainty (Weitzman, 1974). This is an outgrowth of a more general point about heterogenous costs and benefits: selecting a single price with the fee ensures that the marginal costs of the policy are equated across producers—a desirable outcome for a cost-effective policy—compared to a single quota amount. In other words, with heterogenous irrigators, it is easier to adopt a fee and let the farmers decide the right amount of groundwater to use for themselves rather than imposing a uniform quota or going to the trouble of sorting out individual quotas. Notably, making the quotas tradeable can help overcome this problem, as has been seen in recent deployments of such schemes in California (Ayres et al., 2021).

Notably, it has also been argued that a uniform pumping tax may not be optimal, even in the SLV, because external and private marginal costs are not homogenous (Ekpe, 2024). That is, not all irrigators can be represented by the same marginal externality that has been assumed in **Figure 4** and pumping at some wells is more damaging than at others due to factors like permeability, well density, crops grown, and so on. From this perspective, the fee may not be a true Pigouvian fee because everyone is not being charged the marginal external costs they cause. Creating "transfer coefficients" that tailors a fee to the external marginal costs at each well would be quite resource intensive to calculate, particularly with a constantly changing hydrologic system. Simpler uniform policies can be ineffective and, given potential negative outcomes for several irrigators, lack political support from the irrigators themselves (Guilfoos et al., 2016). Two important points are worth making here. First, these issues of heterogenous external costs are not unique to the use of fees and will complicate any groundwater policy, inclusive of quotas. Second, there is a tradeoff between the efficiency gains of more tailored fee amounts and the transaction costs of designing them. The RGWCD took a middle-of-the-road approach by dividing the region into six subdistricts based on similar farming and hydrologic conditions, adopting different fees and other rules in each. In other words, the fees are not tailored to the individual well, but they are also not a blanket, uniform fee across all the wells in the SLV. The fees are semi-tailored to different wells.

With some empirical uncertainty as to the slopes and positions of the curves in **Figure 4**, a quota would provide certainty of the maximum groundwater extracted while the deployment of the fee leaves the water amount unknown a priori and is dependent on how responsive irrigators are to the price of water, which can be captured as the elasticity. This metric describes how a percent change in the price of an input will change the percent quantity utilized. The slope of the private marginal net benefit curve (private marginal benefit slope minus the slope of the private marginal cost curve in **Figure 4**), combined with the current price and water levels, determines the irrigator's elasticity to the introduction of a per unit fee. Presumed to be negative, economists consider between 0 and −1 to be inelastic (low response to a change in price) while less than −1 is elastic (a large change in response to a price change). As a proxy, the flatter the marginal benefit curve appears in **Figure 4**, the more elastic irrigators are. An argument against the use of a fee to reduce water use is that irrigators are inelastic (Ogg and Gollehon, 1989; Moore et al., 1994; Schuerhoff et al., 2013) and indeed estimated price elasticities for irrigation are low. While some studies have identified large elasticities of nearly –2 (Shumway, 1973), most find much smaller elasticities below −0.40 and meta-analyses find median elasticities of around −0.16 (see Koundouri, 2004 and Scheierling et al., 2006 for reviews). If taken literally, this would mean that with the Subdistrict #1 fee initially doubling the price of water, we would expect water use to be reduced by only 16% at an elasticity of −0.16. However, there are concerns that measurement errors and endogenous drawdown contribute to biases in these estimates, and irrigators may actually be more elastic (Mieno and Brozović, 2017).

Finally, without full knowledge of the marginal curves beforehand, it is also uncertain how the irrigators will come out financially and whether the fee represents an actual improvement for their economic situation. A water policy that brings the aquifer to a sustainable use may not be sustainable in the broader sense if the irrigators are made worse off economically or even have to close their farming business. In principle, they may become better off economically even though they are paying more for the water because they are no longer exposed to (inefficient) external costs and are able to adjust other inputs that may offset the remainder of their additional water costs and reduced yields.

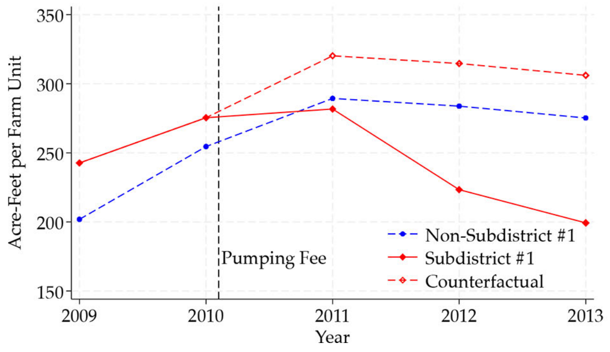
In summary, the irrigators opted to raise their own pumping costs for a combination of reasons, including (1) they risked being cut off entirely by the state government if they did nothing, (2) an economic incentive (e.g., a fee) allows each irrigator the freedom to reduce water use how they see best, (3) the spatial symmetry of the groundwater problem means some gains will be realized by neighbors reducing their pumping, and (4) they needed to generate revenue to meet other policy goals. What was unknown at the outset was: (a) how much groundwater extraction would be reduced; (b) precisely how irrigators would adjust their farming practice to achieve those reductions; (c) whether the benefits of reducing the externality would, net of the adjustment costs, make the irrigators better off economically; and (d) whether the water savings would translate into a stabilization and recovery of the aquifer. In the next section, we review the existing evidence on how this home-made policy intervention shook out.

4.2. Economic fee outcomes

4.2.1. Water use and margins

In terms of water reductions, the pumping fee proved exceptionally effective. With Subdistrict #1 moving first, the surrounding irrigators in the other subdistricts provided a nice quasi-experimental comparison. Farmers outside of the subdistrict provide a policy counterfactual for what irrigators would have pumped without facing the pumping fee, but accounting for the shared local weather shocks and other input prices and crop market values each year that would also influence pumping decisions. The methodology does not require pumping is exactly the same in the pretreatment period, just that the two groups were following the same trend prior to intervention. This difference-in-difference application to estimate the short-run effect on groundwater use can be seen in **Figure 5**, based on Smith et al. (2017).

Pumping records, only available for the 2 years before the fee's implementation, support the assumption that irrigators within and beyond Subdistrict #1 followed the same pumping trends prior to the fee even if those inside pumped more. From 2011 onward, after the fee went into place, those in Subdistrict #1 reduced their water use in nominal terms. However, the a



b

Average farm unit groundwater pumping (AF)			
	Subdistrict #1 farms	Non-Subdistrict #1 farms	Difference
2011-2013 (Post)	234.80	282.81	-48.01
2009-2010 (Pre)	259.05	228.20	30.85
Nominal change	-24.25	54.61	-78.86
Percent change	-9.4%	23.9%	-30.4%

Figure 5. Difference-in-Difference conceptual illustration for Subdistrict #1 groundwater pumping. Covering 2009–2013 pumping, this figure captures average pumping for consistent farm units across those years. Panel (a) illustrates visually how a counterfactual is constructed based on the non-subdistrict pumping. Panel (b) averages pumping by pre- and post-fee implementation to further illustrate the Difference-in-Differences application. Source: Adapted from Smith et al. (2017).

reduction was even larger based on the dashed redline, which reconstructs what they would have pumped based on the trend from the surrounding regions. The table in **Figure 5** breaks this down further. If we only considered the difference before and after the fee for Subdistrict #1 farms, we would observe a 24.25 AF reduction, or 9.4%. But this ignores that pumping in the region increased outside of Subdistrict #1 by 54.61 AF. In other words, absent the fee, pumping would have likely increased as it did outside Subdistrict #1. Among other reasons, surface water supplies were 24% lower in the post-period, increasing demand on the substitute groundwater.[9]

Alternatively, if we only took the difference between Subdistrict #1 farmers and non-Subdistrict #1 farmers after the fee, we would only come to a 48.01 AF reduction. However, when we take the difference-in-differences, we find the total reduced pumping in response to the fee within Subdistrict #1 is 78.86 AF per farm unit, or a 30.4% reduction of pre-fee pumping levels. Deploying a more sophisticated econometric specification, Smith et al. (2017) found irrigators in Subdistrict #1 reduced their groundwater extraction by 32%. Given estimated pumping costs, the irrigators exhibited an overall price elasticity of −0.77, more elastic than many of the extant empirical estimates.

The margins of adjustment also varied. First, on an extensive margin, the higher fees tended to keep irrigators from planting alfalfa, a water-thirsty crop whose market price doubled during that time frame and had expanded acreage in SLV beyond the Subdistrict #1 borders. In addition to switching crops, irrigators increased fallowed acres by 12 acres per farm relative to a mean of 16 acres. Second, conditional on planting a given crop, irrigators reduced more on the intensive margin (groundwater per planted acre) and also reduced field size by 6%. This pattern, though, was not uniform across crops. Potato fields were among the least elastic and did not budge on the watering intensity, only by planting slightly fewer acres. This fact underscores the flexibility provided by the fee. Spuds are worth the most (per acre) in SLV and have the most linear relationship between yields and irrigation application, explaining the relative lack of response. Finally, irrigators could also be incentivized to adopt more efficient irrigation technology, although this channel was not detectable in the first 3 years. This is likely due to the short time span, relatively high penetration of center pivots already, and lack of data on center pivot efficiency, such as the use of low-energy precision application systems (Smith et al., 2017).

Indeed, the long-run elasticity is generally expected to be larger, having provided more time for irrigators to make larger changes. However, conducting a similar analysis at the well-level with a longer time period (2011–2021), Gebben and Smith (2024b) find that the effect has not grown, and if anything, shrunk slightly. Through the additional years, groundwater pumping reductions have remained around 30% of pre-fee amounts, but the fee also doubled to $150/AF in those later periods, suggesting a smaller price response. Burlig et al. (2021), in another groundwater setting, have found long-run elasticities to be lower than short-term elasticities as well (−0.72 and −0.48, respectively). They speculate that it is because of dynamics particularly relevant to perennial crops: a larger short-run change that can be displaced in the long run when future crop choices are made. But in California, the perennials are often vineyards or fruit trees that can take years to reach maturity and then produce for over a decade. In SLV, alfalfa is the dominant perennial and it has a distinct investment and revenue cycle; harvesting alfalfa can occur in the first year of planting and it may only be left in 2–6 years. Instead, we speculate that it could be that the longer time period allowed irrigators to discover more about the true costs of decreasing groundwater use and they learned that paying the fee

9. This calculation is also based on the flows from the USGS Del Norte Gauge (08220000).

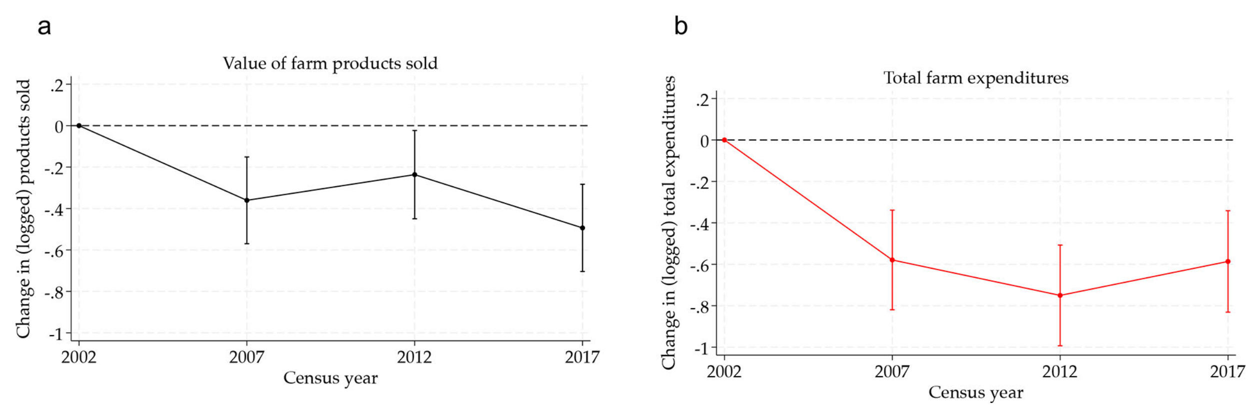


Figure 6. Estimated changes in farm production and expenses, Micro Census Data. This figure plots the estimated difference-in-difference estimates of Subdistrict #1 farms relative to SLV farms outside of Subdistrict #1, using a baseline year of 2002. Panel (a) plots the market value of all farm products sold for the year. Panel (b) plots total farm expenses for the year. Source: Adapted from Gebben and Smith (2024a).

was worthwhile, in part explaining why the fee has consistently been increased.

This suggests that the initial fee may have been set too low. One way to measure the net effects of a policy on a firm is to consider how it has changed the net present value of the farms. This is known as an approach known as Hedonic valuation (Rosen, 1974) that has been used to decompose an asset's value along various dimensions and can recover the value of water rights or changes in water availability via climate or policy (see Crouter, 1987; Faux and Perry, 1999; Petrie and Taylor, 2007; Hornbeck and Keskin, 2014; Edwards, 2016; Edwards et al., 2024). In the context of Subdistrict #1, the similar farms beyond the borders can again provide a counterfactual. First, the formation of the subdistrict itself in 2006 was met with trepidation and farm values sunk further from the lower levels reached during the 2002 drought. In other words, the simple idea that the farmers would "do it themselves" did not translate into the farms selling for a higher value and in fact led many to believe the benefits would be severely outweighed by the costs of reducing groundwater extractions. However, farmland values within Subdistrict #1 did recover significantly after the fees were implemented in 2011, gaining back some 86% of the loss in value following Subdistrict #1's initial formation (Gebben and Smith, 2024a). Irrigators learned the real costs (and benefits) of the pumping fee, and it was not nearly as severe as had initially been anticipated. On average, farm values in Subdistrict #1 remain 6% below their values before 2006, taking into account general trends in farm values in the SLV. Notably, the values within Subdistrict #1 post-2011 have been trending up since 2006, consistent with irrigators gaining confidence that the fees have made them better off on net.

How could the increasing the costs of a key input lead to a higher valuation of the farms affected? This may be because irrigators realized other co-inputs can also be reduced along with water reductions while water could simply be applied more efficiently now that "waste" has higher costs. Using farm-level census responses in the SLV from 2002 to 2017, Gebben and Smith (2024a) found that farms in Subdistrict #1 did see lower revenues relative to 2002, but that they were able to reduce their total expenditures by even more (see **Figure 6**). This supports that adjustments in other inputs could offset the additional water costs and lower production. Still, the net effect based on this data is slightly reduced farm values (around 20%), suggesting the policy may not have sufficiently addressed the externalities in the SLV.

This brings us to our final empirical point. Despite the groundwater pumping reductions, the water table itself is struggling to recover. In **Figure 7**, we plot RGWCD data on water storage in the unconfined aquifer (adapted from Gebben and Smith, 2024b). The total volume is unknown, but relative changes can be traced back through 1976. The water table remained rather stable prior to 2002 but dropped about a million acre feet by 2005 following the drought. Wetter years saw some recovery from 2006 to 2010. Despite the 30% lower pumping amounts following when the fee was introduced in 2011, the aquifer declined to its lowest point in 2013. As highlighted above, the 30% is relative to the counterfactual and the nominal reduction in pumping was closer to 10% and dry conditions limited potential recharge. Hard-won gains were made then through 2017, but dry weather—including a drought in 2018 worse than the 2002 drought—setback the efforts and as of 2023 the aquifer remains in a poor state, some 1.21 million AF less water than in 2000. These figures are raw numbers and the counterfactual, without the efforts of Subdistrict #1, shows that the situation could have been much worse. Drawing on Gebben and Smith (2024b) overall pumping reduction estimates for each year, we subtract those here to show the additional storage losses absent intervention. This accumulates to 1.17 AF through the 2022 irrigation season. This is a simplification that ignores recharge dynamics and pumping dynamics, were the water table to have dropped by more, but illustrates that without the pumping fee and other conservation efforts, the aquifer would be in a much worse state, with 2.38 million AF gone rather than 1.21

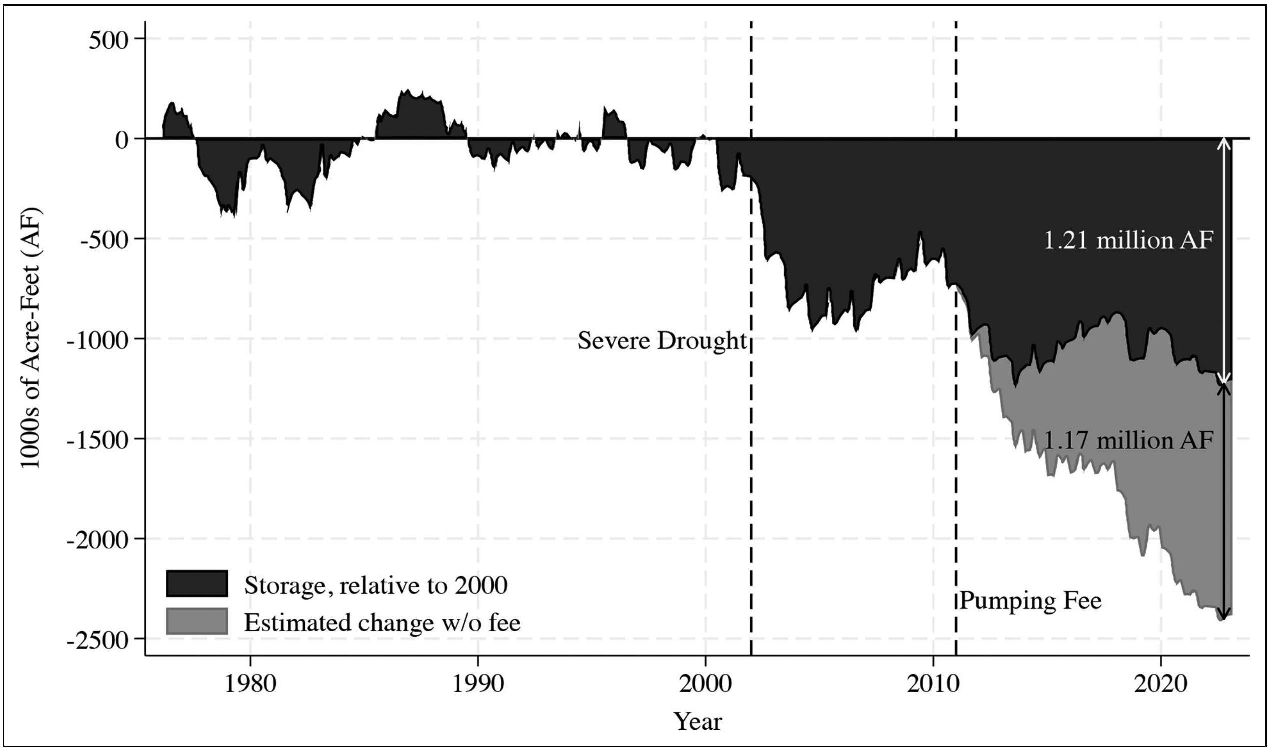


Figure 7. Unconfined aquifer storage, west central San Luis Valley. Figure shows changes in unconfined aquifer storage. The storage changes are originally measured relative to 1976 by Davis Engineering Services, Inc. for the Rio Grande Water Conservation District. The estimated change w/o Subdistrict #1 subtracts the estimated water savings each year from all the conservation efforts (fee and fallow program) from Gebben and Smith (2024b), providing a rough counterfactual. Source: Adapted from Gebben and Smith (2024b).

million AF. Still, the lack of recovery in absolute terms is problematic and suggests that additional measures may be needed to bring groundwater use in better balance with recharge, as is the goal of Subdistrict #1.

5. Lessons learned

Irrigators in SLV opted to increase their own costs for water extraction because they found this option to be the most locally feasible response to the severe drought conditions. Their previous overuse of groundwater needed to be addressed because a failure to do so would likely have led to a heavy-handed crackdown by the Colorado state government. They opted to deploy the self-taxation scheme to create tangible economic incentives to reduce groundwater use rather than choosing more rigid policies dictating specific water-reducing requirements. Along many dimensions, the policy worked: the irrigators proved more responsive to the price change than expected, reducing use by around 30%; irrigators reduced use in different ways according to their own situation, although the dominant channel was reducing watering intensity except on potato fields which became slightly smaller; and the irrigators were predominantly able to offset the costs of the policies by adjusting co-inputs and the reduced externalities of their neighbors.

Given this success, might this approach prove beneficial to other groundwater systems facing challenges? It is our opinion that farmer-led initiatives, like the one in SLV, ought to be considered. At the same time, there are no panaceas for groundwater shortages, or any other common-pool resource problem (Ostrom, 2007). To illustrate this point, we can compare the choice of intervention in SLV with that of the uniform quota that irrigators in Kansas chose to introduce. As pointed out by Allen and Smith (2023), there are several factors that make both intervention approaches the "right" choice for each of the two systems. For example: (1) SLV needed to generate revenue for the surface-water forbearances, (2) SLV could "afford" the fee because the crop value per acre in the valley is nearly 10 times that of the Kansas region, (3) a hard quota limit could severely impinge on SLV farmers where 90% of crops are irrigated, whereas Kansas irrigators, where only 16% is irrigated, can transition more readily to dry farming, and (4) irrigators in Kansas have similar access to water and all primarily irrigate corn, allowing for the use of a simpler uniform limit on groundwater extractions compared to the heterogeneity of irrigators and crops in SLV. Still, the tax can be an appropriate choice for particular regions. Indeed, irrigators in Pajaro Valley, California, have faced a volumetric pumping fee for years, recently doubling it from \$80/AF to over \$160/AF. There, too, the irrigators proved to be responsive, reducing water use by 22%, exhibiting a price elasticity around -1 (Bruno et al., 2024). Notably, however, the region also grows high-value crops like strawberries and a suite of vegetables, underscoring the importance of substantial crop income to afford significant pumping fees.

As highlighted above, however, the pumping fee has not delivered on stabilizing, let alone recovering, the aquifer. In contrast, a quota or cap on pumping would have ensured limits on extraction, although potentially at great costs to the short-run bottom-line of the irrigators. This does not necessarily mean that the pumping fee has been ineffective, but rather an indication that the problem is more severe and will require more drastic cutbacks in groundwater use, independent of what tool accomplishes those reductions. What is clear is that the situation would have been much worse had the SLV farmers not been proactively pursued the self-taxation scheme.

Irrigators in SLV continue to innovate with additional measures. From the beginning, they recognized the need to bring some land completely out of production, targeting 40,000 acres of the 160,000 acres in Subdistrict #1. Here, too, they have utilized economic incentives, using a portion of the revenues from the fees in local fallowing programs and leveraging Federal funds through a Conservation Reserve Enhancement Program (CREP) available since 2016. Not only has this led to reductions in pumping directly, but nearby wells also reduce their pumping since the degree of the "common pool" issues is reduced with fewer local cones of depression. In total, the fallowing subsidies are estimated to relate to an average of 9% of annual pumping reductions since 2016 (Gebben and Smith, 2024b). In yet another surprise, RGWCD helped to coordinate the first-of-its-kind groundwater conservation easement in 2022 (Wright et al., 2024). An innovative extension of unbundling surface property rights and selling a portion of them which has long been used by land trusts to limit development or enhance sustainability practices on working land, this expands the potential sources of funds and parties, like the Nature Conservancy, that can potentially draw on land-based laws rather than water rights to address groundwater overdraft.

Lastly, the irrigators of SLV have incrementally increased the pumping fee to further reduce groundwater extraction. During its first 7 years, the policy increased the fee from \$45 to \$150. In a remarkable turn of events, and recognizing that more still needs to be done, SLV irrigators decided in 2024 to drastically increase their pumping fee to \$500/AF (although at the time of writing, the implementation has been delayed due to court challenges). This development, despite it remaining a pumping fee on paper, is likely to fundamentally shift irrigators in Subdistrict #1 to a de facto cap-and-trade system. Recall that (most) irrigators in Subdistrict #1 not only have groundwater wells but also have access to surface water. Each year, each farmer's surface water is recharged into the aquifer, and they are only charged the fee on their pumping net of surface water applied to recharge. At \$500/AF, this steep price will act as a barrier—almost more akin to a fine—to exceeding this limit (to pump a larger quantity of groundwater than what their surface water allocation is that year). In other words, the cap will more-or-less be fluctuating each year as the total annual surface water inflows, implying that Subdistrict #1 irrigators will effectively withdraw the same amount of water that they put into the aquifer each year. Should an irrigator extract fewer acre-feet than their surface water inflows, they will be able to sell these withdrawal credits to another irrigator that wants to pump more than their surface water rights allow. This secondary market has existed from the start of Subdistrict #1 and a handful of trades have been made over the years, but irrigators explained that at \$150/AF, most simply pay the fee to extract more groundwater.[10] At \$500/AF, it is a different story, they say, and they anticipate that an active market for pumping allowances will form and far fewer irrigators will "dip" into the aquifer reserves.

The new fee will intensify the current heterogeneous effects of the fee, with junior surface right holders and groundwater users with no surface rights at all (roughly 14% of the parcels in Subdistrict #1) having to purchase more water on the secondary market for allowances. Meanwhile, because the much larger fee will be a deterrent, but not an actual "fine," irrigators continue to have the flexibility to use more groundwater when conditions (low run-off year) warrant it. There is good evidence that cap-and-trade systems can also enhance the values of irrigated farms, essentially creating property rights to internalize the externalities (Ayres et al., 2021), but this flexible type of cap that SLV is experimenting with is unique, making this farmer-led policy innovation worth watching to unfold.

Data accessibility statement

No new data have been utilized in this paper. Citations to original papers supporting this work are provided in text.

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10. Officials of RGWCD reported to us that from 2012 to 2020, 15,385 AF had been traded in total, or about 1,700 AF each year on average and a mere fraction of the 300,000 AF extracted annually.

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Competing interests

Authors declare that they have no competing interests.

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