Water Market Dynamics in the Presence of Environmental Variability and Government Subsidies

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PRELIMINARY DRAFT

Abstract

The challenges associated with effectively managing water resources are highly salient in arid regions of the world. Water markets have been promoted as an efficient solution, and the foundational requirement for such an approach – a system of comparatively well-defined, tradable property rights – has emerged in some particularly water-stressed areas. Yet, comprehensive, data-driven empirical assessments of water markets' effectiveness in promoting timely reallocation remain scarce. In this paper, we explore whether environmental shocks spur market transactions and also study how public subsidies play a role in these dynamics. We compile a unique dataset that accounts for all recorded water right transactions, all subsidies for water use efficiency, as well as precipitation and temperature patterns in Chile from 1990 to 2020. Our panel dataset enables estimation of the impacts of both persistent environmental shocks (i.e., droughts) and government subsidies at sub-national scale. We provide evidence on water market performance in the face of environmental variability, as well as the nation-wide effects of government subsidies for irrigation technology on exchange.

JEL Codes: D23, P14, P48, Q15, Q25, Q28

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1 Introduction

The promise of market-based mechanisms for addressing challenging environmental and natural resource problems has been a focus of economists for many decades (Coase, 1960; Stavins, 2011). In theory, these mechanisms ought to encourage efficient outcomes by aligning incentives for conservation and reallocation, as well as providing opportunities for low-cost negotiation to resolve competing resource demands. We contribute to this literature by exploring how environmental shocks spur additional water market transactions that could help to redistribute the resource, and how these interact with irrigation infrastructure subsidies. Despite predictions of efficient market allocation, however, transaction costs and other barriers to trading water often hamper exchange and render markets less effective. A better understanding of these obstacles is of interest both academically and for policy applications. In particular, it has important implications for how well suited market approaches may be for climate change adaptation. In addition, we provide insight into how investment subsidies for asset-specific complementary capital affect the dynamics of markets for renewable resources.

Surface water and groundwater, as common-pool resources, may suffer from inefficiently high levels of extraction in the absence of well-designed management and coordinating institutions (Ostrom, 1990). The challenges associated with effectively managing water are already highly salient and pervasive in arid regions of the world. Moreover, changing climatic regimes are expected to increase water scarcity and stress by reducing availability, increasing variability, changing the timing of flows and recharge, and potentially increasing demand, especially for irrigation purposes (Vörösmarty et al., 2000; Covich, 2009; McDonald et al., 2011; Tack, Barkley and Hendricks, 2017). Accordingly, as scarcity and volatility increases, the development of social institutions that can encourage timely, sensible reallocation of water across locations and uses will become more important.

Economists have proposed markets as a solution for many common-pool resource problems, and as an important element of adapting to climate change (Anderson and Libecap, 2014; Anderson et al., 2018). Water is no exception, with markets having been pursued as a key component of management strategies in Chile, Australia, and many states in the Western U.S. (Grafton et al., 2011; Rey et al., 2019). Price signals generated by market participants as they face different environmental, financial, and productivity conditions can prompt both reallocation and intelligent investment decisions in water-related capital and infrastructure, which in turns lead to an increase in efficiency in the system as a whole. Providing a better understanding of the performance of this approach in the face of environmental variability is a key goal of this paper.

The advantage of any market-based institutional regime depends in large part on how easily resource use can be rearranged to realize allocative efficiency gains. This includes the ability to identify high-valued uses at any given point in time, as well as service new demands as they emerge throughout time. In short, markets are most effective when transaction costs are relatively low. Experiences to date with water markets have been mixed, however, in part due to costly barriers arising from measurement difficulties, regulatory restrictions, and political economy pressures. Developing tools to reduce these transaction costs has thus become an important task for improving market function in particular, and adaptive capacity more generally (Grafton et al., 2011; Leonard, Costello and Libecap, 2019).

In this paper, we focus our analysis on one of the few water markets that has been implemented at national scale: Chile's. Chile has maintained a formalized system of tradable property rights to water since 1981. This regulation allowed for the rights of private appropriators to be diverted for consumptive use, but also to be traded. Since then, debate and controversy has emerged regarding how effective the resulting market has been in reallocating water use, with increasing recognition that the market has historically been hampered by consequential transaction costs (Bauer, 2004, 2014). For example, recent studies have documented significant costs of regulatory trading restrictions (Edwards et al., 2018). As a result, new attempts to understand market dynamics in Chile can not only help to improve domestic water allocation, but also provide insights for better institutional design elsewhere. In general, Chile is a good candidate for a case study on water markets, because it presents both areas of reliable abundance as well as regular scarcity under the same institutional framework.

In this paper, we compile a unique dataset that accounts for all recorded water right transactions, all subsidies for water use efficiency, as well as precipitation and temperature patterns in Chile from 1990 to present. Our panel dataset enables estimation of the impacts of both persistent environmental shocks (i.e., droughts), as well as their interaction with government subsidies for irrigation efficiency improvements. We find that persistent drought is associated with an increase in trading for both surface and groundwater rights, suggesting that the market has, overall, provided opportunities for adaptation. Furthermore, government subsidies appear to play a significant role in trading: a 10% increase in year-on-year subsidy disbursements is associated with a 0.2-0.7% increase in transactions in periods of reduced precipitation. However, additional analysis suggests the effects are concentrated when subsides are allocated to small-scale users who may face greater barriers to trading due to credit constraints and missing infrastructure.

The remainder of the paper is structured as follows: Section 2 provides a discussion of transaction costs in water markets, as well as background on the Chilean water market and its development. Section 3 provides a theoretical framework for the problem. Section 4 introduces our data sources. How we employ these data for econometric estimation is described in Section 5. Section 6 summarizes our preliminary results. Section 7 places the results in context and discusses paths forward.

2 Background

2.1 Chile's Water Market Development

The institutional rules governing water in Chile have long recognized private claims to the resource, despite shifts throughout time in the strength of legal protections. In 1967, reforms granted the government substantial control over water resources, but these were overturned in 1981 during Pinochet's rule (Bauer, 2004). The reform claimed water to be a "national good for public use," but affirmed private property rights to water (Donoso, 2015). The 1981 law also unbundled water rights from land tenure and use. This allowed irrigators to trade water used in relatively low-value applications away from their own properties and greatly expanded the scope for markets—thus began the modern era of water marketing in Chile.

Three subsequent reforms are worth noting. In 1999, the Dirección General de Aguas (DGA) increased requirements for irrigation subsidies, requiring formal documentation of water property to be eligible for grants, as well as allowing subsidies for multiple applicants.[1] This change in response to relatively low and concentrated amount of trading (Hearne and Donoso, 2014). Additional reforms in 2005 granted the DGA extended authority to define volumetric claims, levy fees on unused water rights, and impose ecological flow mandates when new water rights are registered in basins with unclaimed flows (Edwards et al., 2018). Nonetheless, the registration of private claims and recording of transactions of those rights remain inconsistent, and the DGA has not successfully adjudicated all claims in many watersheds (Lajaunie et al., 2011). Groundwater rights are particularly lagging in terms of quantification and formalization. This lack of institutionalization has been attributed to the presence of high transaction costs due to uncoordinated stakeholders and a lack of conveyance infrastructure (Hearne and Donoso, 2014). Finally, additional adjustments to the regulation came in 2010, when the the regulation increased subsidy amounts from 70 to 90% of the proposed project cost in the case of small-scale producers, as well as additional considerations that made qualification easier in the case of new irrigation projects.[2]

[1] See the procedures from Law N19,604 here, https://www.bcn.cl/historiadelaley/nc/historia-de-la-ley/6664/

[2] See the procedures from Law N20,401 here, https://www.bcn.cl/historiadelaley/nc/historia-de-la-ley/6664/

Meanwhile, Chile also introduced a subsidy program for irrigation system efficiency improvements in the mid-1980s. The stated goal was to encourage prosperous agriculture by increasing water use productivity. By some accounts, the policy has proved nominally successful: growth in the agricultural sector has outpaced that of the rest of the economy in recent decades (Hearne and Donoso, 2014). One constraint of this subsidy program is that it can only benefit natural and legal persons that hold property rights. Proposed infrastructure investments are evaluated on a case-by-case basis, and if approved, a given fraction of the total cost is covered with public funds. Importantly, this policy influences water market outcomes by increasing water efficiency and developing key conveyance infrastructure. What impact these subsidies might have on the market in practice will depend on the existing level and scope of transaction costs.

Overall, during the lifetime of tradable water rights in Chile, debate has arisen regarding how effective the water market really is in enabling flexible reallocation. As Bauer (2014) notes, initial enthusiasm for the Chilean water market in the 80s and 90s was tempered by later realization that the level of clarity in rights definition (i.e., volumetric certainty, legal security, and clear expectations of how third-party impacts would be handled) that would enable low-cost, routine transactions was not present. Nonetheless, other voices argue that the Chilean water market is broadly meeting needs and reallocating use reasonably well despite a lack of regular large-scale water transfers (Hearne and Donoso, 2014).

2.2 Transaction Costs in Water Markets

Ample opportunities arise for technical, social, and regulatory issues to hamper trade in water. Some of these are usefully summarized by Leonard, Costello and Libecap (2019) in the context of the western United States. These costs include in large part the barriers that regulatory agencies impose to address external impacts of transfers, the costs of defining rights and assessing such external impacts (e.g., measurement), conveyance constraints, and pressure from those who suffer negative pecuniary impacts. These barriers arise in other countries as well, and a representative but not exhaustive list of general sources of transaction costs includes:

- **Measurement requirements**: Where rights are defined to diversions (which is typically the case), a trade may require estimation of existing consumptive uses of water (e.g., crop evapotranspiration) to assess whether downstream users will be harmed by a proposed transfer. In basins where a detailed adjudication of water use and entitlements has not already been undertaken, this imposes costs on exchange parties.
- **Conveyance constraints**: Marketing surface water typically requires ensuring deliv-

ery to the new user. This might entail either changing a point of diversion within a given physical system or moving water out of one system to another. In either case, a suitable conveyance network may not exist, may suffer from capacity constraints, or—even where infrastructure exists and has capacity—may be subject to market power on the part of the conveyance owner. This necessarily imposes sometimes significant costs that may render trades uneconomical.

- **Intersectoral differences**: Much interest in water markets concerns transfers from relatively low-value agricultural uses to municipal or industrial uses. Costs described in the preceding two bullet points apply especially to such transfers: While agriculture-to-agriculture trades may entail external costs (e.g., if a transfer entails reduced flow in shared distribution infrastructure), the scope and scale of these may be larger in intersectoral, inter-basin trades and require more effort to demonstrate or avoid. Furthermore, these distinct use types are often not located near one another, increasing the need for costly conveyance.
- **Security of rights**: In some cases water rights are subject to use restrictions (e.g., that water must be put to "beneficial use" in the western US) or perhaps even subject to risk of government expropriation. For example, a beneficial use restriction may cause water that is freed up due to irrigation efficiency improvements to be viewed as having been "wasted" or used non-beneficially prior to its sale, potentially rendering rights to that water volume void (Bretsen and Hill, 2008). Insofar as these uncertainties reduce the expected net gains from acquiring or attempting to sell rights, exchange is less likely to occur.
- **Political economy pressures**: Opposition to water trades often arises from local communities that do not hold water rights yet are nonetheless believed to rely on agricultural production for their economic well-being. Where water trades entail a reduction in irrigated acreage, external parties may exert political influence to block such transfers. Just as policies to mitigate greenhouse gas emissions often elicit opposition from coal-dependent communities (in addition to extractive industries themselves), water markets suffer from similar local political economy obstacles.

Our primary focus is to consider how these transaction costs may inhibit trading in response to variation in environmental conditions. When a drought restricts supply or high temperatures induce additional consumptive water demand, an efficient allocation will see some low-value uses that were undertaken during relative abundance curtailed or given up altogether. If this is accomplished through market mechanisms, trade volumes could increase.

Evidence for such responses in other water markets around the world is mixed. Two examples, the Murray-Darling Basin market in Australia and California's water market, showcase this disparity. From 1996 to mid-2010 Australia experienced what is now called the "Millenium Drought," a long-term persistent dearth of rainfall that stressed agricultural communities as well as municipal drinking water suppliers. Nonetheless, trading volumes were relatively high compared to those during subsequent La Niña events, especially for annual allocations.[3] Evidence suggests that the market was broadly successful in reallocating water for short- and medium-term needs (Hughes, Gupta and Rathakumar, 2016).

Thereafter, California experienced a similar, if somewhat shorter, drought from 2012 through 2015; in contrast to the Australian experience, observed volume of water traded did not increase (if anything, it appears to have declined). While it is likely that informal trading helped to reduce the costs of addressing scarcity within agricultural irrigation districts, intersectoral trades were few. This has many causes, including constraints due to limited conveyance infrastructure (Regnacq, Dinar and Hanak, 2016). A salient example of a regulatory barrier to trading is state water conservation mandates that water utilities faced during this period. The State of California imposed administrative water conservation targets, relative to a pre-drought baseline, on major municipal water purveyors. While it is not the case that all mandated conservation could be cost-effectively substituted through market transactions, trading with agriculture, or even between municipalities, may have reduced some of the hundreds of millions in losses suffered by utility ratepayers (Nemati, Buck and Sunding, 2018). More broadly, recent trading volume in California's market appears to be largely insensitive to the drought conditions, as documented by Hanak and Stryjewski (2012).

In Chile, transaction costs and other restrictions that inhibit trading have been documented as well. The national DGA has authority to restrict water transfers to achieve some political objectives, and these interventions may inhibit both cost-effective permanent reallocation and adaptation to temporary drought. One salient example is the determination by regulators that agricultural rights purchased on the market in northern Chile may not be used for mining activities; the motivation is the protection of indigenous agricultural uses and riparian ecosystems. These restrictions may deliver net benefits if environmental or indigenous uses have large spillovers and coordination among beneficiaries is costly. However, the northern reaches of Chile are the most arid in the country and where the most high-valued uses of water can be found (Hearne and Donoso, 2014). As a result, the costs of misallocation are very high. In lieu of a market remedy, mining firms have invested in costly desalination. The costs of these restrictions have been estimated in the tens of millions of dollars per year (Edwards, Cristi and Díaz, 2012; Edwards et al., 2018). In addition to regulatory constraints,

[3] In the Murray-Darling, entitlements represent claims to water in perpetuity, the actual volume of which that is available in any given year being administratively determined according to pre-determined rules. Available volumes are known as allocations.

administrative capacity shortfalls have historically limited the government's ability to accurately define claims and enforce rights, which also reduces incentives to trade. In particular, this could result both in a diminution of perceived security as well as a need to undertake costly measurement procedures when attempting to market water. Indeed, resolving conflict over volumetric entitlements in Chile has historically often involved costly private litigation (Grafton et al., 2011). We assess whether—under such conditions—Chilean water markets appear broadly capable of responding to changing environmental conditions.

3 Theory

In this section we outline a simple model depicting the decision making of firms when faced with climate uncertainty that affects water availability building on Pommeret and Schubert (2018), who study emission permit dynamics in the face of uncertainty and irreversibility. Their model is partially amenable to the water problem because we are concerned with incentives for extracting water and investing in conveyance or irrigation technology. Note, however, that this model assumes banking, which is not a one to one relationship with water dynamics, but it provides some guidance in terms of the decision making regarding inter temporal allocation of water. The question of interest is how environmental variability affects individual decisions for water consumption and investment on irrigation technology.

Consider a two period competitive water market with N risk-neutral firms. Other than water reduction, assume all other production decisions as given. The cost of reducing water consumption in firm i is given by $C_i(Q_i, K_i) = c_i Q_i^{\alpha} K_i^{-\beta}$ as consumption reduction and water efficiency capital (henceforth technology), respectively. The parameters satisfy $c_i > 0$, $\beta > 0$, and $\alpha > 1 + \beta$. Conveniently, the aggregate cost function is the envelop of the individual cost functions. That is, if $Q = \sum_i Q_i$ and $K = \sum_i K_i$, then aggregate cost of water reduction is given by $C(Q, K)$. The cost function satisfies $C(0, K) = 0$, it is convex in consumption reduction, $\partial C_i/\partial Q_i > 0$, $\partial^2 C_i/\partial Q_i^2 > 0$, and concave in technology, $\partial C_i/\partial K_i < 0$, $\partial^2 C_i/\partial K_i^2 > 0$.

A single-period market clearing condition implies:

$$C(Q,K) = cQ^{\alpha}K^{-\beta} \;\text{ with }\; c = \left(\sum_i c_i^{\frac{1}{1+\beta-\alpha}}\right)^{1+\beta-\alpha} \tag{1}$$

It follows that individual consumption reduction and technology investment are given by:

$$Q_i = Q\left(\frac{c}{c_i}\right)^{\frac{1}{\alpha-(1+\beta)}} \;\text{ and }\; K_i = K\left(\frac{c}{c_i}\right)^{\frac{1}{\alpha-(1+\beta)}} \tag{2}$$

In the absence of a cap and fixing individual output, each firm extracts an unregulated set amount of water $\bar{U}_i$ both time periods. It follows that total unregulated extraction is given by $\bar{U} = \sum_i \bar{U}$. Suppose now that the regulator sets an overall cap on extraction at time t, W_t, which is then distributed to individual firms as W_{it}. For the cap to be effective, it must be that $W_t < \bar{U}$ and $W_t = \sum_i W_{it}\ \forall\ t \in \{1, 2\}$. Firms are also allowed to bank extraction permits across periods. Banking is denoted as B_{i1}, and total banking in the market is given by: $B_1 = \sum_i B_{i1}$. One can think of banking in the water context as farmers storing water in the form of artificial reservoirs. In the Chilean context these structures are known as "tranques."[4]

At time 1, the firm knows the rights assigned, but in the next period there is a chance that its allocated extraction rights might be adjusted due to changes in the recharge of the water basin. On the one hand, the total cap could be increased to $W_1 + \bar{\Delta}$, $\bar{\Delta} > 0$, with probability q. On the other hand, the total cap could be reduced to $W_1 - \underline{\Delta}$, $\underline{\Delta} > 0$, with probability $1-q$. To ensure the validity of the market, the cap is always binding, $W_1 + \bar{\Delta} < \bar{U}$. It follows that each firm's extraction rights in the next period could be adjusted to $W_{i1} + \bar{\Delta}_i$ with probability q, or to $W_{i1} - \underline{\Delta}_i$ with probability $1 - q$. Consequently, $\bar{\Delta} = \sum_i \bar{\Delta}_i$ and $\underline{\Delta} = \sum_i \underline{\Delta}_i$, and $\mathbb{E}_1[W_{i2}] = W_{i1} + q\bar{\Delta}_i + (1 - q)\underline{\Delta}_i$. It follows that total individual intertemporal consumption changes are given by $Q_{i1} + Q_{i2} = 2(\bar{U}_i - W_{i1}) + \underline{\Delta}_i - q(\underline{\Delta}_i + \bar{\Delta}_i) = \eta_i(q)$. For a given firm, $\eta_i(q)$ could be either positive or negative, but total reduction in consumption, $\eta(q) = \sum_i \eta_i(q)$, must be strictly positive.

Firm i chooses water reduction, Q_{it}, technology levels, K_{it}, and banking, B_{i1}, so as to minimize the total discounted cost from water reduction. The unit price of technology is exogenously given by k, and the firm-level of technology investment is denoted as I_{it}. Assume further that investment is fully reversible and capital can be traded at price k. The firm takes water right prices, p_t, as given. The firms' discount factor is common and given by δ. With this setting, the Bellman equation for an initial level of technology at time 1, K_{i0}, is given by:

$$V_{i1}(K_{i0}, W_{i1})) = \min_{Q_{i1}, I_{i1}, B_{i1}} \{C_i(Q_{i1}, K_{i0} + I_{i1}) + kI_{i1} - p_1 \left(W_{i1} - (\bar{U}_i - Q_{i1}) - B_{1i}\right) + \delta\mathbb{E}_1 \left[V_{i2}(K_{i1}, W_{i2}))\right]\} \tag{3}$$

[4]As climate conditions increase water scarcity, the Chilean government has increasingly encouraged this type of productive adaptation. See for instance Bill N16193-01, which was introduced to facilitate and encourage artificial reservoirs for small-scale producers. Available at: https://www.camara.cl/legislacion/ProyectosDeLey/tramitacion.aspx?prmID=16740&prmBOLETIN=16193-01

with

$$\mathbb{E}_1\left[V_{i2}(K_{i1}, W_{i2})\right] = qV_{i2}(K_{i1}, W_{i1} + \bar{\Delta}_i)) + (1-q)V_{i2}(K_{i1}, W_{i1} - \underline{\Delta}_i)) \tag{4}$$

This problem can be solved using standard dynamic programming (See Appendix for solutions and proofs). First, consider the case when there is no uncertainty and, at period 1, all firms know the cap in period 2. Optimal water consumption reduction, technology investment, and banking in period 1 would be given by:

$$Q_{i1}^* = \frac{\eta_i(q)}{1+f(\delta)}\ ;\ f(\delta) = \left(\left(\frac{1-\delta}{\delta}\right)^{\beta}\frac{1}{\delta}\right)^{\frac{1}{\alpha-(1+\beta)}} \tag{5}$$

$$K_{i1}^* = \left(\frac{\beta c_i}{(1-\delta)k}Q_{i1}^*\right)^{\frac{1}{1+\beta}} \tag{6}$$

$$B_{i1}^* = \frac{(\bar{U}_i - W_{i2}) - f(\delta)(\bar{U}_i - W_{i1})}{1+f(\delta)} \tag{7}$$

It follows that under the existence of a binding cap, first period water consumption reduction is always positive. Banking on the other hand, could be either positive or negative depending on the relationship between uncapped consumption, and caps on both periods in relation to $f(\delta)$. We denote this benchmark as the deterministic scenario, which will be the baseline to establish how the firm reacts to uncertainty. Consider now the case when firms face uncertainty over the cap in the second period. Denote this solution with a # symbol. It can be shown that optimal water consumption reduction, technology investment, and banking in period 1 would be now given by:

$$f(\delta)Q_{i1}^{\#} = \left(q\ \underline{Q}_{i2}^{\#\,\frac{\alpha-(1+\beta)}{1+\beta}} + (1-q)\ \bar{Q}_{i2}^{\#\,\frac{\alpha-(1+\beta)}{1+\beta}}\right)^{\frac{1+\beta}{\alpha-(1+\beta)}} \tag{8}$$

$$K_{i1}^{\#} = \left(\frac{\beta c}{(1-\delta)k}Q_{i1}^{\#}\right)^{\frac{1}{1+\beta}} \tag{9}$$

$$B_{i1}^{\#} = Q_{i1}^{\#} - (\bar{U}_i - W_{i1}) \tag{10}$$

The total effect of uncertainty, relative to the deterministic case, can be formalized as follows:

Proposition 1 *Under uncertainty over the total extraction cap in the second period, W_2, both total water consumption, Q_1, and total technology investment, I_1, increase (decrease) if and only if $\alpha > (<)2(1+\beta)$.*

In words, if the marginal cost of reducing water consumption is convex (concave), uncertainty encourages firms to decrease (increase) their water consumption and investment in technology. In general, firms have an incentive to invest because it reduces the marginal cost of decreasing water consumption, which is exogenously imposed by the regulator. Accordingly, there is an intrinsic tradeoff between reducing consumption across periods, and the possibility of having the allocation reduced in period 2 creates incentives for banking and investing so as to avoid an excessive increase in costs due to further limits in extraction. As the cap could become binding with some probability, total reduction in water consumption in period 1 increases. The convexity of the cost of reducing consumption then implies that the marginal value of a unit of water rights will increase accordingly, and so does the price at which water rights are transacted in the market in the initial period.

These adjustments drive two distinct effects. First, uncertainty around the future cap encourages water use efficiency through an overall reduction in consumption as well as investment in technology. Second and more importantly for this study, an increase in the value of the water permits results in low-reduction-cost firms releasing their permits to the market. This result is formalized as follows:

Corollary 1 *Under convex costs of water consumption reduction and uncertainty over the total extraction cap, the price of water permits increases and so does the volume of permits released in the market.*

This corollary is a particularly powerful prediction, and it lies at the core of some of the hypothesized advantages of markets. In the face of scarcity, markets would allocate the resource from low to high value users. Operationally, this results follows from the convexity of the cost function. Our task is now to evaluate if the prediction holds in an empirical setting. The next sections cover the data utilized, as well as our strategy to evaluate if this prediction holds in our case study.

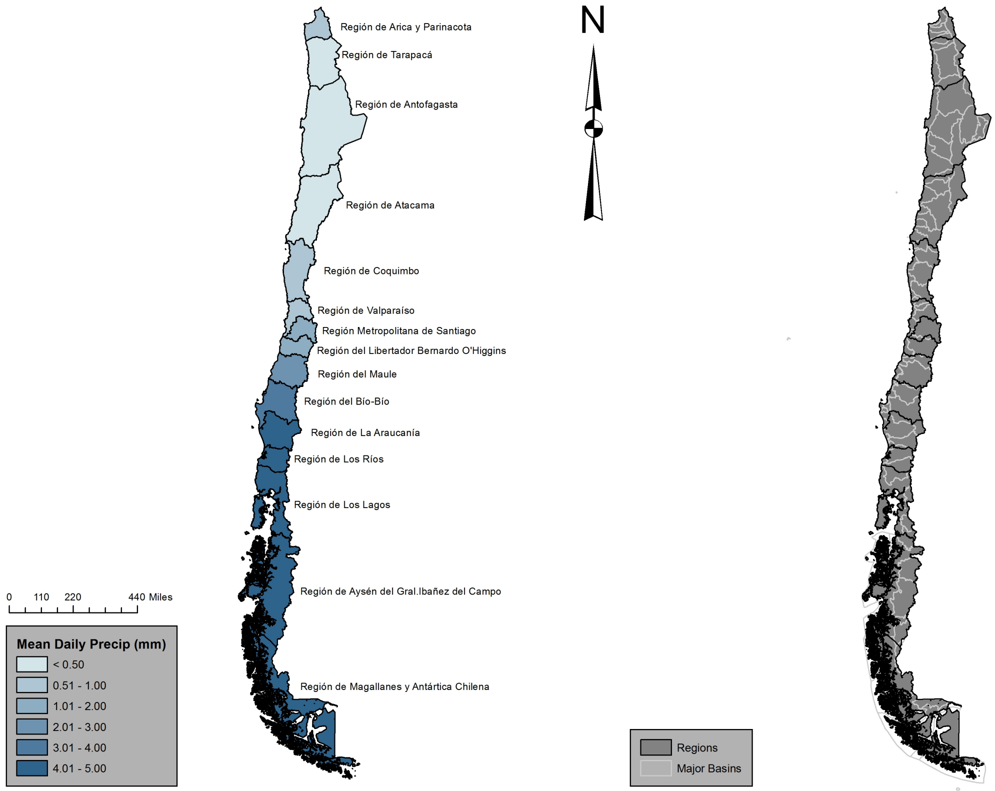
4 Data

Our dataset is compiled from two main sources: the US National Oceanic and Atmospheric Administration (NOAA) and the Chilean agency in charge of managing access, disposal and treatment of water resources in Chile (DGA).[5]

Precipitation and temperature data are taken from NOAA's Precipitation Reconstruction over Land (PREC/L) data product. Historical daily measures are available for the time period covered by our transaction and subsidy data at 0.5 × 0.5 degree resolution. The left panel of Figure 1 shows mean daily precipitation by region.

[5]DGA stands for "Dirección General de Aguas.i"

Figure 1: Chile: Precipitation & Watersheds

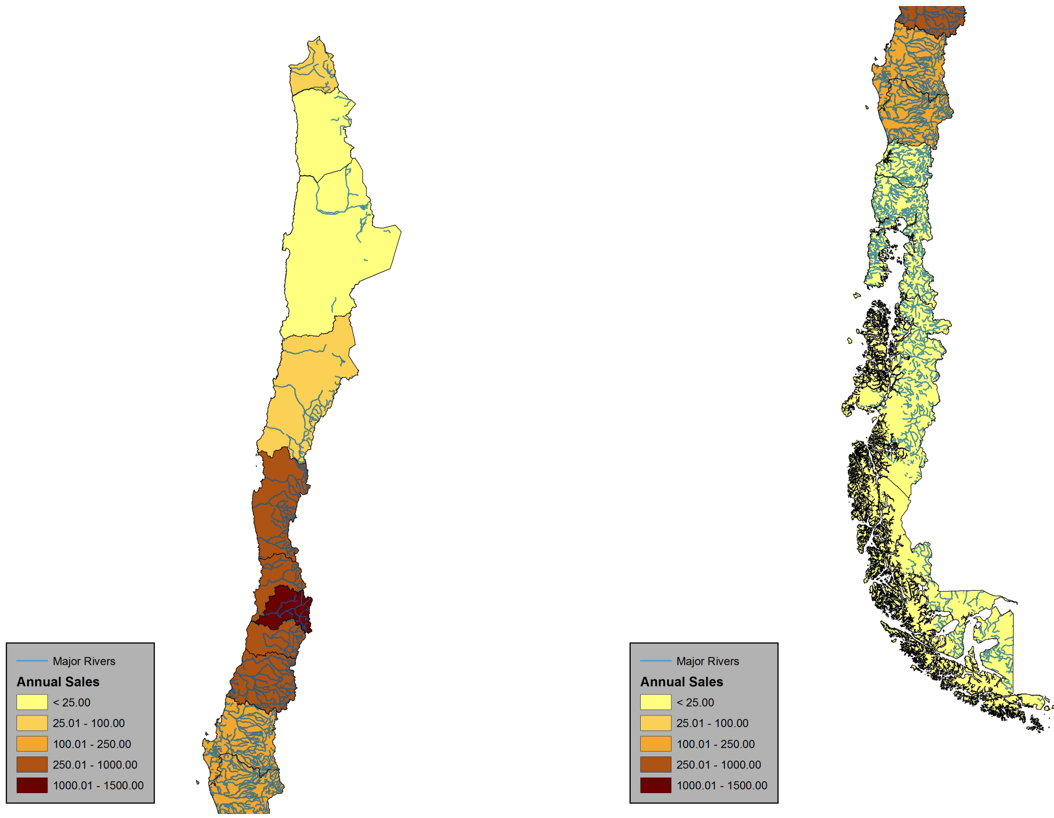


Notes: Maps of Chile with regions outlined. Left panel shows daily precipitation mean from 1950-2020 by region, while right panel illustrates how regional boundaries sometimes span multiple watersheds.

We couple these measures with DGA data containing all subsidy disbursements and permanent transactions from 1990 to 2020. The transaction data include transfers of both surface water diversion and groundwater extraction rights. We restrict our attention to transfers flagged as market sales in order to omit those between family members as well as bequests. The subsidy data include project-level information on the amount of subsidy provided as well as total project costs. Subsidies have been disbursed regularly in all Chilean administrative regions; Figure 3 presents the logarithm of subsidy disbursements by region.

Table B.1 from Appendix B.1 summarizes these measures by administrative region. We conduct our analysis using the subregion-level cross-sectional units known as comunas (i.e., municipalities within an administrative region).

Figure 2: Chile: Rivers & Trading Frequency



NOTES: Maps of Chile with regions outlined and colored by trading frequency (mean annual sales, 1979-80 to 2014-15). Left panel shows north part of the country, and right panel south.

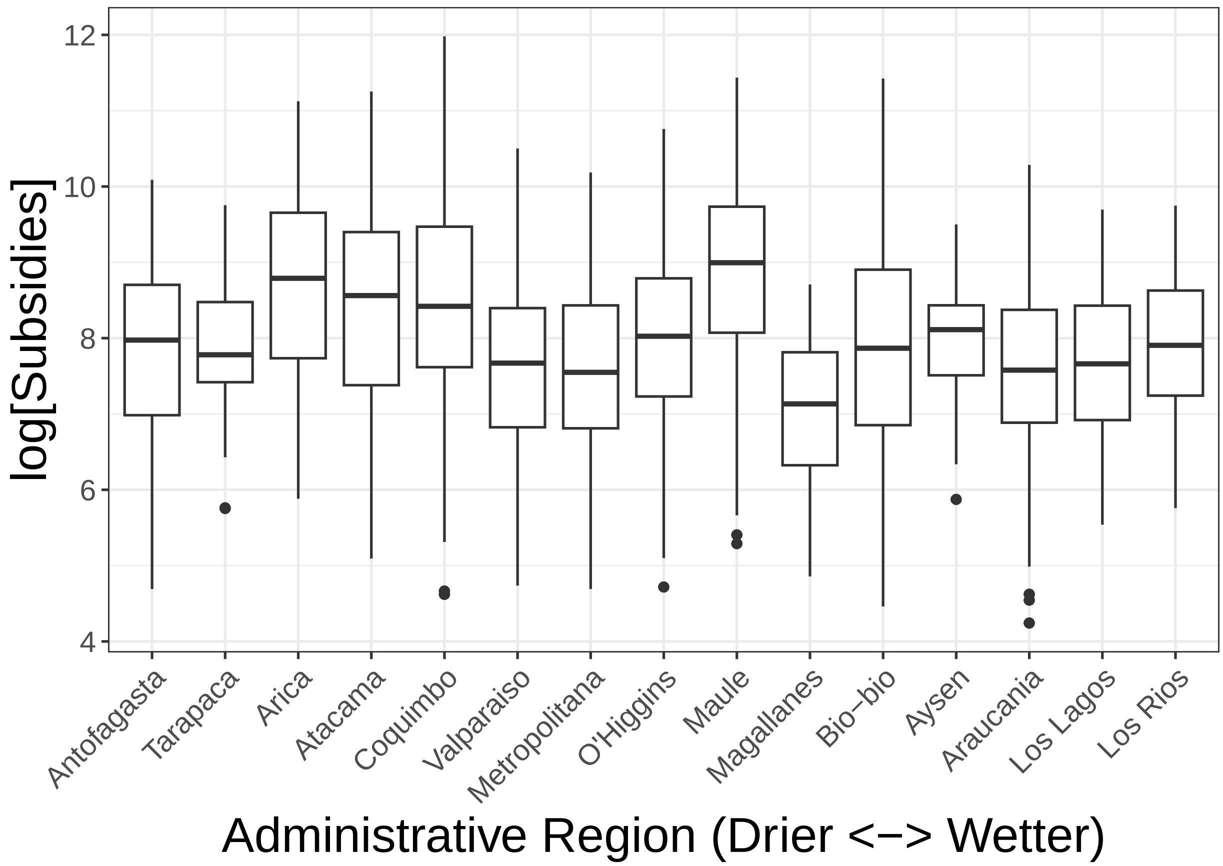
5 Empirical strategy

This section describes our estimation strategy and econometric assumptions. To evaluate how the market responds to climate variability, we estimate several different specifications based on the following linear model:

$$\log(T_{crt}) = \alpha + \beta \ \text{asinh}(S_{ct-1}) + \gamma' \mathbf{V}_{ct} + \delta' [\mathbf{V}_{ct} \times \log(S_{ct-1})] + \phi_c + \theta' \mathbf{X}_{rt} + \epsilon_{crt} \qquad (11)$$

in which T_{ct} are transactions in comuna c in year t, S_{it-1} is the subsidy disbursement amount in the previous year, and $\mathbf{V}_{ct}$ is a vector of climatic variables (i.e., precipitation and temperature). ϕ is a comuna-fixed effect, and $\mathbf{X}_{rt}$ is a vector of region and year fixed effects. The climatic variables represent, for any given year t, the 3-, 5-, or 7-year (preceding) running-average of the deviations from the long-term (1947-2020) mean, normalized by the standard deviation. These measures include deviations from annual total precipitation and mean annual temperature and are designed to capture the degree of persistent environmental

Figure 3: Subsidy Distributions by Region



NOTES: Mean, interquartile range, and 5- and 95-percentile values are shown for each Chilean region. Drier regions occupy the left side of the horizontal axis, with annual average precipitation increasing to the right.

deviation. We choose this measure because very short-term environmental shocks—say, a single dry year —are likely to induce adaptations in local, informal markets, perhaps even leveraging water-sharing agreements within a small water user association. These types of exchanges are typically not reported to the DGA and would not appear in our data. Our results therefore characterize the decisions to reallocate water that are based on persistent drought and/or medium- to long-term periods of high temperatures. For ease of interpretation we will work with the negative of the precipitation deviation so as to reflect particularly dry years.

Identification requires that both subsidies and climate variables are uncorrelated with the error term. Naturally, only climate variables are plausibly exogenous to other determinants of individual transactions. In contrast, subsidy disbursement is almost certainly not random and indeed likely to be correlated with regional and local unobservables that impact trading. This fact limits any causal interpretation of the estimates reported in the next section; nonetheless, the fixed effects approach described above will account for systematic distribution of subsidies to high-value places or years. We believe, even in the absence of a quasi-experimental setting or instrumental variables approach, that Eq. (11) provides a strong basis for understanding how subsidy disbursement may be broadly associated with market activity. Moreover, we will use the dynamics inherent to the panel, as well as the changes in subsidy regulation to shed further light into how subsidies and climate stressors relate to trading patterns.

6 Results

Table 1 presents the estimation results for several variations on our estimating equation, Equation (11). In particular, in columns (1) to (5) we test for the robustness of our parameters of interest to different combinations of fixed effects. Our preferred climatic measure is the 5-year running-average deviation, but Appendix B provides several replications of the analysis under different climate time lengths.

Table 1: Main Panel Estimation Results

	(1)	(2)	(3)	(4)	(5)
asinh(Subsidies)	0.06***	0.03***	0.00	0.00	0.00
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
(-)Precip. Dev.	0.05*	0.04	−0.08	−0.08	−0.04
	(0.03)	(0.04)	(0.06)	(0.06)	(0.12)
Temp. Dev.	0.10*	0.14***	−0.14**	−0.14**	−0.26*
	(0.05)	(0.05)	(0.06)	(0.06)	(0.15)
asinh(Subsidies)×(-)Precip. Dev.	0.07***	0.08***	0.05***	0.05***	0.06***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
asinh(Subsidies)×Temp. Dev.	0.00	0.01	0.02***	0.02***	0.02**
	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
(-)Precip. Dev.×Temp. Dev.	0.18***	0.18***	0.04	0.04	0.04
	(0.05)	(0.05)	(0.06)	(0.06)	(0.13)
asinh(Subsidies)×(-)Precip. Dev.×Temp. Dev.	−0.04*	−0.03	−0.02	−0.02	−0.02
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Observations	9,912	9,912	9,912	9,912	9,912
Comuna FE		X	X	X	X
Year FE			X	X	
Region FE				X	
Region-by-Year FE					X

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Standard errors are clustered by comuna. Climate variables based on 5-year running-average deviations.

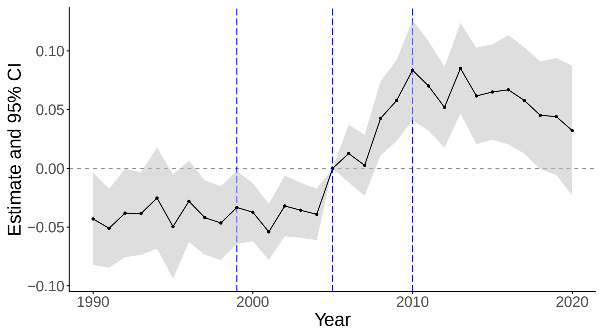
The estimated relationship between lagged subsidy disbursements and trading volume is clearly sensitive to the inclusion of spatial and time fixed effects. Given the large variation in the distribution of regional subsidy amounts shown in Figure 3, it may be that subsidies flow to areas where markets are particularly active for unobserved reasons, e.g., agricultural production is heterogeneous. The inclusion of both region and year fixed effects, as well as comuna fixed effects sheds further light onto these concerns; after including those, subsidies appear to have a negligible effect on their own. The saturated fixed effect approach in column (5) will be our preferred specification for all subsequent analyses.

Meanwhile, the relationship between medium-term temperature anomalies and trading volume is much clearer. After controlling for year and comuna fixed effects, as higher temperatures intensify across years, less water is traded. However, two facts are worth noting in interpreting this result. First, water rights in the Chilean system are defined in terms of diversion and not consumptive use; if high temperatures increase crop evapotranspiration, return flows from irrigated fields may decline with no associated real-time increase in perceived scarcity for many or most diverting parties. In other words, the institutions governing the water management system may not accurately convey this increased scarcity to users. Second, it may not be the case that warm years are associated with increased scarcity: El Niño events in Chile are associated with both increased annual temperature and precipitation. As a result, warm years are also associated with more rainfall, which is likely the dominant driver of water scarcity and ultimately market outcomes. On its own, however, there is no significant relationship between medium-term (negative) precipitation anomalies and the amount of trading in the country.

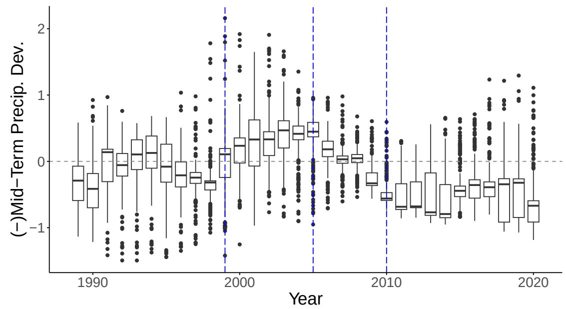
Finally, coefficient estimates on the interaction between climate variables and subsidies across the country suggest subsidies might matter depending on the climate conditions affecting the different markets. Specifically, the coefficients in Table 1 suggest subsides and dry medium-term conditions are associated with an increase in the amount of trades (asinh(Subsidies)×(-)Precip. Dev.). This coefficient is highly robust to the inclusion of multiple fixed effects and statistically significant at the 1% level. The interaction between subsidies and temperature is also positive and significant (at the 1 and 5%) across the models with spatial and temporal fixed effects.

Interactions between the climate variables, as well as with the subsidies are not statistically significant. These results suggest that a substantial share of the variation in trades is fully captured by the location of these markets across the country as mentioned above.

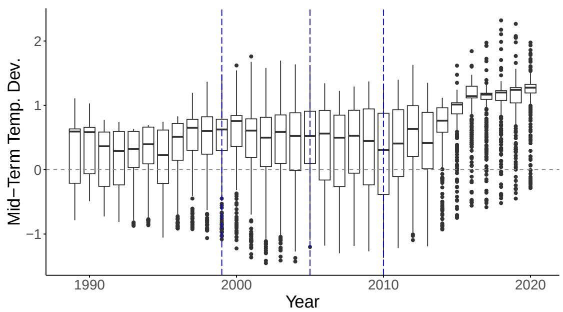
These results, however, highlight a puzzling pattern. How come subsidies had a negligible effect on trades on their own? Have they no effect in terms of the allocation of use and trade of rights across the system? We shed further light into this issue by relaxing the effect of subsidies and making them time-variant. The rest of the estimating variables remain unchanged. This relaxation also allows us to explore the timing and effects that policy changes have had in the patterns of trade. Recall that there are *three* relevant policy changes after 1990. First, the requisite of formal ownership of water to apply to subsidies in 1990. Second the introduction of fees on unused water rights, as well as the requirement of ecological flow mandates for brand new registered rights in 2005. Third and final, the increase in subsidy shares from 70 to 90% for small firms in 2010. We explore these dynamics in Figure 4.



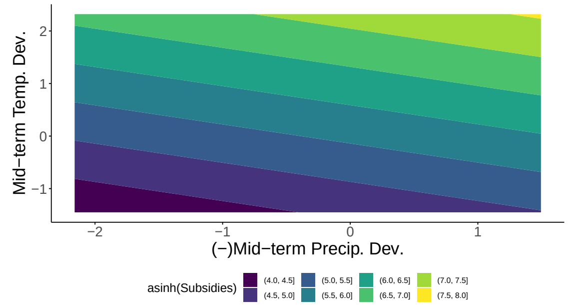
(A) asinh(Subsidy) vs asinh(Transactions)



(B) Precipitation Patterns over Time



(C) Temperature Patterns over Time



(D) Climate Variables and Subsidies

Figure 4: Dynamic and Inter-Variables Patterns

Panel (A) plots the dynamic relationship between subsidies and trades. Policy changes are indicated by the vertical, dashed, blue lines. The figure indicates a significant shift in the relationship between transactions and subsidies from 2005 onwards and it coincides with the policy change in which fees started to be leveraged on unused water rights. After the policy change, subsidies are associated with positive trades, which in turn would explain the overall close to zero effect, in average, over time. A potential explanation to this pattern is the possibility of farms intensifying production as the market matures, and then using capital investments to facilitate trade, which is encouraged by the penalties leveraged for standing rights. The effect of subsidies appears to dissipate by the end of the sample which might suggest that most of the potential allocations facilitated by these subsidies have already taken place by 2020.

This pattern, however, needs to be put in context. At the same time that these policy changes take place, and trade patterns evolve, there are significant shifts in climate conditions. Panels (B) and (C) illustrate this evolution as it becomes clear that conditions across the country are become both drier and hotter, especially after 2010. If this is the case, it is then natural to ask if many of the patterns identified in Table 1 are also a result of subsidies flowing to places suffering dry or hot spells as reflected by their deviations from historical means. This linkage is confirmed in panel (C) where we predict subsidies for a representative comuna. The contour plot confirms that subsidies increase in both past precipitation and temperature. This linkage then explains, in part, our main results. Subsidies appear to flow to places under stress for production, which can be used to decrease transactions costs and facilitate the allocation of rights under these new conditions. It is worth noting how extreme the conditions have become across the country, and how markets have reacted to these changes.

We now explore whether these responses vary depending on the source of water. These results are presented in Table 2 and reveal important patterns within the sample. First, we note that on their own, subsidies are only significantly associated with groundwater transactions; moreover this relationship is negative, which suggests a potential role of subsidies in production intensification and efficiency gains. We explore this question below using additional information on the different purposes of subsidies as reported by the DGA.

Second, we see that for both groundwater and surface water the interaction between subsidies and medium-term precipitation anomalies is statistically significant and positive. That is, subsidies in uncommonly dry years are associated with an increase in transactions. The estimates are relatively robust across specifications and suggest an approximate elasticity of 0.02 and 0.06 for groundwater and surface water, respectively.

Medium-term temperature variation remains negative for both sources of water, but it's only significant for groundwater. We note that this is the largest effect we are able to measure with these data, and highlights the potential decision making process of different players in the market. Our estimates suggest that a 10% increase in medium-term temperature deviation is associated with about a 2.7% increase in the amount of transactions registered in a given comuna. The interaction between subsidies with mid-term temperature deviation is also positive and point to an elasticity of 0.01.

Next, we shed light on how different types of subsidies affect trades. When assigning subsidies, DGA tracks multiple feature of the grantees, including the purpose of the project being subsidized. In particular, DGA identifies if the grant is used for irrigation, conveyance, or drainage purposes. Moreover, DGA also keeps track of the scale of operation of the grantee, which can be grouped into large, medium and small operations. These categories follow formal classifications used for tax purpose and are thus also reflective of the volume of

Table 2: Panel Estimation Results by Source

	Groundwater			Surface		
	(1)	(2)	(3)	(1)	(2)	(3)
asinh(Subsidies)	0.00	−0.01**	−0.01***	0.01	0.01	0.00
	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)
(-)Precip. Dev.	−0.03		−0.02	−0.03		−0.06
	(0.08)		(0.07)	(0.11)		(0.11)
asinh(Subsidies)×(-)Precip. Dev.	0.02**		0.02**	0.05***		0.06***
	(0.01)		(0.01)	(0.01)		(0.02)
Temp. Dev.		−0.28**	−0.27**		−0.22	−0.18
		(0.11)	(0.11)		(0.15)	(0.14)
asinh(Subsidies)×Temp. Dev.		0.02***	0.01***		0.02*	0.01
		(0.01)	(0.00)		(0.01)	(0.01)
(-)Precip. Dev.×Temp. Dev.			−0.01			0.04
			(0.08)			(0.12)
asinh(Subsidies)×(-)Precip. Dev.×Temp. Dev.			0.00			−0.02
			(0.01)			(0.02)
Observations	9,912	9,912	9,912	9,912	9,912	9,912
Comuna FE	X	X	X	X	X	X
Region-by-Year FE	X	X	X	X	X	X

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Standard errors are clustered by comuna. Climate variables based on 5-year running-average deviations.

production. As noted in the background section, only individuals with formal water rights are eligible to receive subsidies. These results are shown in Table 3, where we keep track of the nature of the water right, the type of project that is being subsidized, and the scale of operation, respectively. We do not include drainage subsidies in the text are these are a relatively tiny share of subsidies overall, and have negligible effects for the purpose of this paper.

These results illustrate several patterns that explain our previous observations. According to our analysis, most of the significant effects measured in the data appear to come from trades in groundwater. This is consistent with the observation that groundwater was the less developed sector in the industry, and thus point to subsidies potentially playing an important role reducing transaction costs between across multiple right holders. We note, however, that surface water trading is also exhibiting meaningful patterns associated with subsidies and climate, but these are constrained to the interaction between subsidies and mid-term precipitation deviation.

We break down the results by panel. First, Panel A in Table 3 shows that subsidies destined to support conveyance infrastructure only have a statistically significant (95%) effect when it comes to groundwater and large firms. Moreover, these results are negative.

Table 3: Panel Estimation Results by Source, Type of Subsidy, and Firm Size

	Groundwater				Surface			
	(All)	(Large)	(Medium)	(Small)	(All)	(Large)	(Medium)	(Small)
Panel (A): Conveyance subsidies								
asinh(Subsidies)	-0.01**	-0.04**	-0.01	-0.01*	-0.00	-0.05*	-0.00	-0.00
	(0.00)	(0.01)	(0.01)	(0.00)	(0.01)	(0.03)	(0.01)	(0.01)
(-)Precip. Dev.	-0.02	0.04	0.00	-0.00	-0.05	0.11	0.03	-0.01
	(0.07)	(0.08)	(0.08)	(0.07)	(0.11)	(0.12)	(0.11)	(0.11)
Temp. Dev.	-0.27**	-0.26**	-0.27**	-0.27**	-0.17	-0.19	-0.20	-0.17
	(0.11)	(0.11)	(0.11)	(0.11)	(0.13)	(0.14)	(0.14)	(0.13)
asinh(Subsidies)×(-)Precip. Dev.	0.02**	-0.03	0.04***	0.02*	0.08***	-0.04	0.09***	0.08***
	(0.01)	(0.03)	(0.01)	(0.01)	(0.02)	(0.04)	(0.03)	(0.03)
asinh(Subsidies)×Temp. Dev.	0.02***	-0.01	0.01*	0.02***	0.01*	0.04	0.01	0.01
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.05)	(0.01)	(0.01)
(-)Precip. Dev.×Temp. Dev.	0.01	-0.01	-0.02	0.03	0.10	-0.04	-0.01	0.10
	(0.08)	(0.10)	(0.09)	(0.08)	(0.12)	(0.18)	(0.15)	(0.12)
asinh(Subsidies)×(-)Precip. Dev.×Temp. Dev.	-0.01	0.04	0.01	-0.01	-0.04	0.06	-0.02	-0.05
	(0.01)	(0.05)	(0.02)	(0.02)	(0.03)	(0.07)	(0.04)	(0.03)
Panel (B): Irrigation subsidies								
asinh(Subsidies)	-0.00	-0.01**	-0.01	0.01	0.01	-0.01	0.00	0.03***
	(0.00)	(0.01)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
(-)Precip. Dev.	-0.01	0.03	0.00	0.01	-0.01	0.10	0.01	0.04
	(0.07)	(0.08)	(0.07)	(0.07)	(0.11)	(0.12)	(0.11)	(0.11)
Temp. Dev.	-0.26**	-0.26**	-0.28**	-0.24**	-0.17	-0.20	-0.20	-0.12
	(0.11)	(0.11)	(0.11)	(0.11)	(0.13)	(0.14)	(0.13)	(0.12)
asinh(Subsidies)×(-)Precip. Dev.	0.02**	0.01	0.02**	0.03**	0.05***	0.02	0.05***	0.06***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)
asinh(Subsidies)×Temp. Dev.	0.01*	-0.01	0.01**	0.01	0.00	0.01	0.01	-0.01
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)
(-)Precip. Dev.×Temp. Dev.	-0.01	-0.03	-0.01	0.01	0.03	-0.05	0.02	0.07
	(0.08)	(0.10)	(0.09)	(0.08)	(0.13)	(0.18)	(0.14)	(0.13)
asinh(Subsidies)×(-)Precip. Dev.×Temp. Dev.	-0.00	0.05**	0.00	-0.01	-0.02	0.03	-0.02	-0.04*
	(0.01)	(0.02)	(0.01)	(0.01)	(0.02)	(0.03)	(0.02)	(0.02)
Observations	9,912	9,912	9,912	9,912	9,912	9,912	9,912	9,912
Comuna FE	X	X	X	X	X	X	X	X
Region-by-Year FE	X	X	X	X	X	X	X	X

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Standard errors are clustered by comuna. Climate variables based on 5-year running-average deviations.

Potentially, this pattern can be interpreted as subsidies being used to intensify production after controlling for climate and the remaining interactions in a sector of the market that is still underdeveloped relative to surface water. Relatedly, mid-term temperature deviation has a consistent negative and significant effect across firm size, but only for groundwater. In other words, trading responds to these changes only in the sector that is still underdeveloped, potentially suggesting climate adjustments having a major role (1% increase in mid-term temperature deviation leads to a 0.2% decrease in trades) in terms of market allocation. We emphasize that this effect is robust to geographical and spatial patterns across the country.

In the previous regressions we observed that the interaction between subsidies and mid-term precipitation deviation seemed to have the most robust and consistent relationship with trades. Table 3, reinforces these results, but adds further nuance to the pattern. Specifically, trades are significantly associated with conveyance subsidies to medium and small firms across sources of water. However, this result is two to three times bigger for surface water. The differences between sources can be explained, in part, by the crucial role that conveyance structure plays in reducing transaction costs; the subsidy program targets such infrastructure, which, as noted by Hearne and Donoso (2014), remains scarce in many regions of the country. Surface water has been the most active developed sector historically, which implies groundwater could be less susceptible to these constraints as intra-basin trading does not necessarily require the transportation of water, but rather the spatial shift in pumping effort. We note that the interaction between conveyance subsidies and mid-term temperature deviation has a positive and significant association with trades, but only in small firms when it comes to groundwater.

Panel B in Table 3 shows that irrigation subsidies share similarities with conveyance subsidies, though a few minor differences arise. First, subsidies to improve irrigation for large firms are associated with decreases in overall trades of groundwater. This pattern potentially follows from a decrease in demand due to improved efficiency, or because of an increase in surface or production volume that follows directly from these investments. Noticeably, however, irrigation subsidies for small firms are also associated with an increase in trades in the case of surface water. If the subsidy targets on-farm irrigation infrastructure to improve efficiency, pressurization of existing distribution systems to replace flood irrigation, then this might free up water surface-irrigated farms, as groundwater systems are already pressurized.

We note that pure climate and climate interacted patterns remain consistent with conveyance subsidies, both in terms of source of water as well as the size of the firm. Remarkably, we observe that the interaction between subsidies and dry years is only significant for medium and small firms, but also stronger for surface water. Surface water access relies heavily on snowpack, which is much more likely to be directly affected by year-to-year variation in precipitation. Surface diverters may be inclined to make up shortfalls in times of scarcity on the surface water market before turning to groundwater. Due to the storage capacity of aquifers, groundwater users will be buffered against scarcity in the short term. Although recharge declines during drought and water tables may sink (which affects the net returns to pumping), these impacts are likely to be lesser than those felt by surface water users.

In Appendix B.2 we explore the robustness of our results to 3- and 7-year running averages for our climatic variables. These do not appreciably alter the results.

7 Discussion

The ability to routinely reallocate water across uses at low cost is one of the primary motivations for adopting a market-based approach to water management. However, empirical evidence of markets' effectiveness in this regard is limited. Previous work has identified gains from trade in several contexts, but typically in isolated cases (e.g., Grafton and Horne (2014) in the Murray-Darling and Ayres, Meng and Plantinga (2019) in California's Mojave Desert). Meanwhile, there is a broad awareness of high and sometimes prohibitive transaction costs in water markets (Loch, Wheeler and Settre, 2018; Leonard, Costello and Libecap, 2019). This paper is the first to use a rich nation-wide dataset to provide evidence about the extent to which market participants can successfully adapt to changing environmental conditions. Furthermore, we consider how a nationwide government irrigation subsidy program may affect market activity.

The estimation reveals that persistent drought and subsidies are associated with increased market transactions. This behavior arises both for surface water rights, which are constrained during drought due to reduced flows, and groundwater extraction rights. Despite the fact that groundwater remains physically accessible even in dry times, extraction can be restricted by the DGA during intense drought, leading to a demand for reallocation even within this market. While it is not possible specifically to characterize the motivations for these transactions, market reallocation to higher-valued uses as adaptation to shifting environmental conditions is likely. The presence of subsidies is arguably able to facilitate these transactions. Furthermore, any increased activity appears to be closely linked to firm size: only subsidies to medium- and small-scale agricultural producers are associated with increased trading. One interpretation of these results is that subsidy programs that target conveyance constraints and irrigation efficiency improvements hold promise for unlocking water transfers involving otherwise constrained, small-scale users.

Future work should consider how different uses of subsidy funds interact with firm size to relax constraints on trading. Exploring to what ends subsidy funds were ultimately put will reveal whether plausibly relaxing the constraints identified in this paper can indeed explain any associated increases in trading. Further work could also usefully investigate the "irrigation-efficiency paradox" in the Chilean case—i.e., to what extent subsidy disbursement encourages the sale of conserved water versus expansion of irrigated acreage via intensification (Grafton et al., 2018). This seems to be an important feature of the Chilean market, as evidenced by the negative effect of mid-term temperature deviations in the overall magnitude of trades.

Communities across the globe are currently grappling with the question of which water management institutions will best suit their future needs in a changing climate. Water resources in arid areas often already suffer from mismanagement and misallocation (some remain in pure open access), and future increases in both scarcity and environmental variability will only increase the benefits of flexible institutions. As a result, there is a pressing need for a better understanding of whether and how a market approach can effectively produce accurate price signals and facilitate adaptation. This work suggests that markets can deliver, while also recognizing the role that government actions may play in reducing transaction costs.

Finally, we note that we are only able to observe permanent trades. Temporary trades, either formal or informal, are likely taking place as a form short-term adaptation to climate conditions across the country and are an important part of the story when it comes to the overall efficiency of the market. Exploring these temporary transactions, and their role in climate adaptation, is an area ripe for further research in water economics but also for formulating broader climate adaptation strategies..

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A Proof

A.1 Cap is known with certainty

Following the solution proposed by Pommeret and Schubert (2018), consider the case in which the cap in the second period is known with certainty. The Bellman equation for the firm's problem is given by:

$$\begin{aligned} V_{i1}(K_{i0}, W_{i1})) = \min_{Q_{i1}, I_{i1}} \big\{ & C_i(Q_{i1}, K_{i0} + I_{i1}) + kI_{i1} - p_1 \left(W_{i1} - (\bar{U}_i - Q_{i1}) \right) \\ & + \delta V_{i2}(K_{i1}, W_{i2})) \big\} \end{aligned} \tag{A.1}$$

The first order conditions in period 2 are thus given by:

$$\frac{\partial C_i(\bullet)}{\partial Q_{i2}} = p_2 \tag{A.2}$$

$$-\frac{\partial C_i(\bullet)}{\partial K_{i2}} = k \tag{A.3}$$

Going back in time, the first order conditions for period 1 are:

$$\frac{\partial C_i(\bullet)}{\partial Q_{i1}} = p_1 \tag{A.4}$$

$$-\frac{\partial C_i(\bullet)}{\partial K_{i1}} = k(1-\delta) \tag{A.5}$$

Because aggregate levels are the envelope of firm's individual levels, optimal behavior implies:

$$-\frac{\partial C(\bullet)}{\partial K_2} = k \tag{A.6}$$

$$-\frac{\partial C(\bullet)}{\partial K_1} = k(1-\delta) \tag{A.7}$$

which yields:

$$K_2^* = \left(\frac{\beta c}{k} Q_2^{*\alpha} \right)^{\frac{1}{1+\beta}} \tag{A.8}$$

$$K_1^* = \left(\frac{\beta c}{k(1-\delta)} Q_1^{*\alpha} \right)^{\frac{1}{1+\beta}} \tag{A.9}$$

and

$$\frac{\partial C(\bullet)}{\partial Q_2} = \alpha c \left(\frac{k}{\beta c}\right)^{\frac{\beta}{1+\beta}} {Q_2^*}^{\frac{\alpha-(1+\beta)}{1+\beta}} \tag{A.10}$$

$$\frac{\partial C(\bullet)}{\partial Q_1} = \alpha c \left(\frac{k(1-\delta)}{\beta c}\right)^{\frac{\beta}{1+\beta}} {Q_1^*}^{\frac{\alpha-(1+\beta)}{1+\beta}} \tag{A.11}$$

This relationship suggest that the inter-temporal relationship between prices is given by:

$$\frac{\partial C(\bullet)}{\partial Q_1} = \delta \frac{\partial C(\bullet)}{\partial Q_2} \tag{A.12}$$

which is equivalent to:

$$\left(\left(\frac{1-\delta}{\delta}\right)^{\beta} \frac{1}{\delta}\right)^{\frac{1}{\alpha-(1+\beta)}} Q_1^* = Q_2^* \tag{A.13}$$

Finally, the market clearing condition implies:

$$Q_1^* + Q_2^* = \eta(q) \tag{A.14}$$

which results in the optimal total water consumption reduction in period one:

$$Q_1^* = \frac{\eta(q)}{1 + \left(\left(\frac{1-\delta}{\delta}\right)^{\beta} \frac{1}{\delta}\right)^{\frac{1}{\alpha-(1+\beta)}}} \tag{A.15}$$

with $q = \{0, 1\}$.

Equation A.15 indicates that optimal water consumption reduction is a fixed fraction of the total mandated reduction. Trivially, it follows that Q_1^* is decreasing in q and $\bar{\Delta}$, and that K_1^* is decreasing in k.

A.2 Cap is uncertain

Consider the case in which the cap in extraction is uncertain. The firms' problem is now given by the following Bellman equation:

$$\begin{aligned} V_{i1}(K_{i0}, W_{i1})) = \min_{Q_{i1}, I_{i1}} \big\{ & C_i(Q_{i1}, K_{i0} + I_{i1}) + kI_{i1} - p_1 \left(W_{i1} - (\bar{U}_i - Q_{i1})\right) \\ & + \delta \mathbb{E}_1 \left[V_{i2}(K_{i1}, W_{i2}))\right]\big\} \end{aligned} \tag{A.16}$$

with

$$\mathbb{E}_1 \left[V_{i2}(K_{i1}, W_{i2})\right] = qV_{i2}(K_{i1}, W_{i1} + \bar{\Delta}_i)) + (1-q)V_{i2}(K_{i1}, W_{i1} - \underline{\Delta}_i)) \tag{A.17}$$

Similarly, this problem can be solved using backward induction. First, consider the case in which the cap is increased, $W_1 + \bar{\Delta} < \bar{U}$. The value function at period 2 is given by:

$$V_{i2}(K_{i1}, W_{i1} + \bar{\Delta}_i) = \min_{Q_{i2}, I_{i2}} \left\{ C_i(\bar{Q}_{i2}, \bar{K}_{i1} + \bar{I}_{i2}) + k\bar{I}_{i2} - \bar{p}_2 \left(W_{i1} + \bar{\Delta}_i - (\bar{U}_i - \bar{Q}_{i2}) \right) \right\} \quad \text{(A.18)}$$

with probability q. Second, consider the case in which the cap is decreased, $W_1 - \underline{\Delta} < \bar{U}$. The value function for this state of the world is given by:

$$V_{i2}(K_{i1}, W_{i1} - \underline{\Delta}_i) = \min_{Q_{i2}, I_{i2}} \left\{ C_i(\underline{Q}_{i2}, \underline{K}_{i1} + \underline{I}_{i2}) + k\underline{I}_{i2} - \underline{p}_2 \left(W_{i1} - \underline{\Delta}_i - (\bar{U}_i - \underline{Q}_{i2}) \right) \right\} \quad \text{(A.19)}$$

with probability $1 - q$.

To keep track of the relevant scenarios, variables in the case of an increase in the extraction cap are denoted with a bar, while those in the case of a decrease in the extraction cap are denoted with an underscore, respectively. The first order conditions in period 2 are then given by:

$$\frac{\partial C_i(\bullet)}{\partial \bar{Q}_{i2}} = \bar{p}_2 \quad \text{(A.20)}$$

$$-\frac{\partial C_i(\bullet)}{\partial \bar{K}_{i2}} = k \quad \text{(A.21)}$$

and

$$\frac{\partial C_i(\bullet)}{\partial \underline{Q}_{i2}} = \underline{p}_2 \quad \text{(A.22)}$$

$$-\frac{\partial C_i(\bullet)}{\partial \underline{K}_{i2}} = k \quad \text{(A.23)}$$

Similarly, first order conditions for period 1 are:

$$\frac{\partial C_i(\bullet)}{\partial Q_{i1}} = p_1 \quad \text{(A.24)}$$

$$-\frac{\partial C_i(\bullet)}{\partial K_{i1}} = k(1 - \delta) \quad \text{(A.25)}$$

In addition to the previous notation, let # denote the solution for the scenario when there is uncertainty over the extraction cap. It follows that aggregate optimal investment satisfies:

$$\bar{K}_2^{\#} = \left(\frac{\beta c}{k}\bar{Q}_2^{*\alpha}\right)^{\frac{1}{1+\beta}} \tag{A.26}$$

$$\underline{K}_2^{\#} = \left(\frac{\beta c}{k}\underline{Q}_2^{*\alpha}\right)^{\frac{1}{1+\beta}} \tag{A.27}$$

$$K_1^{\#} = \left(\frac{\beta c}{k(1-\delta)}Q_1^{*\alpha}\right)^{\frac{1}{1+\beta}} \tag{A.28}$$

and

$$\frac{\partial C(\bullet)}{\partial \bar{Q}_2} = \alpha c\left(\frac{k}{\beta c}\right)^{\frac{\beta}{1+\beta}} \bar{Q}_2^{*\frac{\alpha-(1+\beta)}{1+\beta}} \tag{A.29}$$

$$\frac{\partial C(\bullet)}{\partial \underline{Q}_2} = \alpha c\left(\frac{k}{\beta c}\right)^{\frac{\beta}{1+\beta}} \underline{Q}_2^{*\frac{\alpha-(1+\beta)}{1+\beta}} \tag{A.30}$$

$$\frac{\partial C(\bullet)}{\partial Q_1} = \alpha c\left(\frac{k(1-\delta)}{\beta c}\right)^{\frac{\beta}{1+\beta}} Q_1^{*\frac{\alpha-(1+\beta)}{1+\beta}} \tag{A.31}$$

Total inter-temporal reduction in extraction is then given by:

$$\frac{\partial C(\bullet)}{\partial Q_1} = \delta\left(q\frac{\partial C(\bullet)}{\partial \bar{Q}_2} + (1-q)\frac{\partial C(\bullet)}{\partial \underline{Q}_2}\right) \tag{A.32}$$

which is equivalent to:

$$\left(\left(\frac{1-\delta}{\delta}\right)^{\beta}\frac{1}{\delta}\right)^{\frac{1}{\alpha-(1+\beta)}} Q_1^{\#} = \left(q\bar{Q}_2^{\#\frac{\alpha-(1+\beta)}{1+\beta}} + (1-q)\underline{Q}_2^{\#\frac{\alpha-(1+\beta)}{1+\beta}}\right)^{\frac{1+\beta}{\alpha-(1+\beta)}} \tag{A.33}$$

Finally, market clearing conditions imply:

$$\bar{Q}_2^{\#} = \eta(q) - (1-q)(\bar{\Delta} + \underline{\Delta}) - Q_1^{\#} \tag{A.34}$$

$$\underline{Q}_2^{\#} = \eta(q) - q(\bar{\Delta} + \underline{\Delta}) - Q_1^{\#} \tag{A.35}$$

Market clearing conditions along with equation A.33 provide the implicit optimal level of water consumption reduction under uncertainty. Note that optimal allocation balances the potential effects of having both too much or too little water in the next period.

A.3 The effect of uncertainty in extraction

First order conditions and market clearing conditions for both scenarios imply;

$$\frac{\partial C(Q_1^*, K_1^*)}{\partial Q_1} = \delta\frac{\partial C(\eta(q) - Q_1^*, K_1^*)}{\partial Q_1} \tag{A.36}$$

and

$$\frac{\partial C(Q_1^{\#}, K_1^{\#})}{\partial Q_1} = \delta\left(q\frac{\partial C(\eta(q) - \bar{Q}_1^{\#}, \bar{K}_1^{\#})}{\partial Q_1} + (1-q)\frac{q\partial C(\eta(q) - \underline{Q}_1^{\#}, \underline{K}_1^{\#})}{\partial Q_1}\right) \tag{A.37}$$

$$= \delta\left(q\frac{\partial C(2(\bar{U} - W_1) - \bar{\Delta} - Q_1^{\#}, \bar{K}_1^{\#})}{\partial Q_1} + (1-q)\frac{q\partial C(2(\bar{U} - W_1) - \underline{\Delta} - Q_1^{\#}, \underline{K}_1^{\#})}{\partial Q_1}\right) \tag{A.38}$$

(A.39)

which in turn implies:

$$\frac{\partial C(Q_1^{\#}, K_1^{\#})}{\partial Q_1} > \delta\frac{\partial C(\eta(q) - Q_1^{\#}, K_1^{\#})}{\partial Q_1} \tag{A.40}$$

Because $\partial C(\bullet)/\partial Q$ is proportional to $Q^{\frac{\alpha-(1+\beta)}{1+\beta}}$, $\partial C(\bullet)/\partial Q$ is convex in Q if $\alpha > 2(1+\beta)$ and concave otherwise. Evaluating this property in equations A.36 and A.40 implies that $Q_1^{\#} > Q_1^*$ when the marginal cost of reducing extraction is convex, while $Q_1^{\#} < Q_1^*$ when the marginal cost is concave.

B Supplementary Tables

B.1 Summary Statistics

Table B.1: Summary Statistics, by Region

	Mean Total Sales (#)	Mean Surface Sales (#)	Mean GW Sales (#)	Mean Annual Subsidy (Pesos)	Mean Annual Precip (mm/cm^2)	St. Dev. Annual Precip (mm/cm^2)	Mean Annual Temp (°C)	St. Dev. Annual Temp (°C)
De Antofagasta	14.39	11.81	2.17	3504.56	1.29	0.52	1.66	0.88
De Arica Y Parinacota	55.67	44.86	7.86	16421.52	7.41	2.60	12.30	0.77
De Atacama	52.86	42.53	8.97	29398.80	3.21	1.53	3.52	0.64
De Aysen	12.03	11.44	0.33	5034.75	49.12	9.39	3.83	1.05
De Coquimbo	366.47	288.22	26.69	106024.92	11.32	4.28	8.07	1.28
De La Araucania	104.00	91.39	3.03	38227.46	46.36	9.54	9.00	0.56
De Los Lagos	23.94	19.72	4.03	14895.26	59.06	10.80	8.75	0.57
De Los Rios	23.06	20.47	2.11	14034.05	56.56	10.90	9.36	0.57
De Magallanes	3.50	2.89	0.47	2456.61	48.58	9.80	5.00	0.57
De O'Higgins	452.28	377.69	23.42	74683.63	16.54	5.69	10.99	1.17
De Tarapaca	23.47	8.97	12.25	3292.81	3.28	1.40	13.09	1.12
De Valparaiso	376.06	239.67	94.97	63484.14	8.06	3.15	9.95	1.88
Del Bio Bio	231.11	195.47	8.42	74540.02	34.00	7.91	10.15	0.59
Del Maule	544.33	487.33	11.36	207580.24	23.64	6.99	10.99	0.69
Metropolitana	1454.28	1029.44	204.11	37926.54	11.55	4.15	8.79	1.69

B.2 Additional Tables

In addition to the analysis in the main body of the paper, this section compiles several additional analysis for different explanatory variables and subsamples.

Table B.2: Panel Estimation Results with 3 Year Running Average

	(1)	(2)	(3)	(4)	(5)
asinh(Subsidies)	0.06***	0.02***	0.00	0.00	0.00
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
(-)Precip. Dev.	0.06***	0.04	−0.08	−0.08	−0.05
	(0.02)	(0.03)	(0.05)	(0.05)	(0.09)
Temp. Dev.	0.09*	0.12***	−0.16***	−0.16***	−0.29**
	(0.04)	(0.04)	(0.05)	(0.05)	(0.13)
asinh(Subsidies)×(-)Precip. Dev.	0.06***	0.06***	0.05***	0.05***	0.05***
	(0.02)	(0.01)	(0.01)	(0.01)	(0.02)
asinh(Subsidies)×Temp. Dev.	0.01	0.02***	0.03***	0.03***	0.02***
	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
(-)Precip. Dev.×Temp. Dev.	0.13***	0.14***	0.05	0.05	0.02
	(0.03)	(0.04)	(0.04)	(0.04)	(0.09)
asinh(Subsidies)×(-)Precip. Dev.×Temp. Dev.	−0.03*	−0.03*	−0.02	−0.02	−0.02
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Observations	9,912	9,912	9,912	9,912	9,912
Comuna FE		X	X	X	X
Year FE			X	X	
Region FE				X	
Region-by-Year FE					X

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Standard errors are clustered by comuna. Climate variables based on 5-year running-average deviations.

Table B.3: Panel Estimation Results by Source with 3 Year Running Average

	Groundwater			Surface		
	(1)	(2)	(3)	(1)	(2)	(3)
asinh(Subsidies)	0.00	−0.01**	−0.01**	0.01	0.00	0.00
	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)
(-)Precip. Dev.	−0.03		−0.02	−0.03		−0.05
	(0.06)		(0.05)	(0.09)		(0.08)
asinh(Subsidies)×(-)Precip. Dev.	0.02***		0.01**	0.04***		0.05***
	(0.01)		(0.01)	(0.01)		(0.01)
Temp. Dev.		−0.28***	−0.27**		−0.24*	−0.22*
		(0.11)	(0.11)		(0.12)	(0.11)
asinh(Subsidies)×Temp. Dev.		0.02***	0.02***		0.02**	0.02**
		(0.01)	(0.00)		(0.01)	(0.01)
(-)Precip. Dev.×Temp. Dev.			−0.01			0.02
			(0.05)			(0.09)
asinh(Subsidies)×(-)Precip. Dev.×Temp. Dev.			0.00			−0.02
			(0.01)			(0.02)
Observations	9,912	9,912	9,912	9,912	9,912	9,912
Comuna FE	X	X	X	X	X	X
Region-by-Year FE	X	X	X	X	X	X

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Standard errors are clustered by comuna. Climate variables based on 5-year running-average deviations.

Table B.4: Panel Estimation Results by Source, Type of Subsidy, and Firm Size with 3 Year Running Average

	Groundwater				Surface			
	(All)	(Large)	(Medium)	(Small)	(All)	(Large)	(Medium)	(Small)
Panel (A): Conveyance subsidies								
asinh(Subsidies)	-0.01**	-0.03**	-0.01	-0.01**	-0.00	-0.03	-0.00	-0.00
	(0.00)	(0.01)	(0.01)	(0.00)	(0.01)	(0.02)	(0.01)	(0.01)
(-)Precip. Dev.	-0.02	0.02	-0.01	-0.01	-0.03	0.08	0.01	-0.00
	(0.06)	(0.06)	(0.06)	(0.06)	(0.08)	(0.09)	(0.09)	(0.08)
Temp. Dev.	-0.28***	-0.27**	-0.27**	-0.28***	-0.21*	-0.22*	-0.23**	-0.21*
	(0.11)	(0.11)	(0.11)	(0.11)	(0.11)	(0.12)	(0.12)	(0.11)
asinh(Subsidies)×(-)Precip. Dev.	0.02**	0.00	0.03***	0.01*	0.06***	0.02	0.08***	0.06***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)
asinh(Subsidies)×Temp. Dev.	0.02***	-0.02	0.01*	0.02***	0.02**	0.00	0.02*	0.02**
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.04)	(0.01)	(0.01)
(-)Precip. Dev.×Temp. Dev.	0.01	-0.01	-0.01	0.01	0.05	-0.05	-0.01	0.05
	(0.05)	(0.07)	(0.06)	(0.05)	(0.09)	(0.13)	(0.10)	(0.09)
asinh(Subsidies)×(-)Precip. Dev.×Temp. Dev.	-0.01	0.02	0.00	-0.01	-0.03	-0.00	-0.03	-0.04*
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.03)	(0.03)	(0.02)
Panel (B): Irrigation subsidies								
asinh(Subsidies)	-0.00	-0.01**	-0.01	0.01	0.01	-0.01	0.00	0.03***
	(0.00)	(0.01)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
(-)Precip. Dev.	-0.01	0.01	-0.00	0.00	-0.01	0.08	0.01	0.03
	(0.06)	(0.06)	(0.06)	(0.06)	(0.09)	(0.10)	(0.08)	(0.08)
Temp. Dev.	-0.27**	-0.27**	-0.28***	-0.25**	-0.21*	-0.22*	-0.23**	-0.16
	(0.11)	(0.11)	(0.11)	(0.10)	(0.11)	(0.12)	(0.12)	(0.10)
asinh(Subsidies)×(-)Precip. Dev.	0.01	0.01	0.01	0.02**	0.04***	0.02	0.04***	0.05**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)	(0.02)
asinh(Subsidies)×Temp. Dev.	0.01*	-0.01	0.01***	0.01	0.00	0.01	0.01	-0.00
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)
(-)Precip. Dev.×Temp. Dev.	-0.01	-0.02	-0.01	0.01	-0.01	-0.06	-0.02	0.02
	(0.06)	(0.07)	(0.06)	(0.05)	(0.10)	(0.13)	(0.10)	(0.09)
asinh(Subsidies)×(-)Precip. Dev.×Temp. Dev.	-0.00	0.03**	0.00	-0.01	-0.02	0.01	-0.01	-0.03**
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)	(0.02)
Observations	9,912	9,912	9,912	9,912	9,912	9,912	9,912	9,912
Comuna FE	X	X	X	X	X	X	X	X
Region-by-Year FE	X	X	X	X	X	X	X	X

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Standard errors are clustered by comuna. Climate variables based on 5-year running-average deviations.

Table B.5: Panel Estimation Results with 7 Year Running Average

	(1)	(2)	(3)	(4)	(5)
asinh(Subsidies)	0.06***	0.03***	0.00	0.00	0.00
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
(-)Precip. Dev.	0.03	0.01	−0.06	−0.06	−0.01
	(0.04)	(0.05)	(0.08)	(0.08)	(0.15)
Temp. Dev.	0.10*	0.14***	−0.12*	−0.12*	−0.21
	(0.06)	(0.05)	(0.06)	(0.06)	(0.17)
asinh(Subsidies)×(-)Precip. Dev.	0.08***	0.08***	0.05**	0.05**	0.06**
	(0.03)	(0.02)	(0.02)	(0.02)	(0.02)
asinh(Subsidies)×Temp. Dev.	0.00	0.00	0.02*	0.02*	0.01
	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
(-)Precip. Dev.×Temp. Dev.	0.21***	0.23***	0.00	0.00	0.04
	(0.06)	(0.06)	(0.07)	(0.07)	(0.16)
asinh(Subsidies)×(-)Precip. Dev.×Temp. Dev.	−0.04	−0.03	−0.01	−0.01	−0.02
	(0.03)	(0.03)	(0.02)	(0.02)	(0.03)
Observations	9,912	9,912	9,912	9,912	9,912
Comuna FE		X	X	X	X
Year FE			X	X	
Region FE				X	
Region-by-Year FE					X

* p < 0.1, ** p < 0.05, *** p < 0.01
Standard errors are clustered by comuna. Climate variables based on 5-year running-average deviations.

Table B.6: Panel Estimation Results by Source with 7 Year Running Average

	Groundwater			Surface		
	(1)	(2)	(3)	(1)	(2)	(3)
asinh(Subsidies)	0.00	−0.01*	−0.01**	0.01	0.01	0.01
	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)
(-)Precip. Dev.	−0.01		0.00	−0.01		−0.04
	(0.10)		(0.09)	(0.14)		(0.13)
asinh(Subsidies)×(-)Precip. Dev.	0.03**		0.02*	0.05***		0.06**
	(0.01)		(0.01)	(0.01)		(0.02)
Temp. Dev.		−0.26**	−0.24**		−0.18	−0.14
		(0.12)	(0.11)		(0.18)	(0.16)
asinh(Subsidies)×Temp. Dev.		0.02***	0.01***		0.01	0.01
		(0.01)	(0.01)		(0.01)	(0.01)
(-)Precip. Dev.×Temp. Dev.			0.00			0.04
			(0.11)			(0.14)
asinh(Subsidies)×(-)Precip. Dev.×Temp. Dev.			0.00			−0.02
			(0.02)			(0.03)
Observations	9,912	9,912	9,912	9,912	9,912	9,912
Comuna FE	X	X	X	X	X	X
Region-by-Year FE	X	X	X	X	X	X

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Standard errors are clustered by comuna. Climate variables based on 5-year running-average deviations.

Table B.7: Panel Estimation Results by Source, Type of Subsidy, and Firm Size with 7 Year Running Average

	Groundwater				Surface			
	(All)	(Large)	(Medium)	(Small)	(All)	(Large)	(Medium)	(Small)
Panel (A): Conveyance subsidies								
asinh(Subsidies)	-0.01*	-0.03***	-0.00	-0.01*	-0.00	-0.05*	-0.00	0.00
	(0.00)	(0.01)	(0.01)	(0.00)	(0.01)	(0.02)	(0.01)	(0.01)
(-)Precip. Dev.	0.00	0.06	0.03	0.01	-0.03	0.11	0.05	0.00
	(0.10)	(0.10)	(0.10)	(0.09)	(0.13)	(0.14)	(0.14)	(0.13)
Temp. Dev.	-0.24**	-0.24**	-0.24**	-0.25**	-0.13	-0.15	-0.15	-0.13
	(0.11)	(0.11)	(0.11)	(0.11)	(0.16)	(0.16)	(0.17)	(0.16)
asinh(Subsidies)×(-)Precip. Dev.	0.03**	-0.02	0.04**	0.03*	0.08***	-0.01	0.09***	0.08**
	(0.01)	(0.03)	(0.02)	(0.02)	(0.03)	(0.04)	(0.03)	(0.03)
asinh(Subsidies)×Temp. Dev.	0.01**	-0.02	0.01	0.01**	0.01	0.02	0.01	0.01
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.04)	(0.01)	(0.01)
(-)Precip. Dev.×Temp. Dev.	0.02	0.00	-0.02	0.04	0.08	-0.03	-0.03	0.11
	(0.11)	(0.13)	(0.12)	(0.10)	(0.14)	(0.21)	(0.18)	(0.14)
asinh(Subsidies)×(-)Precip. Dev.×Temp. Dev.	-0.00	0.08	0.02	-0.01	-0.03	0.05	-0.01	-0.04
	(0.02)	(0.07)	(0.03)	(0.02)	(0.03)	(0.08)	(0.04)	(0.04)
Panel (B): Irrigation subsidies								
asinh(Subsidies)	-0.00	-0.01*	-0.01	0.01	0.01	-0.01	0.01	0.04***
	(0.00)	(0.01)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
(-)Precip. Dev.	0.02	0.06	0.02	0.03	0.01	0.11	0.03	0.04
	(0.09)	(0.10)	(0.10)	(0.09)	(0.13)	(0.14)	(0.13)	(0.13)
Temp. Dev.	-0.24**	-0.24**	-0.25**	-0.22**	-0.13	-0.16	-0.15	-0.08
	(0.11)	(0.11)	(0.11)	(0.10)	(0.15)	(0.16)	(0.16)	(0.14)
asinh(Subsidies)×(-)Precip. Dev.	0.02*	0.01	0.03**	0.03**	0.05**	0.02	0.06**	0.06**
	(0.01)	(0.02)	(0.01)	(0.01)	(0.02)	(0.02)	(0.02)	(0.03)
asinh(Subsidies)×Temp. Dev.	0.01	-0.01	0.01**	0.01	-0.00	0.01	0.00	-0.01
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)
(-)Precip. Dev.×Temp. Dev.	-0.00	-0.02	0.01	0.02	0.02	-0.05	0.03	0.09
	(0.11)	(0.13)	(0.11)	(0.11)	(0.15)	(0.21)	(0.16)	(0.14)
asinh(Subsidies)×(-)Precip. Dev.×Temp. Dev.	-0.00	0.05*	-0.00	-0.01	-0.02	0.03	-0.02	-0.04
	(0.01)	(0.03)	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)	(0.03)
Observations	9,912	9,912	9,912	9,912	9,912	9,912	9,912	9,912
Comuna FE	X	X	X	X	X	X	X	X
Region-by-Year FE	X	X	X	X	X	X	X	X

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Standard errors are clustered by comuna. Climate variables based on 5-year running-average deviations.