Governing Environmental Markets: Evidence From Irrigation In Water Markets*

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Abstract

Water resources present a classic tragedy of the commons that is of increasing relevance as a result of climate change. This paper provides evidence of how property rights institutions, particularly local irrigators' organizations, impact water markets' efficiency. Our analysis is based on a unique dataset that integrates administrative records, hydrological measures, geographic information, and satellite imagery. We develop a novel misallocation test, which suggests that these organizations reduce misallocation caused by the natural advantage of upstream users to over-extract. We show that these efficiency gains are a result of both water redistribution and individual adaptation: downstream farmers increase their water consumption and agricultural yield. Large farms extend their growing season, adopt more efficient irrigation technologies, and overall gather more benefits from this institution. Upstream farmers reduce their water consumption, but their productive outcomes remain unchanged. We also document increases in river streamflow during the irrigation season and reductions in water rights claims. Our results provide micro-evidence of the consequences of effective governance for both allocative efficiency and equity. *JEL codes: D23, D24, H41, O13, Q12, Q15, Q25.*

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1 Introduction

Climate change is closely intertwined with the Tragedy of the Commons. It arises from a commons problem—the unrestricted emission of greenhouse gases—and generates new commons challenges, such as the increasing frequency of droughts worldwide (IPCC, 2021). The establishment of environmental markets over those resources aims to address these issues by restricting open access and forcing agents to internalize the externalities of their actions. However, our understanding of the institutions necessary to sustain the operation of these markets remains limited. This is particularly important since managing common pool resources presents inherent challenges—such as high exclusion costs and monitoring difficulties (Ostrom, 1990, 2009)—that complicate market implementation. In this paper, we use intra-country variation in property rights institutions to show empirically that water markets may fail to allocate water efficiently despite well-defined property rights, and study how specialized enforcement institutions can improve their operation.

We study water allocation in 12 large-scale river basins in Chile, where a unique setting allows us to isolate the role of local enforcement institutions. In Chile, water is allocated through water rights that, unlike many natural resource markets in developing countries (e.g. Chari et al., 2021; Manysheva, 2022), are full property rights: they are perpetual, tradable, inheritable, independent of land tenure rights, and constitutionally protected against expropriation. Yet these strong protections have led regulations and courts to restrain government action, making it difficult to enforce property rights, particularly to protect downstream users from upstream over-extraction. In this context, local formal irrigation organizations called Water Boards (Juntas de Vigilancia) have been established with both the goal and power to enforce water rights and resolve conflicts among users.

We show that water markets achieve within-basin allocative efficiency only when supported by these specialized enforcement institutions, despite property rights being well defined across the territory. In a competitive market equilibrium, the marginal value of the resource should be equal across locations, with deviations from this benchmark indicating a Pareto inefficient allocation. We develop a novel misallocation test that exploits idiosyncratic variation in rainfall to compare the shadow value of water at different locations within a basin. This "sufficient statistic approach" measure identifies economic misallocation even after accounting for adaptation, entry and exit decisions, and private arrangements made by the agents. Our results show that the average shadow value of water remains constant within basins governed by Water Boards. In contrast, in areas without such board, the shadow value of water is higher in downstream than in upstream locations, indicating over-extraction by upstream users relative to a socially optimal allocation.

We explore two sets of mechanisms through which Water Boards achieve efficiency improvements: water redistribution and farmers' private responses, including crop and irrigation technology choices. To analyze these mechanisms, we used census data alongside remote sensing-based estimates of water consumption, agricultural yields, and growing season length, at the farm-plot level, for all irrigated land in Chile. This granular data enables us to compare farms within and outside Water Boards' jurisdiction, while accounting for their relative position within the basin.

The establishment of a Water Board is endogenous. Conflicts over water are more likely in agricultural areas where water is scarce. Moreover, incentives vary among agents depending on their location: downstream users are particularly motivated to establish an authority to ensure their water access, while upstream users prefer to remain outside such authority to avoid restrictions on their water consumption. To address these identification challenges, we exploit driving distance to the most upstream provincial capital city in each basin. This distance captures variation in the cost of creating Water Boards, as they must be established through a court process that can only be initiated in these upstream capitals. In our context, most basins cover several provinces, meaning that downstream water users do not have legal or bureaucratic reasons to drive to these locations other than for this process.

Our instrumental variable (IV) estimates reveal that property rights enforcement substantially affects water allocation and agricultural productivity both through large-scale redistribution and private investments. Water Boards increase water consumption per area by more than 50% among farms located in the most downstream tercile of each basin, while they reduce consumption among farms in the most upstream tercile by around 15%. We observe qualitatively similar effects in agricultural yield: an increase of 35% among downstream irrigated farmers, and a decrease of 4% among upstream ones. These effects are substantially larger than OLS estimates, suggesting that naive comparisons understate the impact of Water Boards.

Although Water Boards improve overall water allocation, our analysis suggests efficiency gains are unevenly distributed. We find that downstream increases in water consumption are twice as high for large farms compared to smaller farms, while upstream reductions are more substantial among smaller farms. This pattern is consistent with the political economy of Water Board formation: their creation appears to be driven by intra-elite conflict, where large downstream farmers–those with substantial resources–are leading the establishment of boards to keep in check large upstream farmers.

We also show that the redistribution performed by Water Boards expands production possibilities and allows for complementary private investments: downstream large farms switch to summer crops, extend their growing season, and adopt more efficient irrigation technologies. These effects help to explain how property rights enforcement can lead to net increases in water access, with increases in consumption among downstream users exceeding the reduction among upstream farmers.

We further explore the role of enforcement on allocative efficiency by examining river streamflows— the main channel through which Water Boards redistribute water for irrigation. Taking advantage of Water Boards' independent and autonomous establishment over time, we use a difference-in-differences design to estimate their effect. We find that Water Board adoption increases river streamflows by 24% in the dry season, when incentives to over-extract are strongest, and reduces water rights claims on the river.

Therefore, we conclude that Water Boards address misallocation by physically enforcing property rights, redistributing water consumption to farms that otherwise would not have access to river waters due to unchecked upstream over-extraction. We illustrate our interpretation in figure I: in normal times (fig. Ia), fixed irrigation infrastructure provides enforcement (see Section 2). During droughts, without Water Boards (fig. Ib), upstream farmers can over-extract, leaving downstream users without their water allotment. Water Boards (fig. Ic), instead, enforce proportional allocation based on water rights: they stop upstream farmers from over-extracting, allowing water to continue their way to downstream farmers.

Overall, our results indicate that individual adaptation and markets cannot fully offset the lack of effective governance in ensuring efficient resource use (Coase, 1960; Medema, 2020; Deryugina et al., 2021). Chile's water rights system satisfies the Coase Theorem's requirement of clearly defined property rights in a context of strong Rule of Law[1]. However, it fails to meet a less discussed condition of property rights enforcement, a consequence of a regulatory design that favors decentralized transactions over government intervention (Bauer, 2004; Tamayo and Carmona, 2019). This reflects a fundamental tension in environmental markets, where enforcement requires administrative actions under changing conditions: empowering users over governing authorities may reduce some market frictions but weaken enforcement. At the same time, we illustrate how institutional arrangements that empower local communities may enhance efficiency (Ostrom, 1990), even in a context with well-defined property rights.

We also offer new evidence on the distributive effects of property rights *enforcement*. Our farm plot-level analysis suggests that the creation of Water Boards is driven by intra-elite conflict, where large downstream farmers—those with substantial resources—establish boards to limit over-extraction by large upstream users. The board's governance structure, with votes weighted by water rights streamflow property, further reinforces the influence of large rights holders. Although it is not possible in our context to construct an appropriate counterfactual for a similar institution with a different governance structure, this situation illustrates how environmental markets, aiming to increase efficiency, may also exacerbate inequalities.

Related Literature. Our paper contributes to a range of literatures, including management of common pool resources, frictions in developing markets, the economic impacts of agricultural infrastructure and the economics of climate change. We first contribute to the body of work in environmental economics on the management of common resources. Water is considered a common pool resource, given the difficulties in enforcing exclusion,

[1]Chile ranks 23 worldwide in the V-DEM Rule of Law Index with a score of 0.96, the same as the United Kingdom, France and Singapore. https://ourworldindata.org/grapher/rule-of-law-index?tab=table

and the rivalry on its consumption (Ostrom and Gardner, 1993), implying the emergence of a "Tragedy of the Commons", where free-riding behavior leads to the over-exploitation of the resource (Hardin, 1968). Conventional approaches to managing common pool resources allocate the decision rights over the resource to either the state or private agents through privatization, but implicitly assign the tasks of monitoring and enforcing the decisions to the state. The literature on the different institutional arrangements over water is extensive; Meinzen-Dick (2007) and Ostrom (2010) provide good reviews and discussions on this topic.

In a classic work, Ostrom (1990) identifies local communities as a third possible managing agent and discusses conditions under which communities can succeed in environments where neither state management nor privatization can, by introducing locally managed monitoring and enforcement and decision-making. Among these conditions, she identifies monitoring capability, availability of sanctions among community members, and closed access to outsiders. One of her conclusions is that the state should empower local communities instead of replacing them. Most of the related literature has focused on testing the previous conditions in case studies or lab-in-the-field experiments in small-scale settings (e.g. Cardenas and Carpenter, 2008; Cárdenas and Ostrom, 2004; Henrich et al., 2006). In the environment we are studying –distribution of water within basins encompassing several local communities–, these conditions do not apply[2]. This paper, therefore, empirically tests one of Ostroms's main conclusions, and extends her work by showing how local communities can address free-riding problems in wider environments by relying on tools usually reserved for the state, like the authority to resolve legal disputes or establish legal punishments.

Another strand of the literature focuses on contexts with private property rights over water, opening questions about how water markets work. The prior work closest to our own includes Rafey (2023), who estimates the gains from trading water rights in the context of Australia, where the government exerts stronger monitoring, control, and enforcement of property rights over water across the full country. Studies that compare markets versus others allocation mechanisms include Ryan and Sudarshan (2022), who estimate the effi-

[2]First, agents cannot observe the actions of people outside their community; second, they cannot exclude others from locating into the basin by purchasing either land or water rights, and finally, the externalities are asymmetric, as people located downstream do not have informal tools to punish upstream people actions, so is not possible the emergence of informal agreements driven by repeated interactions, along the lines of the "Folk's Theorem".

ciency losses from rationing groundwater relative to a counterfactual Pigouvian allocation, and Donna and Espín-Sánchez (2023), who study how liquidity constraints may imply that markets are less efficient than a quota system on allocating water in Spain. This work studies the efficiency gains associated with different institutional arrangements. More generally, we contribute to the literature that studies the operation of environmental markets, which has recently focused on pollution permits (Colmer et al., 2024; Greenstone et al., 2025). Our work complements them by exploring how governance and enforcement are preexisting conditions for the proper operation of markets as an allocative mechanism. We also extend this literature by making a methodological contribution: we provide a misallocation test for surface water, a resource whose consumption is not measured in many contexts around the world, and so the conventional methods to estimate productivity (e.g. Levinsohn and Petrin, 2003, used by Rafey (2023)) cannot be implemented. Our method is based on a sufficient statistic approach, similar to Ryan and Sudarshan (2022), but recovering the marginal product of a resource without measuring inframarginal consumption

A related line of research explores the economic consequences of water infrastructure. Duflo and Pande (2007) estimates the productivity and distributional impacts of dams using an instrumental variable approach, showing that even though the net impacts are positive but modest, they have substantial distributional consequences, with downstream areas getting substantial benefits at the expense of upstream areas. Asher et al. (2022) and Blakeslee et al. (2021), using different identification strategies based on the local geography, estimate the structural transformation consequences of canals; both papers show that canals increase agricultural productivity but do not affect the productivity of other sectors, which they attribute to labor displacement. Our contribution is to show how the productivity and distributional consequences of infrastructure –in particular, canals– are shaped by the interaction between institutions and geography. We are also part of the first wave of papers using remote sensing to measure agricultural water consumption at the farm level (e.g. Boser et al. (2024)).

We contribute to a growing empirical literature on agriculture and adaptation to climate shocks, that increasingly relies on design-based strategies to understand the causal effects of climate shocks and different adaptations. Early contributions include Schlenker et al. (2005), Lobell et al. (2014) and Burke and Emerick (2016), who use different methods to characterize the extent to which adaptation can mitigate the agricultural costs of climate shocks. More recent contributions include Hagerty (2021), who studies short and long-term adaptations to changes in water availability by farmers through crop and operation decisions. Our contribution is to provide a new misallocation test on a key resource, and also to show how institutions may shape how farmers adapt, and the effectiveness of such adaptations.

We also contribute to the literature on the economic consequences of natural resources privatization and misallocation. While this literature is extensive, to our knowledge, this is the first paper to causally estimate the economic impact of enforcement of private property rights, and also over water specifically. Most of the related work identifies misallocation caused by legal limits to the exercise of property rights, which translates into market frictions. We provide evidence of the opposite: how limits to government action–in place to avoid their interference over markets–can also be a source of misallocation (Bauer, 2004, e.g.).

Related work includes De Janvry et al. (2015), which finds that land titling enables land reallocation towards more efficient farmers and labor reallocation through migration, and Chari et al. (2021) that shows how a property rights reform that allows farmers to lease out their land increases productivity and output by reallocating land towards more efficient producers. Our work shows that a necessary condition for the realization of such efficiency gains is the proper enforcement of property rights under trade. A related strand of the literature is the one studying the economic consequences of input misallocation. Recent examples of this literature include Manysheva (2022) who quantifies the efficiency gains from reducing frictions in the land market in the presence of credit constraints, and Gollin and Udry (2020), who improve on previous misallocation estimates by addressing measurement error.

The rest of the paper is organized as follows: Section 2 provides an overview of Chile's water property rights system and the role of Water Boards. After describing our data in Section 3, we present our misallocation test and its results in Section 4. Section 5 analyzes the key mechanisms driving our findings—water redistribution and farmers' private responses—with particular attention to how effects vary by farm size. Section 6 further explores the water redistribution mechanisms by studying the impact of Water Boards on river streamflows. Section 7 concludes.

2 Context

We study the introduction of Water Boards, a local governance institution that manage rivers in periods of water scarcity and solve legal conflicts among users. Thanks to their local nature, Water Boards know and interact with water users –in contrast to most centralized bureaucracies in charge of water management. In this section, we provide background information on the study area, the system of property rights over water, and the characteristics of Water Boards.

Geography. The area under study covers latitudes -30 to -38 and the full longitudinal range of Chile in this area (approximately -68 to -72.5) as shown in the central panel of figure II. This area covers 87% of Chile's population and 85% of the agricultural GDP. The geography is marked by both the Andes –which defines the eastern border of the country– and Coastal Mountain Ranges that extend in a North-South axis. Most agricultural activity takes place in the Central Valley that separates both ranges, and most rivers run from the Andes (East) to the Coast (West)(Fernández and Gironás, 2021). This rugged geography makes very costly the construction of infrastructure connecting basins. In our analsys, we focus on 12 large-scale rivers that run across the full longitudinal range of Chile in this area –i.e. with river heads in the Andes, at the border with Argentina, to the river mouth in the Pacific. We present these basins in figure III.

The climate in this area is Mediterranean with rainfall increasing in a North-South gradient; and a dry season that goes from November to March. Rivers in this area are mostly fed by both rainfall and snow-melting (Varas and Varas, 2021; CNR, 2018). This implies that rivers reach their maximum stream levels in the boreal winter and spring, and decline reaching minimum levels in summer and early fall (between February and April). Importantly, longer days make summer a key period for agricultural production, implying that irrigation is most important in the driest months.

Background on the Chilean System of Private Property Rights. Since 1981, Chile has been the only country in the world where perpetual private property rights over water (water rights in what follows) have constitutional protection against expropriation, which has resulted in limited administrative action by governments (Bauer, 2004; World Bank, 2011a, 2021). These rights are fully transferable, separated from land, and they are legally considered real estate; so a water rights purchase is legally equivalent to a purchase of land (CNR, 2018)[3]. These rights are defined in terms of a stream of water (measured in liters per second) to be extracted from a specific location and source and following a monthly schedule; all these attributes are defined during the creation of each water right. Figure A.II in Appendix A presents an example of a water right.

These rights can be claimed for free through public requests to the Directorate of Water (DGA, a national public institution similar to the US Bureau of Reclamation), the technical government institution in charge of assessing water resources and applying the law on water matters. These rights can be created until the DGA declares the river exhausted. After a source is declared exhausted, any user needing water rights in the area must purchase them from other users. They can be freely traded among both individuals and firms, without any interference by the government, and legally they are considered real estate (Biblioteca del Congreso Nacional, 1981).

The law that regulates water matters is the Water Code of 1981. Enforcement in principle relies on the actions of the DGA, which is supposed to address water stealing and over-extraction. However, the higher courts have overruled and systematically limited the scope of DGA's action (Bauer, 2004). A second enforcement layer is that the infrastructure in place shall be built consistently with the water rights owned. The diameter of the pipe–checked by DGA agents at the time of reclamation–connecting the farm to the canal or well limits the total extraction capacity (CNR, 2018). This coarse measure limits over-extraction in normal times by limiting the maximum water intake, but it does not during droughts:

[3] The titles also include the property over the infrastructure that allows the distribution of water, but there are legal figures that allow to mandate one user to share the infrastructure with other users that own water rights (CNR, 2018).

while the law establishes that users should limit their water extraction proportionally to the reduction in total streamflow (Biblioteca del Congreso Nacional, 1981), the infrastructure does not adapt accordingly.

Background on Water Boards. Droughts reduce the total stream flow, and the law establishes that these reductions should be prorated proportionally among all users: a reduction of 50% of the total river streamflow should imply a 50% reduction in the maximum extractions by each user. Until recently, public agencies have not been able to intervene effectively in the allocation of water under scarcity, due to restrictions on administrative government action and lack of resources, leaving a void in the enforcement of drought-induced reductions (Bauer, 2004).

In response to droughts, early in the XX century agricultural users created Water Boards as a representative of the water users (Peña, 2021). After the passing of the the Water Code of 1981, Water Boards have the legal authority to 1) determine and enforce water allocations across legal users under extraordinary circumstances, such as drought, 2) adjudicate disputes among users within their jurisdiction, 3) keep track of Water Rights claims, and 4) provide common goods such as legal assistance and common infrastructure, and define its own funding sources.

Water Boards enforce water allocations during droughts by implementing a system of irrigation shifts, where they calculate the number of days or hours of unrestricted irrigation that correspond to a farmer, given their water allotment and the total water available for distribution. They enforce this irrigation time by opening and locking canal gates, such as the one depicted in figure V. This technology is not unique to the Chilean context (Ostrom, 1990, page 77).

They report only to their constituents –who elect them with votes weighted by their Water Rights streamflow property– during their 2 or 3-year tenure. They are subject to regulation by the DGA, but courts have curtailed DGA's intervention (Bauer, 2004). Therefore, Water Boards are effectively the highest administrative authority in water-related issues in the basins under their jurisdiction, except for emergency situations

The creation of Water Boards is triggered by either an agreement by at least half of the water rights owners within the area under consideration, or a lawsuit by at least one water user. This process is under the jurisdiction of an ordinary judge housed in the most upstream province capital city within the basin in question[4]. During this process, each community agrees on the final jurisdiction and statutes, which are subject to restrictions by the Water Code. The location and establishment date of these boards are presented in figure IV.

Administrative and legal jurisdiction. Water Boards' jurisdictions covers surface water bodies within their boundaries[5]. We present in figure VI flowcharts of how Water Boards relate to the administrative (figure VIa) and legal institutions (figure VIb) in Chile on water matters. Administrative decisions, such as cutting allotments in the context of drought, will be decided by the Water Board, for water rights within their jurisdiction[6]. If any user wants to dispute this decision, they can appeal to the DGA; however, in practice, DGA's capacity is limited and its decisions have been overruled by courts in several lawsuits (Bauer, 2004; World Bank, 2011b).

In the case of legal actions, any people and firms owning water rights should ask for a ruling from the Water Board that has jurisdiction over the source[7]. Part of the duties of a Water Board is to appoint a "Judge of Waters", who most of the time is part of the board or an employee of the board. This judge has full authority to solve legal disputes and to enforce their ruling, with the authority of the Water Board. In the absence of a Water Board, instead, the only option users face is to initiate legal action on ordinary courts (civil or penal courts, depending on the nature of the conflict). Water Boards substitute ordinary courts on water matters, with additional field expertise.

Appeals to Water Board rulings -or lawsuits against the boards themselves- must be made to the Appeals Courts -which almost in all cases have jurisdiction over Regions, the

[4]Articles 269^{th} and 270^{th} of the Water Code of 1981(Biblioteca del Congreso Nacional, 1981).

[5]In 2005, their jurisdiction expanded, to include groundwater (CNR, 2018; Fernández and Gironás, 2021).

[6]For water rights registered in canals, Water Boards make decisions regarding allotments for the full canal, and the corresponding Canal Association will solve the matter within the canal. Users willing to dispute their Canal Association decisions may direct their complaints to the Water Board.

[7]If the users under conflict own water rights linked to a canal, their first step is to address their Canal Association, which manages water issues within a given canal. If the agents are unsatisfied with their ruling, they can appeal to their Water Board, or ordinary courts, if there is no Water Board with jurisdiction in the area. Water Boards also have jurisdiction over all conflicts that may arise among canals themselves, as long as they are within the Boards' jurisdiction.

first level administrative unit in Chile-, and eventually can be escalated to the Supreme Court. Bauer (2004) discusses how higher courts lacked water-specific knowledge and have ignored in their rulings substantive water issues, focusing exclusively on the legal issues at hand and emphasizing the "letter of the law."

3 Data

We gathered a richness of information that reflects the *de jure* and *de facto* allocation of water across space and time, together with detailed agricultural information to measure outcomes and climatic controls. Our analysis has three stages: first, our misallocation test, implemented using farm level census data, combined with weather data at the county level; then a farm level analysis based on remote sensing and administrative data, and finally our basin level analysis.

3.1 Farm level, Misallocation Test

2007 Agricultural Census. The misallocation test uses data from the 2007 Agricultural Census, collected by the National Statistic Bureau (INE, the official statistical office of Chile). This Census includes operation-level information on land use and extension, crop choice, capital and employment decisions, managerial characteristics and legal organization. Importantly, includes information on production for more than 20 annual crops, and self-reported information on the use of irrigation and the sources and legal status of irrigation water, together with affiliation to agricultural organizations (including specifically Canal Associations).

Climate Data. The Center for Climate and Resilience Research (CR^2) created daily climatic estimates for the entire Chilean territory at a $70km \times 70km$ resolution, by calibrating satellite measures with local input from climatic monitoring stations (Alvarez-Garreton et al., 2018). These estimates include precipitation, potential evapotranspiration and minimum and maximum temperatures. We aggregate these climatic estimates at the plot, county or the drainage basin level, according to the analysis on which the data is being used.

3.2 Farm Level Analysis

Water Organizations. The information on the jurisdictions and establishment date of Water Boards was provided by the DGA. This institution also provided the maps of the jurisdictions of each board, and also information on the location and jurisdiction of Canal Associations.

Land plot limits. SII (the Chilean Tax Authority) maintains for tax purposes a Land Cadaster, with detailed information on each plot of land in the country. CIREN geocoded the Land Cadaster for 2013. Our sample corresponds to land plots located less than 1km away from a canal. We obtained the canal locations and data from the DGA and CIEDESS, a local research center focused on natural resources.

Satellite information on Evapotranspiration and Greenness. EEFlux is a platform that provides Evapotranspiration estimates through the METRIC method (Allen et al., 2015) using as input images from Landsat 7, 8, 9 and Sentinel 1 and 2. This method recovers Evapotranspiration from an Energy Balance condition that equates the measured sun radiation on the surface to the calculated surface reflectance, estimated soil heat absorption and Evapotranspiration (which is recovered as a residual)(Allen et al., 2015). We use images captured since the year 2000 using as input Landsat-7 images, with a resolution of $30m \times 30m$, a resolution fine enough to allow us to perform farm-level analysis. We also use NDVI and EVI estimates based on Landsat 7 images from the USGS, and so they also have a resolution of $30m \times 30m$.

3.3 Basin level analysis

Basins, Streamflows and Climate. The DGA publishes the maps of the network of rivers, together with the boundaries of all basins and aquifers identified in the country. Also, the DGA maintains a network of 803 monitoring stations in rivers and canals across the country since 1913. Our main sample is composed of 516 of these stations that have been created before 1980 and operated for at least 10 years after this. CR^2 has identified the drainage areas of each monitoring station.

Water Rights. Since 2010, the DGA has collected information on water rights from different local agencies and registrars where the titles were created. Using this information, the DGA maintains a Water Rights Cadaster, that includes detailed information about each water right, including monthly extraction schedule, water source (surface water or groundwater), original owner's name, and geographic coordinates of the water intake. From the original owner's name, we classify water rights as belonging to people or firms, and identify firms' economic sector.

4 Misallocation Test

In this section, we provide evidence that water misallocation occurs only in areas without Water Boards. We propose a misallocation test based on the idea that if irrigation water can be reallocated within a basin through a frictionless market, the marginal product of water (MPW) should be equalized within the basin.

The argument proceeds as follows. First, consider the problem of a farmer choosing the amount of water rights to acquire at the beginning of the season; this corresponds to the maximum amount of irrigation the farmer could use during the irrigation season. Rainfall substitutes for irrigation water at a fixed rate, but follows a known random distribution (Rafey, 2023). The First Order Condition of this problem is that the farmer acquires water rights such that the expected marginal product of water is equal to the expected shadow value of water in the irrigation season. Second, the effect of an unexpected rainfall shock during the irrigation season is equal to the marginal product of water (times the marginal rate of technical substitution between rainfall and irrigation water), as a consequence of the Envelope Theorem, combined with the presence of fixed inputs (Hsiang, 2016; Deryugina and Hsiang, 2017). Finally, a benevolent Social Planner maximizing the total value of the production by society will equate the expected shadow values of water across users[8].

To test empirically the null hypothesis of equal average marginal product of water across locations, we identify unexpected rainfall shocks at different positions within the basin. By measuring how these shocks affect profits, we can calculate the semielasticity of profits to rainfall, which equals the marginal value of water. Our results show that in areas without Water Boards, the marginal value of water declines significantly from downstream to upstream locations, showing a pattern of misallocation consistent with the natural advantage of upstream users to over-extract. In contrast, areas governed by Water Boards show no significant differences in marginal returns across locations.

4.1 Model of Agricultural Production and Irrigation under Water Rights

Environment. Consider a Social Planner's problem of allocating water rights to N farmers, who can freely choose inputs for agricultural production. Agricultural production follows a cycle over the year, with 3 seasons: a Planting season $s = 0$, a Growing season ($s = 1$) and Harvest time ($s = 2$). Water supply has different impacts depending on this stage; in what follows, we assume that irrigation is only useful in $s = 1$.

At stage $s = 0$ each farmer $i \in N$ chooses crop c, capital K_i and land S_i, which are fixed over the full production cycle. At stage $s = 1$, the farmer chooses the flexible inputs, namely labor L_i and effective irrigation w_i. Effective irrigation is capped by the amount of water rights allocated to the farmer $\bar{w}_i$. Rainfall r is a perfect substitute for irrigation water, up to a technical rate of substitution constant θ. Rainfall is a random variable with a distribution known by all agents. We assume that input and output prices are known in advance, and all markets are competitive.

There is a Social Planner who allocates Water Rights to each user; each user will extract after rainfall uncertainty is realized. The timeline of decisions is therefore:

[8] We focus on the allocation of water rights instead of effective water because in our setting, there is limited short-term trading, as a consequence of limited storage capacity in most basins (Bauer, 2004; **?**). This explains why we focus on the expected shadow value of water rather than the effective shadow value. In any case, the analysis is equal to a first-order approximation to a similar analysis for the allocation of water itself.

Time= 0 : Social planner allocates water rights. Farmers choose crops, capital and land.

Time= 1 : Farmers hire labor and apply irrigation water subject to their Water Rights caps

Time= 2 : Profits are realized

Finally, each production function F_c is increasing, continuous, strictly concave, and monotone[9].

Farmers' problem. We solve by backward induction: the problem of user i at stage $s = 1$ is to choose the optimal irrigation and labor quantities to maximize profits:

$$\max_{L_i, w_i} \quad p_c F_i^c(S_i, K_i, L_i, w_i + \theta r_i) - \lambda_i^s(w_i - \bar{w}_i) - c_L L_i$$

The First Order Conditions of this problem are

$$\begin{aligned} FOC\ (w_i) \quad &: \quad p_c F_{i\ w}^{c\prime} = \lambda_i^w \\ FOC\ (L_i) \quad &: \quad p_c F_{i\ L}^{c\prime} = c_L \end{aligned}$$

Under the assumptions above, each farmer will just use the total amount of water rights allocated to them. The shadow value of water will be equal to the marginal product of irrigation water.

In stage $s = 0$ the problem of the farmer is to choose the optimal Capital, Land, and

[9]While the first two properties are assumed to keep the analysis simple (i.e. to guarantee that the demands for all factors are functions and not correspondences) and it is possible to replace them without loss of generality, the last assumption may be more controversial, as it rules out scenarios where excessive rainfall adversely affects production. While such a scenario is certainly realistic, in the area under study—with mostly dry Mediterranean weather with a well-marked rainfall season in the winter—is rare, and it did not take place in the period under analysis (2006-2007 Austral agricultural year).

Consider the case where irrigation increases production until a total water input threshold, after which water damages production: any rainfall that falls below this threshold will just supplement the water input provided by the farmer up to this threshold, after which it will just crowd-out the farmer's input (i.e. the farmer will reduce its water input up to keep water below the threshold). In this scenario, the shadow value of water is zero, and so the problem and the shadow value preserve their meaning.

crop: The fixed inputs are chosen based on

$$\max_{K_i,S_i} \quad \mathbb{E}_r \left\{ pF_i^c \left(S_i, K_i, L_i \left(K_i, S_i, \bar{w}_i\right), w_i \left(K_i, S_i, \bar{w}_i\right) + \theta r_i\right) - c_S S_i - c_K K_i | I_0 \right\}$$

The First Order Conditions of this problem are

$$\begin{aligned} FOC\ (S_i) \quad &: \quad \mathbb{E}_r \left\{ p_c F_{i\ S}^{c\prime} | I_0 \right\} = c_S \\ FOC\ (K_i) \quad &: \quad \mathbb{E}_r \left\{ p_c F_{i\ K}^{c\prime} | I_0 \right\} = c_K \end{aligned}$$

where the Envelope Theorem rules out any indirect effects on any flexible inputs. Given the choices for each input, we can define the expected profits for farmer i conditional on choosing crop c:

$$\begin{aligned} \pi_i^c(\bar{w}_i) \equiv &\mathbb{E}_r \left\{ p_c F_i^c \left(S_i\left(\bar{w}_i\right), K_i\left(\bar{w}_i\right), L_i\left(\bar{w}_i\right), w_i\left(\bar{w}_i\right) + \theta r_i\right) \right. \\ & \left. - c_S S_i\left(\bar{w}_i\right) - c_K K_i\left(\bar{w}_i\right) - c_L L_i\left(\bar{w}_i\right) - \lambda_i^w \left(w_i\left(\bar{w}_i\right) - \bar{w}_i\right) | I_0 \right\} \end{aligned} \tag{1}$$

The farmers, therefore, will choose the crop with maximum expected profits. The farmer's expected profits are

$$\bar{\pi}_i(\bar{w}_i) \equiv \max \left\{ k : \pi_i^k(\bar{w}_i) \right\} \tag{2}$$

Social Planners' Problem. Let's define the Social Welfare Function as the sum of the expected production of all farmers within the basin:

$$\Omega\left(\bar{\mathbf{w}}\right) \equiv \sum_i \bar{\pi}_i(\bar{w}_i)$$

The problem of the social planner is to allocate water rights across users to maximize the expected total production value, subject to the total availability of water:

$$\max_{\{\bar{w}_i\}|_{i=1}^N} \mathcal{L}(\mathbf{w}) = \sum_i \bar{\pi}_i(\bar{w}_i) - \lambda^W \left(\sum_i \bar{w}_i - \bar{W} \right) \tag{3}$$

Note that the social planner's objective function is just the sum of value functions of all farmers; therefore, as a consequence of the Maximum Theorem, the social planner's objective function is continuous on each water right $\bar{w}_i$. The first order condition with respect to $\bar{w}_i$ is

$$\frac{\partial \mathcal{L}(\mathbf{w})}{\partial \bar{w}_i} = 0 \iff \frac{\partial \bar{\pi}_i}{\partial \bar{w}_i} = \lambda^W \tag{4}$$

Therefore, the optimal allocation satisfies $\frac{\partial \bar{\pi}_i}{\partial \bar{w}_i} = \frac{\partial \bar{\pi}_j}{\partial \bar{w}_j}$, $\forall i, j \in N$[10]. Note that:

$$\frac{\partial \bar{\pi}_i}{\partial \bar{w}_i} = \frac{\partial \mathbb{E}_r \left\{ p_k F_i^K | I_0 \right\}}{\partial \bar{w}_i} = \mathbb{E} \left\{ \lambda_i^w | I_0 \right\}$$

where K represents the crop chosen by the farmer, and the second equality is a consequence of the Envelope Theorem.[11] In the socially optimal allocation, therefore, the expected shadow value of water is equal across farmers; any deviation from that implies the opportunity to increase expected welfare by redistributing water rights from users with a high shadow value of water to users with a low shadow value.

The effect of a rainfall shock and the Marginal Product of Water. Consider the effect on social welfare of an unanticipated rainfall shock over farm i at $s = 1$. As the water rights allocation is fixed, then:

$$\frac{\partial \Omega}{\partial r_i} = \theta \lambda_i^w$$

. So the total effect of an unexpected rainfall shock on production is equal to the shadow value of water of the affected farmer, times the marginal rate of technical substitution between irrigation water and rainfall. Note that Rafey (2023) estimate θ to be equal to 1.048 for annual irrigated crops, which is approximately equal to 1.[12]

Two key conclusions emerge from the previous discussion. First, the optimal allocation of water rights equalizes the expected marginal product of irrigation water across users. Second, the effect of an unexpected rainfall shock is equal to the marginal product of

[10]This is not true in the presence of fixed costs. In that case, the previous statement is true for every pair of farms i, j that are optimally receiving water, and so, the fixed cost is sunk.

[11]The application is direct in this case; a more general discussion can be found in Hsiang (2016); Deryugina and Hsiang (2017)

[12]The estimates of θ for other crop choices are 1.081 for perennial crops, for annual non-irrigated crops is 0.591 and for dairy is 0.148.

irrigation water.

4.2 Test Implementation

We can test the null hypothesis of equal average marginal product of water across locations by identifying unexpected rainfall shocks by position within the basin, for treated and control areas, and then to measure their impact over profits; the semielasticity of profits to these rainfall shocks will equate the marginal value of water (Deryugina and Hsiang, 2017). Our Agricultural Census data do not measure the effective water input for each parcel; but as rainfall is a perfect substitute for irrigation water, up to an absorption rate (equal to the marginal rate of technical substitution between rainfall and irrigation water) (Rafey, 2023), we exploit the timing of rainfall to get within county variation in water input received during the irrigation season -which we call “useful rainfall”- at the parcel level across the production cycle. This will allow us to test for differences in the average shadow value of water among farms with canal-based irrigation and with water rights, in different locations in the same basin.

We implement our misallocation test using the 2007 Chilean Agricultural Census, which contains a rich set of technology and input choices (including irrigation technology, planted surface, hired and total workers, machinery use, and property of water rights), which we combined with soil quality estimates and daily climate data at the county level, including precipitation and temperature by calendar day. The sample for the estimation includes farms with irrigation from canals, owning or renting water rights, and with a cultivated area below 50 hectares, and located in counties whose centroids belong to one of the 12 basins under study.[13]

[13] We eliminate farms above 50 hectares to eliminate outliers; including farms above this threshold does not change the results qualitatively, but the standard errors are higher.

We estimate

$$
\begin{aligned}
\log\left(\frac{Y}{\text{Hectares}}\right)_{irc}^{2007} &= \beta_1\text{Board}_c + \beta_2\text{Useful Rain}_{rc} + \beta_3\text{Distance to Sea}_c \\
&+ \beta_4\text{Board}_c \times \text{Useful Rain}_{rc} + \beta_5\text{Board}_c \times \text{Distance to Sea}_c \\
&+ \beta_6\text{Useful Rain}_{rc} \times \text{Distance to Sea}_c \\
&+ \beta_7\text{Board}_c \times \text{Useful Rain}_{rc} \times \text{Distance to Sea}_c \\
&+ \beta_X \mathbb{X}_i^{2007} + \mu_c + \mu_r + \varepsilon_{irc}
\end{aligned} \tag{5}
$$

where $\log(Y/\text{Hectares})$ is the logarithm of the value of output per hectare obtained by farm i on planting crop r in county c, Useful rainfall$_{r,c}$ is the rainfall received during the irrigation season of crop r in county c, in cubic meters per hectare per months $(m^3/ha/month)$, Distance to Coast$_c$ is the distance to the river mouth from the centroid of each county c through the river, in kilometers.[14] $\mathbb{X}_i^{2007}$ is the set of controls, which includes the logarithm of the total labor hired during the 2007 agricultural year, a vector of capital and technology choices and the irrigated surface. Board$_c$ equals 1 if the farms belong to a county whose centroid falls inside the jurisdiction of a water board. Finally, μ_c is a county fixed effect, and μ_r is a crop fixed effect.

On estimating equation 5, we are exploiting within-county, within-crop variation in the timing of rainfall, which is arguably exogenous on most determinants of agricultural production. County fixed effects will capture common shocks to all farms and average expectations, and individual farm controls–including crop fixed effects– will capture long term and short term determinants of output. On estimating equation 5, we are exploiting within-county, within-crop variation in the timing of rainfall, which is arguably exogenous on most determinants of agricultural production. One threat to our identification strategy is the presence of imbalances: farmers may try to match the pattern of rainfalls to optimize their water (Kala, 2019); if our controls do not capture the farmers' information, then it is possible to have biased estimates.

In table III we present a Balance Table for useful rainfall, after including our main

[14] This distance corresponds to the length of the least cost path connecting each county centroid to the river mouth, through the river network representing the hydrology of each basin. For details, see Annex C.

controls: basin fixed effects, 0.5×0.5-degree-cell fixed effects, and crop fixed effects. There are no systematic differences for our sample. For our main sample (irrigated fields) we only observe a decrease in rainfall as we move from the coast to upstream locations, but there is no significant differential rainfall pattern between farms located in counties with and without water boards. In the case of our placebo sample, there are some differences in useful rainfall that disappear once we include 0.5×0.5-degree-cell fixed effects. In any case, any difference that may have had appear in this table would be controlled by the inclusion of county fixed effects, which are included in our preferred specification.

Equation 5 allows us to estimate directly the functions needed for our Misallocation Test. First, we estimate the Average Shadow Value of Water as a function for the distance to the coast, in the absence of water boards:

$$\frac{\partial \mathbb{E}\left\{\pi_i \mid I_0, \text{Distance to Sea, No Board}\right\}}{\partial w_i} = \beta_2 + \beta_6 \times \text{Distance to Sea} \tag{6}$$

Second, we estimate the Average Shadow Value of Water as a function for the distance to the coast, under water boards:

$$\frac{\partial \mathbb{E}\left\{\pi_i \mid I_0, \text{Distance to Sea, Board}\right\}}{\partial w_i} = (\beta_2 + \beta_4) + (\beta_6 + \beta_7) \times \text{Distance to Sea} \tag{7}$$

We test for misallocation by comparing the shadow value of water as a function of each farm's position in the river. We investigate how the shadow value of water varies with distance from the river mouth, specifically examining whether the marginal value of water differs between the top of the river (its head) and the location where it drains to the sea.

Results. In table II we present the results of estimating equation 5, considering an array of location-fixed effects. Our preferred specification is in column 4, which we also present graphically in figure VII. The estimated coefficient associated with rainfall (β_6) implies that for farms in our sample - water right owners, affiliated to canal associations and with irrigation - an extra unit of water ($m^3/ha/month$) would increase yield by 42% if they are at the river mouth. When taking into account the coefficient associated with the interaction of useful rainfall and distance to the mouth, we see that for farms located approximately $200km$ upstream, the increase becomes a non-significant reduction of 10%. The estimated average MPW is presented as the red function in figure VII and clearly displays a higher average shadow value of water in locations downstream versus upstream.

This result is consistent with misallocation: farms located downstream are water-restricted, while farms located upstream are not; a marginal displacement of water through the river from upstream locations to downstream locations would increase the total value of production, but the lack of enforcement prevents such reallocation. At the bottom of table II we present the p-values of the test of equality of MPW across locations; for all specifications, we reject the null hypothesis of no misallocation at the 10% confidence threshold[15].

In contrast, for counties within the jurisdiction of Water Boards, the average shadow value of water is similar, regardless of their distance to the river mouth. For counties located next to the coast, there is a non-significant reduction in value per hectare of around 5% per extra cubic meter of water per hectare per month), which is approximately the same for farms located $200km$ upstream. The average shadow value of water as a function of the distance to the coast is presented as the blue function in figure VII, is flat compared to the function for places with boards, and never significantly different from zero. These results do not allow us to reject the null hypothesis of no misallocation in counties under the jurisdiction of a Water Board, as it is reflected in the last row of table II. The results are similar controlling for basin, 0.5-degree cells, and county fixed effects.

Placebo exercise: rainfed farms. To address concerns regarding potential confounders that may cause the former cross-sectional results, we present a placebo exercise, where we estimate equation 5 including the same set of controls, but for rainfed farms. These agricultural operations display different technology choices but are located in the same territory as the former sample, so they are exposed to similar geographies and climates. These parcels rely exclusivley on natural precipitation, so there is no additional water input on top of rainfall, Water Boards have no mechanism to affect their input. Therefore, we expect to

[15] This test was performed considering the standard errors clustered by county; the results do not change by considering the SE clustered by county and irrigation season crop type.

find no effect of Water Boards on these farms.[16].

Table III presents the results of this exercise. Our preferred specification is in column 4, where we again exploit within-county, within-crop variation in useful rainfall across crops. The results suggest that the yield per hectare increases by around 8% per extra unit of water ($m^3/ha/month$) at the coast. The increase in yield for farms located the farthest from the coast (at $219km$) is 11%, which is not statistically different from the effect on the coast. For counties with Water Boards, the corresponding estimates are 12% and 6%; they are not statistically different either. Importantly, all interaction terms involving the water board dummy are not significant and economically small. The last rows of table III show that after including 0.5-degree cells or county fixed effects, we cannot reject that the MPW is equal for all locations, either with or without water boards, as expected.

Figure VIII presents the estimated functions of Average MPW for areas with and without water boards. The most important conclusion from the figure is that none of these funtions exhibit a significant slope, and despite the existence of some (statistically non-significant) differences in levels, both functions are contained in the confidence intervals of the other. This placebo exercise suggests that the estimated effects of rainfall on irrigated parcels (our main exercise) recover a causal relationship between water and yield across different locations, and so our Misallocation Test identifies the underlying misallocation existing in the absence of water rights enforcement. More importantly, our test fails to find such misallocation in places with water boards exerting property rights enforcement, suggesting that we cannot reject the efficiency of water markets supported by Water Boards.

5 Mechanisms: Redistribution and Private Decisions

In the previous section, we documented intra-basin water misallocation between farms except where Water Boards operate. Here, we use multiple approaches to study how Water Boards enhance agricultural productivity through two key mechanisms: water redistribution from upstream to downstream users, and farmers' private responses, including crop

[16] Also, our estimates will correspond to the marginal product of Water for these farms. Manysheva (2022) and Rafey (2023) use this strategy to estimate the production functions of rainfed farms

and irrigation technology choices.

Our analysis relies on a novel database, containing more than 75,000 parcels located less than 1km away from a canal in the whole area of study (i.e. regions IV to IX, in Central Chile). We estimate plot-level water consumption using EEFlux, a new LANDSAT-based product that provides estimates of Evapotranspiration at a 30m resolution every 16 days since 1999 (Allen et al., 2007, 2015). In addition, we also estimate agricultural yield and crop choice using Enhanced Vegetation Index (EVI) estimates from LANDSAT 7[17](Burke and Lobell, 2017; Blakeslee et al., 2021). To illustrate the detailed nature of this data, figures IXa and IXb present our estimates of water consumption and agricultural yield (proxied by actual evapotranspiration and EVI, respectively) for all farms in the Aconcagua Basin. In figure IXa we observe a decline in water consumption when comparing upstream (right) to downstream (left) locations. Similarly, figure IXb presents a similar decline in yield. However, there is substantial intra-location variation, especially in upstream locations.

5.1 Redistribution of Water within Basins

We will first document cross-sectional differences across locations, to then run a regression analysis exploiting the richness of data available to us. To address endogeneity concerns, we will finally implement an Instrumental Variable approach based on the legal costs of establishing a Water Board.

Cross-sectional variation in Water Access. Figure Xa corresponds to a Kernel regression of average Evapotranspiration per unit of surface[18] and the distance to the coast, as a measure of exposure to over-extraction by users located upstream. We can see a decline in

[17]LANDSAT 7 is a satellite program launched in 1999 by the US government. This program provides pictures of all across the globe every 16 days, with a resolution of 30 meters. These images are managed by USGS. More detailed information is available at https://www.usgs.gov/landsat-missions/product-information

[18]The unit used corresponds to mm of water evaporated per pixel, with pixels measuring $30m^2$. Evapotranspiration includes both evaporation of water from the soil and transpiration from the vegetation; as we are including in our sample farms located close to canals in agricultural regions, transpiration will originate mostly from cultivated vegetation. Evaporation, in turn, may happen as long as there is soil moisture available for evaporation; this moisture may come from natural sources -such as rainfall- or artificial ones -such as irrigation. Therefore, Evapotranspiration could be considered an upper bound for water consumption, unless we can measure accurately natural sources of soil moisture; in this paper, we address that by controlling for rainfall during the year and during the summer.

the average evapotranspiration as we get closer to the river mouth, reflecting over-extraction by upstream users; however, while basins with Water Boards have a lower average Evapotranspiration, there is no discernible difference in trends between basins with and without Water Boards.

Figure Xb presents a measure of total water consumption per parcel, incorporating the heterogeneity in farm operations. The figure now illustrates the main mechanism described in this paper: in the absence of Water Boards, upstream farms extract more water than farms within the jurisdiction of Water Boards, while this relationship reverses downstream, with farms without Water Boards extracting less water than their counterparts subject to a Water Board authority.

This difference in the spatial distribution of Water Consumption translates into differences in hydric stress for crops. Following Allen et al. (2015), we construct a Water Availability Index by dividing the actual Evapotranspiration by estimates of vegetal biomass using NDVI[19]; this is a measure of how much water is actually receiving the vegetation within an area. We create this index at the farm level, and figure Xc presents a kernel regression between Water Availability and distance to the coast. Water Availability is constant in areas under the authority of a Water Board, but for areas without any Water Board, there is decreasing Water Availability as we advance towards the coast.

In table IV we present summary statistics of the farms under analysis. There are no salient differences between treated and control farms, except for the fact that farms under water boards seem to face dryer climates, and to have better market access (i.e. being closer to the ports of Valparaiso and San Antonio, and to Santiago, the largest internal consumption market). This is consistent with the idea that Water Boards are adopted in areas where competition for water is stronger, due to scarcity or higher demand. Farms within Water Board jurisdictions seem to be larger. Table A.II in Appendix presents similar summary statistics by location in the basin.

Finally, we estimate the correlation between our main outcomes– water consumption

[19] Allen et al. (2015) present this index as a Hydric Stress Index, with lower values reflecting more hydric stress; we renamed it for the sake of interpretability.

and agricultural yield– and the presence of Water Boards, conditional on the location within the basin. Formally, we estimate:

$$\mathrm{Y}_{iqcb} = \sum_{q=1}^{3} \eta_q \times 1[dist = q] + \sum_{q=1}^{3} \alpha_q 1[dist = q] \times \mathrm{Board}_i + \gamma X_i^d + \mu_b + \varepsilon_{icqb} \tag{8}$$

where i denotes farms, q terciles of distance to the coast, c counties, g cells in a 1×1-degree grid and b basins. X_i^d is a vector of farm-level controls including our market access measures (driving distance to Santiago and main ports); dummies for soil quality quartiles; second-degree polynomials for farm area, annual and summer precipitation; and temperature, measured as extreme heat days", or the number of days with maximum temperatures above 29 degrees Celsius (Hsiang, 2016). μ_g is a basin fixed effect; in our implementation, we estimate equation 8 considering basin, sub-basin and sub-sub-basin fixed effects[20]. Our main vector of interest is $(\alpha_1, \alpha_2, \alpha_3)$ i.e. the correlation between our outcomes and the presence of Water Boards for the first, second and third tercile of distance.

In table V we present our estimates of equation 8. Columns 1 to 3 present our estimates for water consumption, while columns 4 to 6 for yield. Columns 1, 2 and 3 (and 4, 5 and 6) consider basin, sub-basin and sub-sub-basin fixed effects, respectively. For all specifications, there is a positive correlation between the presence of Water Boards and water consumption among downstream farms, although the correlation is significant only after using our finest set of fixed effects. Considering sub-sub-basin fixed effects, downstream farms within Water Boards consume 6% more water than downstream farms outside Water Boards jurisdictions. The relationship is the opposite among upstream farms: for the same specification, upstream farms within Water Boards consume 9% less water than upstream farms outside their jurisdiction. In the case of yield, instead, we observe a significant increase among downstream farms of 3.5%, anda non-significant reduction of 1.5% among upstream farms.

Instrumental Variable analysis. A simple OLS estimation of Water Boards' effects would likely be biased due to endogenous adoption. Areas may establish Water Boards based on unobservable characteristics that independently affect water distribution patterns.

[20]Sub-basins and Sub-sub-basins would be equivalent to level-2 and level-3 basins

In fact, the spatial distribution of Water Boards along the country suggest a non-linear relationship between the presence of Water Boards and water availability (see figure IV). Locations where water is too scarce do not attract enough agricultural activity, and so the demand for water is too low to trigger any conflict; while locations where water is too abundant may attract agricultural activity, but conflict may not escalate under abundance. Similar phenomena may arise from different heterogeneities, such as agricultural suitability, land quality or climate. To address these concerns, we will construct an instrument based on the costs of establishing a new water board in a basin.

We exploit a unique feature of the process of establishment of water boards: the Water Code explicitly states that board establishment may be triggered by an agreement of users or a lawsuit, which shall be presented in front of a judge in the province capital city where the water source is located if a water source is contained within just one province, or in the most upstream province capital city in case the water source crosses province boundaries (Biblioteca del Congreso Nacional, 1981).

In principle, a new Water Board will have jurisdiction over the full extent of the basin (i.e. the area that drains to the mouth of said river) over which it is being established. However, the legal process will define endogenously the borders of a Water Board, for example, by users arguing about the starting and ending points of said river[21]. To address this, we consider the costs of establishing a water board in the full geological basins (i.e. the area that drains to a river mouth in the sea coast), which in all cases run from the Pacific Ocean in the West to the Andes Mountains in the East. As almost all basins will cross province borders, we can identify the most upstream Province Capital City by finding the most eastward province capital city within each basin.

Instrument by location. Before defining our instrument, is worth remarking an asymmetry that pervades the problem of establishing governance under our setting: only upstream users are able to over-extract, and so only downstream users can be worse-off due to the

[21] Consider the example of a basin with one main river and a secondary feeding river; if users in the secondary river want to establish a water board, users in the main river may argue that they are part of a different river.

lack of enforcement[22]. While downstream users may demand the establishment of a water board, upstream users will not. Moreover, the institution is demanded explicitly to impose enforcement over those able to over-extract (i.e. the upstream users). Therefore, while downstream users will demand the establishment of a water board, upstream users will be forced to join it.

The former argument implies that lowering the cost of establishing water boards faced directly by users, in principle, should only affect the likelihood of adoption by downstream users, as upstream users will not demand it. Instead, the adoption of water boards by upstream users should be determined by the costs faced by downstream users. Our instrument for downstream locations consists of the driving distance of the optimal route between a location and said city. Our instrument for upstream locations, instead, will be the average driving distance to the most upstream capital city for the farms located in downstream locations in the same basin.

With these instruments for different locations, controlling for geographical characteristics -including basin location-, we can identify the causal effects of the establishment of a Water Board over the compliers (Angrist and Pischke, 2009), who in this case would be 1) farms located in areas where a Water Board is established because downstream agents have a lower cost of establishing it, due to the upstream capital city being located closer, and 2) farms located in areas that do not adopt a Water Board because the upstream capital city is located too far away.

In figure XI we illustrate the data and our instrument in a blue-to-red gradient. In the case of this instrument, we can see how downstream areas that are closer to the most upstream province capital city (in bluer colors) are eventually under the jurisdiction of a water board, while downstream farms too far from this city are not under the jurisdiction of any board.

We estimate different IV models for three different quantiles of the distribution of distance to the river mouth of each basin. We ran separate regressions given that we expect

[22]The former argument is a simplification, as the same situation may arise within canals at different locations in the basin: farmers located closer to the river may -in absence of proper enforcement- over-extract, leaving farmers located far from the river with less water. However, it is possible that appropriate enforcement at the river level may imply enough water availability on each canal, such that the within-canal enforcement problems become negligible.

the presence of heterogeneous effects, but more importantly, to mitigate potential SUTVA violations[23] .

For downstream locations, the equation is

$$\begin{aligned}\text{Water Consumption}_{igcb} =& \alpha \text{Board}_i + \gamma X_i^d + \mu_g + \varepsilon_{icb} \\ \text{Board}_i =& \beta \text{Distance Upstream Capital}_{ib} + \delta X_i^d + \eta_b + u_{icb}\end{aligned} \tag{9}$$

where i denotes farms, c counties, g cells in a 1×1-degree grid and b basins. X_i^d is a vector of farm-level controls including our market access measures (driving distance to Santiago and the main ports); dummies for soil quality quartiles; second-degree polynomials for farm area, annual and summer precipitation; and temperature, measured as extreme heat days", or the number of days with maximum temperatures above 29 degrees Celsius (Hsiang, 2016). We also control for exposure to over-consumption, using as a proxy the distance over the river between the farm and the most upstream farm[24].η_g is a latitude-longitude cell fixed effect. Our instrument is $DistanceUpstreamCapital$, the driving distance to the most upstream capital city in the basin. In order to emphasize longer distances relative to shorter distances -which may be sensitive to local features of the road network-, we use as our instrument $\max\{50, DistanceUpstreamCapital\}$ given that corresponds roughly to a 45-minute drive in rural roads.

For midsection and upstream locations, instead, our main equation is

$$\begin{aligned}\text{Water Consumption}_{igcb} =& \alpha \text{Board}_i + \gamma X_i^d + \mu_g + \varepsilon_{icb} \\ \text{Board}_i =& \beta \text{Mean}(\text{Distance Upstream Capital}|\text{downstream})_b + \delta X_i^d + \eta_b + u_{icb}\end{aligned} \tag{10}$$

where $Mean(DistanceUpstreamCapital|downstream)$ is the average instrument for downstream locations; all other terms are the same as for downstream locations. We also control

[23]In principle, we assume –as it is our main premise across the paper– that there are downstream externalities in water consumption under scarcity: extraction by upstream users affects water availability of downstream users. We perform separate analyses by quantile of distance to the coast –i.e. by location within the basin– under the additional assumption that these externalities depend on aggregate extraction by users located upstream, and not by other agents located closely.

[24]The results are the same if we measure exposure by the number of farms located upstream, or the total area among farms located upstream.

for the average exposure of downstream farms.

We address spatial correlation using clustered standard errors by county. To assess the strength of our first stages, following Andrews et al. (2019) we provide the Effective F-statistic of Olea and Pflueger (2013)[25].

IV results. Table VI presents the Instrumental Variable estimates of equations 9 for downstream farms, and 10 for midsection and upstream farms for our measure of water consumption (Evapotranspiration per pixel). Columns 1, 2 and 3 present OLS estimates as benchmarks. Columns 4, 5 and 6 present our main IV estimates by section of the river (Downstream, Mid-section and Upstream, respectively). Column 4 implies that Water Boards increase water consumption by downstream farms on 2.14mm per pixel, which represents an increase of almost 60%. Column 5 implies a similar but statistically insignificant increase for mid-section farms, and with a very weak first stage. Column 6 shows a 17% reduction in water consumption for upstream farms. Overall, we observe that once we instrument the presence of a Water Board, we can see an economically significant redistribution from farms located upstream to farms located downstream, but implying net economic gains downstream[26].

In table VII we present similar results for our measure of agricultural yield per area (peak EVI per pixel during the season). The results are similar, but suggest the presence of decreasing returns to scale on water consumption: there is an increase of 18% in yield for farms located downstream, but a reduction of just 4% among upstream farms[27]. Mid-section farms see a non-significant increase similar to downstream farms, but the Effective F statistic suggest the presence of a weak instruments problem.

These results imply a substantial increase in water consumption for downstream farms, which translates into increased yields. Our results also suggest that upstream locations see smaller reductions in water access, that do not translate into reductions in yield. There

[25]This is equal on exactly identified IV models to the robust F-statistic (Kleibergen and Paap, 2006).

[26]Notably, we cannot reject that the OLS and IV estimates for upstream locations are different, which is consistent with the idea that the establishment of a water board is imposed to upstream farmers by decisions taken by users in downstream locations, and so, it can plausibly be exogenous.

[27]In results not reported, the effect over the NDVI index -a measure of agricultural activity- over Summer Months shows an increase of 44%.

are several potential reasons for observing net increases in water consumption and yield (i.e. the benefits for downstream farmers being greater than for upstream farmers), being the most plausible complementarities between reliable water provision and individual and collective investments (e.g. Karlan et al., 2014). We discuss these channels in subsection 5.3.

5.2 Water Boards impacts among small and large farms

In the previous section, we explored the extent of redistribution implemented by Water Boards in a geographical dimension: redistribution from upstream users to downstream users. We will call this vertical redistribution. We can consider also horizontal redistribution, i.e. redistribution across users at the same location. We will focus now on one important dimension of horizontal redistribution: between smaller and larger farms. While understanding the impacts on inequality of property rights institutions in the context of a developing economy is important in itself (e.g. Besley and Burgess, 2000), it is particularly relevant in this context, given that the "the jure" power structure reflects directly the ownership distribution: water boards allocate power according to property, as each water rights owner have a vote that is proportional to their streamflow ownership (e.g. Art. 222 of the Water Code, Biblioteca del Congreso Nacional (1981)). This is a departure from conventional democratic rules that may imply improved economic outcomes (e.g Alesina and Rodrik, 1994) but also could reinforce elite capture dynamics (Bardhan and Mookherjee, 2000; Banerjee et al., 2001). Our fine-grained data allows us to identify these potential redistribution dynamics by measuring directly water consumption across users.

In table VIII we use our Instrumental Variable approach separately by farm size: columns 1, 2 and 3 present the IV estimates for farms below the Median of the farm area distribution, while columns 4, 5 and 6 present the same results but for farms above the percentile 90[28]. To address concerns regarding the scale of each operation, we consider the average consumption of water per unit of area as our outcome measure.

[28] We considered assymetric rules to define smaller ("below percentile 50") and larger farms ("above percentile 80") because the distribution is very asymmetric with a heavy right tail -implying that farms below the median are more similar among themselves than farms above the median-, and also because we will probably have higher measurement error -on the independent variable, which implies more noisy estimates- for smaller farms, given that the pixel size is the same for all farms.

We find that both smaller and larger downstream farms increase their water consumption, but the increase is substantially higher for larger farms: while for small farms the increase in water consumption per pixel is 56%, for larger farms this increase is almost 85%. On the other side, we see that although smaller and larger upstream farms reduce their water consumption, the reduction is stronger for smaller farms: while smaller farms reduce their water consumption per pixel by 22%, larger farms decrease it only by 8%.

In table IX we repeat the exercise for yield per area as our outcome, with similar conclusions. While downstream small farms do not have a statistically significant (although the increase in yield is 28%), large farms increase by 58%. Meanwhile, in upstream areas, small farms reduce their yield by almost 8%, large farms do not see a reduction at all. In summary, the largest benefits are captured by downstream large farms, while the largest costs of the redistribution in place are borne by upstream smaller farms

Interpretation. To understand better the incentives faced by small and large farmers to create Water Boards, in figure XII we plot the average farm size by location in the basin, separately for farms located close and far from the river (i.e. below and above 3.5 kilometers of distance to the river that feeds the canal). The position within the canal is relevant, as those located farther in the canal will be among the first ones to lose water access if water supply is insufficient. The first observation is that for farms closer to the river, farm sizes are similar for areas with and without water boards, and the largest farms are found in upstream locations. However, when looking at areas farther from the river, we see divergence across locations with and without boards at both extremes of the basin: for areas with water boards, the distribution follows a U-shape pattern, while for areas without boards, it follows an inverted U. Farm size is larger among farms within water boards than outside, too.

Smaller farms in downstream locations may lack the resources needed to create or mantain a water board, and upstream farms of smaller scale may lack the capacity to over-extract at a scale that makes worthwhile for downstream users to demand the creation of a Water Board. At the same time, large downstream farms far from the river can receive the largest benefits from reliable water access. This pattern suggests that Water Boards emerge as a result of intra-elite conflict: between the largest upstream users -who can over-extract- and the largest users downstream -who can invest in the creation of the organization. Given the structure of votes within a Water Board -proportional to the ownership of water rights- we may expect control by the elite, but with representation across locations. In Appendix we provide evidence that there is more redistribution across locations within the river in basins with higher land inequality. This supports the interpretation that downstream elites are key to successfully establish Water Boards, and also to keep the river manager accountable on redistributing water downstream.

5.3 Private Investments and Choices

In this section, we explore the impacts of the establishment of water boards on private investments and decisions that are technologically complementary to the increased water availability provided by these institutions. In our analysis, we focus on 1) crop choice, and 2) irrigation technology.

The provision of property rights enforcement by the water boards represents a public good that increases the reliability of the water supply from the perspective of the downstream irrigators. This makes possible the growth of new crops that require irrigation for longer seasons. This also complements technology such as micro-irrigation, that requires a reliable water supply. The adoption of these investments and decisions still may be restricted by credit or liquidity constraints, making them potentially unavailable to some farmers (Karlan et al., 2014, e.g).

Crop Choice. We show in this section that the presence of water boards allows an expansion of the production possibility set, but mostly for large farms. Table XI presents estimates of equations 9 and 10 for two crop choice outcomes: a binary variable identifying if the maturity of a crop happens during the Summer or not (reflected by when the peak of greenness in a farm is happening) (Panel A), and the number of months between the beginning of the season and the month when the greenness peak is reached (Panel B). Columns 1 to 3 (4 to 6) present OLS (IV) estimates for Downstream, Mid-section and Upstream farms, respectively.

In Panel A, column 1, we observe that downstream plots within the jurisdiction of water boards are 15% more likely to have a greenness peak in the Summer months (December or after). Our instrumental variable estimate (column 4), in turn, shows an increase of 66*pp*, an order of magnitude higher. We check if this difference in magnitude is due to a weak instruments problem; the Effective F statistic is not very high, the Anderson-Rubin Test confidence interval excludes zero. Columns 3 and 6 shows the impacts on upstream farms: while our OLS estimate (column 3) implies a reduction statistically indistinguishable in absolute value from the increase among upstream farmers, our IV estimate (column 6) points to a reduction among upstream plots of just a third of the increase among downstream plots.

To explore the extent to which liquidity constraints may limit the farmers' ability to switch, we explore the impacts on crop choice separately for small and large farms in table XII using our instrumental variable approach. Panel A, which has our dummy variable for Summer crops as the outcome variable, shows similar increases among small downstream and large downstream farms. We observe differences among upstream farms: the reduction is only significant among small upstream farms, and their point estimate is more than twice the coefficient found among large upstream farms. In Panel B, we present our estimates of impact on the length of the growing season. We only observe significant increases in season length among large downstream farmers: this group extends their growing season by more than 2 months. We can find statistically significant reductions only among upstream small farmers, although they are minor (less than half a month of reduction).

Irrigation Technology. In this subsection, we will present our estimates of impact on irrigation technology. We use data from the Agricultural Census of 2007 to document how large downstream farms switch to more sophisticated irrigation technologies. This census allows us to distinguish between traditional irrigation , micro-irrigation and macro-irrigation technologies. Among the traditional techniques, the most common is the use of furrow; examples of micro-irriggation include the use of micro-spray and dripping techniques, while in the case of macro-irrigation, the most common strategy is the use of high-volume sprinklers. The decision of choosing an irrigation strategy or another is a private one, subject to profitability and credit concerns, but also to the availability of water: while traditional irrigation techniques have low maintenance costs, macro-irrigation requires high volumes of water, while micro-irrigation requires a reliable water supply to avoid clogging[29]).

The outcome variable in Columns 1 to 4 of table XIII is a dummy variable equal to one if a farm reports using a Traditional irrigation technique, while in columns 5 to 8 the outcome is a dummy equal to one if a farm reports using a micro irrigation technique. Odd (even)- numbered columns present estimates for downstream (upstream) farms[30]. Columns 1, 2, 5 and 6 (3, 4 ,7 and 8) present OLS (TSLS-IV) estimates. Finally, Panel A present estimates for the full sample of farms with irrigation, while Panel B only for large farms, and Panel C for small farms.

Our OLS results in for the full sample (Panel A) only show that plots in upstream areas with Water Boards are 3*pp* less likely to use furrow technology. Our IV estimates, instead, show a reduction of 12*pp* in the use of traditional irrigation technologies. There is a statistically insignificant increase of 8*pp* in the use of micro-irrigation. Our IV estimates in Panel B, instead, show a significant reduction (20*pp*, statistically significant at 10%) in the use of traditional irrigation techniques among downstream large farms, accompanied by an equal increase (21*pp*, statistically significant at 5%) in the use of micro-irrigation techniques in the same group. Panel C shows that there are no changes in the irrigation technologies used by small farmers.

Overall, we conclude this section showing that the provision of property rights enforcement by water boards increases the reliability of the water supply, allowing farmers to grow crops that require irrigation during the summer, and also to switch to more efficient irrigation techniques that require a stable water input. These opportunities seem to be available just for the largest farms, implying that the distributive impacts discussed in section 5.2 may be driven by liquidity constraints.

[29]E.g. see https://lgpress.clemson.edu/publication/micro-irrigation-system-maintenance-to-prevent-clogging/

[30]We do not report results for mid-section farms, as the first stages are too weak.

6 Basin level analysis

In this section, we further explore the effect of Water Boards on water reallocation through two key mechanisms. First, we examine how Water Boards influence the creation of water rights. While they cannot directly prevent the creation of new rights, Water Boards can expedite conflict identification between new applications and existing rights through their detailed local records[31]. Second, we analyze changes in river flow patterns, which reflect the de facto allocation of water. We expect enforcement to increase streamflows particularly during the dry season, when irrigation demands are highest and over-extraction incentives strongest. During the wet season, when either water is abundant or irrigation is less critical, the impact of Water Boards should be minimal.

6.1 Identification Strategy

We exploit the staggered adoption of Water Boards across basins to estimate the causal impact of property rights enforcement on the spatial allocation of water. Table A.V in Appendix A presents the year of establishment of Water Boards, and the number of river segments under their jurisdiction -defined by the locations of streamflow monitoring stations in the river network. Given the data available and the institutional design in place, we focus our analysis on the boards established after 1982[32].

The first challenge in building the counterfactual water availability and reclamation for treated areas is to identify a proper set of control river segments. To ensure a comparable control group, we identify non-treated units that satisfy three conditions: 1) within the common support of the treated group on key characteristics, 2) only non-yet-treated units and 3) the absence of externalities. The first condition is implemented based on two

[31]The process is comprised by the following steps (the process is summarized in figure A.I): **Step 1:** The person or firm interested in claiming the water starts a claim at the DGA.**Step 2:** The DGA sends a field officer, who will check the physical and legal availability of water in the source. **Step 3:** The agent interested in the water right has to publish the claim. There is a 30 business days period open for complaints, and for other potential users to express interest in the newly established right (if it is not possible to create rights for the two users). Any there are complaints, they will be reviewed by a judge; if the judge rules them as valid, the new water right is not created. If any other user is interested in the water right, there is an auction. **Step 4:** The title is created, legalized and registered in a local property registrar. We argue that Water Boards may be in a privileged position to intervene in step 3.

[32]We consider 4 years before and 4 years after the establishment of the board for our analysis, and so we need to exclude those boards established in 1982. The results are not affected by reducing the number of pre-periods to 3 to include the boards established in 1982.

observable measures in the baseline: average streamflows and total water rights in 1980[33]. For each measure, we identify the support of the distribution for the treated and exclude control segments whose values fall out of it.[34].The second condition implies that we only consider river segments where water boards were eventually established, as we expect them to be subject to similar demand trends . Finally, our third conditions implies the exclusion of river segments that are located downstream of any previously established boards, or water boards established before the 1981 Water Code.

Figure XIIIa presents the monthly pre-1985 streamflow and precipitation medians for all river segments without boards before 1980, separating between those that eventually were under a Water Board (treated segments onwards) and those that are not (control segments). Relative to control river segments, treated segments have lower streamflow and total precipitation, with hydrological regimes less dependent on rainfall and more on snow-melting, which is reflected by having streamflow peaks during the Austral Spring (October and November) instead of the Winter. Figure XIIIb presents streamflows over the year and precipitation for the final sample; treated and control units have comparable streamflows across the whole year, and overall a similar hydrological regime.

To gain power, we take advantage of the staggered adoption of the boards by including segments within the jurisdiction of water boards established in future periods as control segments for board establishment events with a time difference of at least 5 years. Table XIV presents the number of river segments in the full sample (excluding those subject to externalities and those with boards before 1981) and those in the Study Sample (i.e. those who satisfy Conditions 1, 2 and 3 above).

Our identification strategy relies on the assumption that the timing of adoption is as good as random, conditional on the set of fixed effects and covariates; such that there are no unobservable trends affecting treated and control units differently around the event. In our case, we argue that all the basins in our sample are facing increasing long-term coun-

[33]Water rights claimed by 1980 were claimed under previous Water Code versions, and they were eligible for regularization under the new rules introduced under the 1981 Water Code. They reflect the intensity of extraction of each river before the 1981 Water Code reform.

[34]Since both quantities are non-negative and the minimum values for the treated and control groups are similar and close to zero, this implies excluding segments with streamflows and water rights higher than the maximum observed for the treated group.

terfactual water demand, and so the differences in adoption timing are driven by long-term water availability and possibly short-term observable water availability shocks, but not by short-term unobservable shocks. In appendix B we provide evidence supporting this interpretation.

Difference-in-Difference Design for Water Rights creation. We implement Cengiz et al. (2019) Stacked DID design to estimate the following baseline equation:

$$\text{Water Rights}_{gst} = \beta \text{Board}_{gst} + \gamma X_{gst} + \mu_t + \eta_g + \varepsilon_{gst} \tag{11}$$

where WR_{gst} denote the total water rights issued in river segment g in basin s and year t and Board_{gt} is an indicator function that equals 1 if segment g is within a Water Board jurisdiction. X_{gst} is a vector of covariates that include rainfall, potential evapotranspiration and temperatures, η_g correspond to segment fixed effects and μ_{st} are year fixed effects[35]. We use georeferenced Water Rights records from the National Water Rights Cadaster, combined with climatic estimates by Alvarez-Garreton et al. (2018) and the geological basin borders identified by CR2.

To address potential pre-trends, we also estimate a dynamic effects specification:

$$\text{Water Rights}_{gst} = \sum_{i=-4}^{4} \beta_i \text{Board}_{gst} \times 1\left[t - t^* = i\right] + \gamma X_{gst} + \mu_t + \eta_g + \varepsilon_{gst} \tag{12}$$

where t^* denotes the year where the event of board establishment takes place. This means that $i = -4, -3, -2, -1, 0, 1, 2, 3, 4$ represent years relative to the event of board establishment. In our specifications, we consider relative year -1 as the baseline period, and include only observations within 4 years of the establishment.

Difference-in-Difference Design for Streamflow. Streamflow effects estimations present the additional challenge of seasonality: rivers and precipitation display seasonal patterns that introduce noise in the estimation, and could potentially bias the estimation of board

[35] Following Cengiz et al. (2019), the time fixed effects are actually separated by treatment adoption event. This applies to all DID estimates throughout the paper.

effects when focusing on the dry season. To address this, we estimate:

$$\text{Stream}_{gmt} = \delta \text{Board}_{gt} + \sum_{k=m}^{m-L} \alpha_2^k \text{Rain}_{gskt} + \alpha_3 \text{PET}_{gmt} + \alpha_4 \text{Water Rights}_{gmt} + \mu_t + \eta_{gm} + \varepsilon_{gmt} \tag{13}$$

where Stream_{gmt} is the streamflow in segment g in month m and year t and Board_{gt} is equal to 1 if segment g is under the jurisdiction of a Water Board in year t. Upstream_{g-1mt} is the streamflow at the head of the segment, Rain_{gsmt}, PET_{gmt} and WR_{gmt} denote monthly rainfall and potential evapotranspiration, and Water Rights issued in the segment. μ_t and η_{gm} are year and segment-month fixed effects, accounting for seasonality at the segment level. We include L lags of precipitation (including the current period precipitation) to account for streamflow fed by snow-melting instead of rainfall runoff.

We also estimate dynamic effects according to the following equation:

$$\begin{aligned}\text{Stream}_{gmt} = &\sum_{i=-4}^{4} \delta_i \text{Board}_{gst} \times 1\left[t - t^* = i\right] \\ &+ \alpha_1 \text{Upstream}_{g-1mt} + \sum_{k=m}^{m-L} \alpha_2^k \text{Rain}_{gskt} + \alpha_3 \text{PET}_{gmt} + \alpha_4 \text{Water Rights}_{gmt} + \mu_t + \eta_{gm} + \varepsilon_{gmt}\end{aligned} \tag{14}$$

This specification will allow us to identify pre-trends.

Equations 13 and 14 are derived from a water balance equation, where the inflows equalize outflows in a basin. The equation does not exactly hold, given the use of proxy variables and measurement error. The most important concern regards the potential endogeneity of water rights: this is literally among our outcome variables, given the mechanisms discussed above –i.e. Water Boards can provide better monitoring, and so to stop the creation of new water rights that may interfere with preexisting ones. Our results are not sensitive on their inclusion. In our main results, we use OLS but in the appendix we include Poisson estimates.

6.2 Results

Water Boards impact on water rights creation. We present our results on the estimation of equation 11 using Poisson Regression in table XV. Column 1 shows the results for the total streamflow allocated through new water rights within 4 years after the establishment of a water board, while column 2 shows the result for total surface water rights per km^2 of the surface of the basin: the coefficient implies a reduction of 36% in the reclamation of the river.

We test for the displacement of the demand towards less regulated sources of water in columns 3 and 4, where we present the results for total groundwater rights (column 3) and for groundwater rights per km^2 (column 4). Aquifers were outside the Water Boards' jurisdiction until 2005. There is an increase in groundwater rights of a similar magnitude to the reduction in surface water rights found in column 2. The coefficients are similar, but they imply an increase of around 55%.

Figure XIV presents estimates of dynamic effects (i.e. equation 12) over total water rights created in the segment, for surface sources and for groundwater sources. There is no evidence of pre-trends for surface rights, and for groundwater rights, anticipation seems limited to the last year before the establishment of the board. Also, the figure shows the reduction in surface water rights and an increase of similar magnitude for groundwater rights but with more noisy estimates.

In Appendix A we include as robustness checks dynamic effect estimates using OLS, by total water rights (figure A.III) and water rights created by km^2 of surface in the basin (figure A.IV); the results are similar. Tables A.VI and A.VII present the full set of estimates of dynamic effects over surface and groundwater water rights, both totals and per unit of surface, using OLS and Poisson regression. Overall, we conclude that water boards reduce the creation of water rights on surface water -where they have jurisdiction-, while there is some non-robust evidence of displacement.

Water Boards impact on streamflows. Columns 1 to 4 of Table XVI presents the results of estimating equation 13 for 4 years after the establishment of the board, for the full year. Water Board establishment events increase the average streamflow more than 10%, even after controlling for potentially bad controls, such as the streamflow from upstream stations (columns 3 and 4) and the amount of water rights created (column 4).

The former results ignore the fact that most irrigation takes place in the dry season. In columns 5 to 8 of table XVI, therefore, we estimate the same models but only for the months of January and February, when water is more scarce and there is more irrigation, and so, incentives to over-extract are stronger. The estimated effect is stable across specifications: water boards increase the streamflow between 0.96 and 1.29 m^3/s, which represents an increase between 15% to and 22% of the average seasonal streamflow.

To understand better the results in table XVI, we estimate equation 13 but interacting the Board establishment dummy with dummies per month. These coefficients will reflect the impact of Water Boards on streamflow for each month. We present the results of this exercise in figure XV.

For both samples, we find increases in the streamflow for the dry season, while in the months with the highest streamflow due to snow-melting (October and November) we observe zero effects or even nonsignificant reductions in streamflow. The increase in the Summer streamflows is almost 45% for January and 30% for February for the Event Study sample, while the increments in the middle of the year (July - August) are just around 13%, and during the Spring (October - November) the effects are nonsignificant and between 0 and -10%. Figure A.V in Appendix A presents the results using Poisson regression.

Dynamic effects. In this subsection, we present estimates of dynamic effects using equation 14. The intra-segment-inter-year variance in streamflows is high for Central Chile, due to short-term cycles with droughts of varying intensity every 2 to 7 years -mostly associated with the ENSO (El Niño-Southern Oscillation cycle)(Fernández and Gironás, 2021). Given this challenge, we estimate dynamic effects binning relative years to gain power. The results are presented in figures XVIa for the full year and XVIb for the dry season. We fixed as the baseline period the bin containing the two years prior to the board establishment event.

In both figures, there is no evidence of pre-trends in years prior to the establishment of the board, and the specifications that control only for the set of fixed effects and contemporaneous climatic variables display persistent effects across all years post-board establishment. While for the full year (figure XVIa) there is weak evidence of increases in the first 2 bins (years 0 to 3), for the dry season (figure XVIb) the evidence is clear, with all specifications giving statistically and economically significant increases in streamflows. In the third bin (years 4 and 5 after board establishment), instead, the results are mixed, so effects continue to be significant in the model that do not control for lags of precipitation or water rights. Tables A.VIII in Appendix A present the full set of estimates of dynamic effects over streamflows during the full year and in the dry season. Overall, we conclude that the boards have at least a short-term positive effect on streamflows.

Extensions. In Appendix B we present three additional analyses. In subsection B.2.2 we perform a mediation analysis, where we estimate that only 14% of the streamflow reduction can be explained by the reduction in Water Rights reclamations, while the remaining 86% is the direct consequence of Water Board establishments. Our interpretation is that the main driver of the streamflow increase is the physical enforcement of property rights. We also show that the streamflow increases are stronger in basins with more land inequality (section B.2.1) and also that the spatial distribution of heterogeneous effects according to basin location reaffirm that the increases in streamflow are linked to the increases in water consumption among downstream farms (section B.2.

7 Conclusions

In this paper, we study how specialized enforcement institutions affect water markets' allocative efficiency, even in contexts with well-defined property rights – perpetual, tradable, inheritable, and constitutionally protected against expropriation. Using a sufficient statistic approach, we find that within basins governed by Water Boards, the shadow value of water remains constant across locations. Instead, we find evidence of misallocation in areas without such boards, where downstream users face higher shadow values due to upstream over-extraction. Using various identification strategies and measures, we further explore how such efficiency improvement results from the interaction of redistribution and individual adaptations. Despite extensive water redistribution, Water Boards' enforcement creates net economic gains, partly through individual adaptation to a more reliable supply.

Our analysis of Water Boards provides insights on the challenges of establishing environmental markets. The operation of these markets must overcome substractability and high monitoring and enforcement costs, characteristics that lead to the Tragedy of the Commons. While water is a leading example among the resources subject to it, these characteristics are present in many others, including fisheries and atmospheric emissions. The directional nature of surface water flows creates a unique analytical advantage: it allows clear identification of affected agents and precise measurement of redistribution in place. However, this same directionality shapes the distinct incentives faced by downstream and upstream users in establishing Water Boards, potentially limiting the direct applicability of our findings to other contexts.

Two key features of successful Water Boards may be replicable. First, a single entity maintains both legal accountability and authority over resource distribution, which is essential to establishing effective governance. Second, the combination of substractability and directional externalities creates strong incentives for downstream users to organize basin-wide enforcement and hold the agents in charge accountable, potentially driving the private provision of the public good of governance and enforcement.

Our results indicate that individual adaptation and markets cannot fully offset the lack of effective governance in ensuring efficient resource use, even in contexts with strong property rights and rule of law. This reflects a fundamental tension in environmental markets: empowering users over governing authorities may reduce some market frictions but weaken enforcement, as administrative actions under changing conditions remain necessary. We show that institutional arrangements that empower local communities can resolve this tension; however, the resulting efficiency gains are unevenly distributed. These findings have important implications for the design of environmental markets, suggesting that successful implementation requires careful attention to enforcement mechanisms and their distributional consequences.

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Tables

Table I: Misallocation Test: Balance table

Outcome: Useful Rainfall (Rainfall during the crop irrigation season)

	Full Sample		Irrigated fields sample		Placebo sample	
	(1)	(2)	(3)	(4)	(5)	(6)
Distance to coast (100km)	0.0412	0.0469	-0.521	-0.958	0.102	0.111
	(0.0539)	(0.0610)	(0.103)***	(0.219)***	(0.0399)**	(0.0540)**
Water Board=1	-0.0814	0.0596	-0.415	-0.618	-0.413	-0.114
	(0.301)	(0.338)	(0.280)	(0.399)	(0.440)	(0.329)
Water Board=1 × Distance to coast (100km)	0.101	0.111	0.138	0.381	0.624	0.299
	(0.211)	(0.237)	(0.196)	(0.263)	(0.294)**	(0.248)
Basin FE	Yes	No	Yes	No	Yes	No
0.5 degree cell FE	No	Yes	No	Yes	No	Yes
Crop FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	79,133	79,132	15,149	15,147	63,838	63,838
R-squared	0.885	0.931	0.910	0.944	0.924	0.946
Outcome mean	0.899	0.899	0.765	0.765	0.931	0.931
Outcome SD	0.944	0.944	0.836	0.836	0.966	0.966

Notes: This balance table presents regressions of the double interaction between a Water Boards dummy and the location in the basin, measured as the distance to the sea through the river network. The outcome variable is useful rainfall: precipitation fell during the irrigation season of the crop planted in the parcel.

Table II: Shadow Value of Water: Impact of useful rainfall on Production irrigated farms, by treatment status

	Outcome is log(Value Yield p/Hectare)			
	(1)	(2)	(3)	(4)
	m1	m2	m3	m4
Useful pp. (m3 per Ha per month)	0.464	0.330	0.462	0.421
	(0.196)**	(0.197)*	(0.221)**	(0.232)*
	[0.201]**	[0.200]	[0.221]**	[0.232]*
Useful pp. (m3 per Ha per month) × Distance to coast (100km)	-0.225	-0.188	-0.250	-0.272
	(0.129)*	(0.125)	(0.139)*	(0.148)*
	[0.131]*	[0.125]	[0.136]*	[0.144]*
Water Board=1 × Useful pp. (m3 per Ha per month)	-0.134	-0.237	-0.396	-0.481
	(0.240)	(0.217)	(0.251)	(0.258)*
	[0.242]	[0.217]	[0.245]	[0.251]*
Water Board=1 × Useful pp. (m3 per Ha per month) × Distance to coast (100km)	-0.00902	0.130	0.235	0.298
	(0.164)	(0.145)	(0.166)	(0.170)*
	[0.166]	[0.144]	[0.161]	[0.163]*
Parcel Controls	Yes	Yes	Yes	Yes
County Controls	Yes	Yes	Yes	No
Basin FE	No	Yes	No	No
0.5 degree cell FE	No	No	Yes	No
Crop FE	Yes	Yes	Yes	Yes
County FE	No	No	No	Yes
Observations	14,716	14,716	14,714	14,712
R-squared	0.598	0.621	0.628	0.642
Misallocation Test: Water Board=0	0.08	0.13	0.07	0.07
Misallocation Test: Water Board=1	0.01	0.42	0.87	0.76

Notes: This table presents estimates of equation 5 for irrigated parcels, with water rights, registered in canal associations. Distance to the coast measured through the river network. Controlling for logarithm of cultivated surface, logarithm of number of hired workers plus 1, dummies for educational level of manager of the farm, legal organization category of the operation, irrigation technology, and County and Crop fixed effects. Standard errors clustered at the county level (round parenthesis) and the county× irrigation season level (squared parentheses).

Table III: Placebo exercise: Impact of rainfall on rainfed farms production.

	Placebo: Outcome is log(Value Yield p/Hectare)			
	(1)	(2)	(3)	(4)
	m5	m6	m7	m8
Useful pp. (m3 per Ha per month)	-0.0606	0.00566	0.0146	0.0830
	(0.0502)	(0.0677)	(0.0493)	(0.0408)**
	[0.0473]	[0.0602]	[0.0466]	[0.0411]**
Distance to coast (100km)	-0.202	-0.168	0.194	
	(0.104)*	(0.114)	(0.0721)***	
	[0.0950]**	[0.105]	[0.0625]***	
Useful pp. (m3 per Ha per month) × Distance to coast (100km)	0.150	0.154	0.0407	0.0141
	(0.0439)***	(0.0447)***	(0.0282)	(0.0287)
	[0.0409]***	[0.0417]***	[0.0291]	[0.0263]
Water Board=0	-	-	-	-
	-	-	-	-
	-	-	-	-
Water Board=1	-0.567	-0.811	0.159	
	(0.299)*	(0.398)**	(0.387)	
	[0.324]*	[0.388]**	[0.368]	
Water Board=1 × Useful pp. (m3 per Ha per month)	0.104	0.143	0.000591	0.0457
	(0.130)	(0.0966)	(0.0593)	(0.0680)
	[0.140]	[0.112]	[0.107]	[0.0707]
Water Board=1 × Distance to coast (100km)	0.687	0.893	0.00530	
	(0.208)***	(0.247)***	(0.277)	
	[0.228]***	[0.248]***	[0.274]	
Water Board=1 × Useful pp. (m3 per Ha per month) × Distance to coast (100km)	-0.146	-0.173	-0.0180	-0.0446
	(0.0980)	(0.0739)**	(0.0499)	(0.0542)
	[0.102]	[0.0822]**	[0.0848]	[0.0540]
Parcel Controls	Yes	Yes	Yes	Yes
County Controls	Yes	Yes	Yes	No
Basin FE	No	Yes	No	No
0.5 degree cell FE	No	No	Yes	No
Crop FE	Yes	Yes	Yes	Yes
County FE	No	No	No	Yes
Observations	63,838	63,838	63,838	63,836
R-squared	0.582	0.588	0.618	0.631
Misallocation Test: Water Board=0	0.00	0.00	0.15	0.63
Misallocation Test: Water Board=1	0.97	0.76	0.56	0.46

Notes: This table presents estimates of equation 5 for non-irrigated parcels, as a placebo exercise. Distance to the coast measured through the river network. Controlling for logarithm of cultivated surface, logarithm of number of hired workers plus 1, dummies for educational level of manager of the farm, legal organization category of the operation, irrigation technology, and County and Crop fixed effects. Standard errors clustered at the county level (round parenthesis) and the county× irrigation season level (squared parentheses).

Table IV: Summary Statistics: parcel level dataset

	No Board					
	Mean	SD	p10	p90	Min	Max
Water Consumption per area	3.77	1.2	2.1	5.2	0.1	7.4
Total (Estimated) Water Consumption	289.18	673.3	11.7	765.6	0.2	23368.2
EVI (max over Summer)	0.45	0.1	0.3	0.6	0.1	0.9
Area (m2)	64399.23	142356.7	4176.2	162067.0	47.6	5350225.5
Latitude	-35.07	1.4	-36.8	-33.2	-37.8	-29.8
Longitude	-71.44	0.5	-72.1	-70.7	-73.0	-70.5
Precipitation (year, plot)	1763.99	782.0	843.0	2828.8	0.0	4267.5
Precipitation (Summer)	50.52	19.6	26.1	80.6	3.9	99.7
Mkt. Acc. (Santiago)	258.16	166.3	48.9	498.8	9.4	616.5
Mkt. Acc. (Valparaiso)	335.06	183.7	107.7	592.2	15.8	709.9
Mkt. Acc. (San Antonio)	273.88	156.9	100.5	506.4	20.4	624.1
Distance to Coast (location in basin)	120.38	40.7	62.9	171.2	1.5	219.8
Dist Upstream Capital	67.75	16.7	50.0	88.2	50.0	179.6
Observations	54877					

	Water Board					
	Mean	SD	p10	p90	Min	Max
Water Consumption per area	3.78	1.2	2.1	5.3	0.1	7.2
Total (Estimated) Water Consumption	298.70	648.0	12.6	745.6	0.2	22422.0
EVI (max over Summer)	0.46	0.1	0.3	0.6	0.0	0.9
Area (m2)	67970.24	140647.0	4132.4	159690.5	188.9	3593806.8
Latitude	-34.22	1.5	-36.6	-32.7	-37.0	-29.9
Longitude	-71.13	0.4	-71.8	-70.7	-72.3	-70.5
Precipitation (year, plot)	1311.22	534.4	782.9	2081.1	0.0	3380.8
Precipitation (Summer)	42.01	12.9	28.8	59.5	2.6	83.9
Mkt. Acc. (Santiago)	202.18	144.9	78.3	475.5	20.7	589.8
Mkt. Acc. (Valparaiso)	267.78	144.3	119.4	546.1	35.5	609.3
Mkt. Acc. (San Antonio)	224.17	134.9	100.5	481.6	43.2	595.3
Distance to Coast (location in basin)	126.08	39.7	63.4	174.6	0.9	212.6
Dist Upstream Capital	74.92	14.6	50.0	88.2	50.0	107.0
Observations	23580					

Table V: Cross-sectional differences in Water Consumption and Agricultural Production.

	Evapotranspiration			Yield (peak EVI)		
	(1)	(2)	(3)	(4)	(5)	(6)
Board x Downstream	0.138	0.131	0.236	0.0179	0.0199	0.0182
	(0.111)	(0.105)	(0.119)**	(0.0113)	(0.0110)*	(0.00887)**
Board x Midsection	0.0151	-0.0488	0.0940	-0.000572	-0.0000164	0.00689
	(0.0697)	(0.0658)	(0.0778)	(0.00907)	(0.00716)	(0.00815)
Board x Upstream	-0.150	-0.396	-0.359	0.00219	-0.00372	-0.00811
	(0.121)	(0.136)***	(0.0687)***	(0.00783)	(0.00767)	(0.00635)
Downstream	-	-	-	-	-	-
	-	-	-	-	-	-
Midsection	0.272	0.318	0.0897	0.00956	0.0125	-0.00369
	(0.0862)***	(0.0957)***	(0.0916)	(0.00776)	(0.00864)	(0.00760)
Upstream	0.0209	0.277	-0.0258	-0.00513	0.000119	-0.0178
	(0.127)	(0.120)**	(0.0880)	(0.0125)	(0.0118)	(0.0101)*
Plot level controls	Yes	Yes	Yes	Yes	Yes	Yes
Basin FE	Yes	No	No	Yes	No	No
(lat, lon) grid FE	No	Yes	No	No	Yes	No
Sub-basin FE	No	No	Yes	No	No	Yes
Observations	78,457	78,457	78,456	78,469	78,469	78,468
R-squared	0.456	0.462	0.528	0.279	0.288	0.323
Mean Dependent Var.	3.771	3.771	3.771	0.510	0.510	0.510

Notes: This table presents estimates of equation 9 and 10 for parcels located within a 1km buffer around canals in the area of study. The outcome variable is the average Evapotranspiration for each plot in the Summer months (January and February) of years 2000 to 2005. Columns 1 and 4 present estimates for farms located downstream (in the lowest tercile of distance to the coast); columns 2 and 5 for mid-section farms (second tercile of distance to the coast); and columns 3 and 6 for plots located upstream (in the highest tercile of distance to the coast). Distance to the coast was measured through the river network. Plot level controls include a quadratic polynomial of plot area, county precipitation during the year, county number of days above 29 Celsius degrees ("killing days"), and plot precipitation during the summer; dummies for 5 categories of soil quality, market access measures (distance to Santiago, Valparaiso and San Antonio), a measure of exposure to externalities (the number of plots upstream to the farm), and 1x1-degree cell fixed effects. Standard errors clustered by county.

Table VI: Total Water Consumption: Instrumental Variables estimation at the parcel level.

	OLS, ETa (mm) per surface			IV, ETa (mm) per surface		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	0.151	-0.00647	-0.349	2.144	1.847	-0.605
	(0.110)	(0.0610)	(0.0785)***	(0.873)**	(1.516)	(0.149)***
Plot level controls	Yes	Yes	Yes	Yes	Yes	Yes
1x1 degree cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	26,780	26,138	25,539	26,780	26,138	25,539
R-squared	0.457	0.473	0.581	0.207	0.130	0.574
Mean Dependent Var.	3.545	4.085	3.665	3.545	4.085	3.665
Effective F-stat				16.856	2.473	59.704
AR test CI				[.5718, 4.547]	$(-\infty, \infty)$	[-.8887, -.2858]

Notes: This table presents estimates of equation 9 and 10 for parcels located within a 1km buffer around canals in the area of study. The outcome variable is the average Evapotranspiration for each plot in the Summer months (January and February) of years 2000 to 2005. Columns 1 and 4 present estimates for farms located downstream (in the lowest tercile of distance to the coast); columns 2 and 5 for mid-section farms (second tercile of distance to the coast); and columns 3 and 6 for plots located upstream (in the highest tercile of distance to the coast). Distance to the coast was measured through the river network. Plot level controls include a quadratic polynomial of plot area, county precipitation during the year, county number of days above 29 Celsius degrees ("killing days"), and plot precipitation during the summer; dummies for 5 categories of soil quality, market access measures (distance to Santiago, Valparaiso and San Antonio), a measure of exposure to externalities (the number of plots upstream to the farm), and 1x1-degree cell fixed effects. Standard errors clustered by county.

Table VII: Agricultural Production: Instrumental Variables estimation at the parcel level.

	OLS, EVI (yield measure)			IV, EVI (yield measure)		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	0.0180	0.000357	0.000809	0.180	0.191	-0.0223
	(0.00935)*	(0.00634)	(0.00630)	(0.0799)**	(0.145)	(0.0190)
Plot level controls	Yes	Yes	Yes	Yes	Yes	Yes
1x1 degree cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	26,792	26,138	25,539	26,792	26,138	25,539
R-squared	0.238	0.277	0.399	0.019	-0.065	0.394
Mean Dependent Var.	0.501	0.524	0.506	0.501	0.524	0.506
Effective F-stat				16.840	2.473	59.704
AR test CI				[.03535, .399]	$(-\infty, \infty)$	[-.06594, .01147]

Notes: This table presents estimates of equation 9 and 10 for parcels located within a 1km buffer around canals in the area of study. The outcome variable is the average across the years 2000 to 2005 of the maximum value of the Enhanced Vegetation Index (EVI) reached within the year; this is a proxy for agricultural yield. Distance to the coast wasmeasured through the river network. Plot level controls include a quadratic polynomial of plot area, county precipitation during the year, county number of days above 29 Celsius degrees ("killing days"), and plot precipitation during the summer; dummies for 5 categories of soil quality, market access measures (distance to Santiago, Valparaiso and San Antonio), a measure of exposure to externalities (the number of plots upstream to the farm), and 1x1-degree cell fixed effects. Standard errors clustered by county.

Table VIII: Inequality and Average Water Consumption: Instrumental Variables estimation at the parcel level.

	Smaller Farms, ETa (mm) per surface			Larger Farms, ETa (mm) per surface		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	1.862	3.487	-0.770	3.492	1.081	-0.279
	(0.969)*	(3.555)	(0.191)***	(1.499)**	(0.862)	(0.149)*
Plot level controls	Yes	Yes	Yes	Yes	Yes	Yes
1x1 degree cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	14,561	12,021	11,386	6,270	7,427	7,447
R-squared	0.254	-0.757	0.561	-0.307	0.396	0.626
Mean Dependent Var.	3.279	3.963	3.585	4.031	4.295	3.833
Effective F-stat	11.286	1.286	55.629	8.796	3.767	61.049
AR test CI	[-.1069, 4.618]	$(-\infty, \infty)$	[-1.123, -.3446]	[1.455, 10.91]	$[-30.76, \infty)$	[-.5604, .04246]

Notes: This table presents estimates of equations 9 and 10 for parcels located within a 1km buffer around canals in the area of study. Distance to the coast measured through the river network. Plot level controls include a quadratic polynomial of plot area, county precipitation during the year, county number of days above 29 Celsius degrees ("killing days"), and plot precipitation during the summer; dummies for 5 categories of soil quality, market access measures (distance to Santiago, Valparaiso and San Antonio), a measure of exposure to externalities (the number of plots upstream to the farm), and 1x1-degree cell fixed effects. Standard errors clustered by county.

Table IX: Inequality and Agricultural Production: Instrumental Variables estimation at the parcel level.

	Smaller Farms, EVI (yield measure)			Larger Farms, EVI (yield measure)		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	0.138	0.301	-0.0420	0.311	0.132	0.00628
	(0.0883)	(0.310)	(0.0169)**	(0.138)**	(0.0907)	(0.0236)
Plot level controls	Yes	Yes	Yes	Yes	Yes	Yes
1x1 degree cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	14,571	12,021	11,386	6,270	7,427	7,447
R-squared	0.137	-0.496	0.446	-0.581	0.090	0.382
Mean Dependent Var.	0.486	0.518	0.503	0.530	0.530	0.506
Effective F-stat	11.286	1.286	55.629	8.796	3.767	61.049
AR test CI	[-.03417, .3998]	$(-\infty, \infty)$	[-.07747, -.008775]	[.1157, .9683]	$[-3.291, \infty)$	[-.04862, .04783]

Notes: This table presents estimates of equations 9 and 10 for parcels located within a 1km buffer around canals in the area of study. Distance to the coast measured through the river network. Plot level controls include a quadratic polynomial of plot area, county precipitation during the year, county number of days above 29 Celsius degrees ("killing days"), and plot precipitation during the summer; dummies for 5 categories of soil quality, market access measures (distance to Santiago, Valparaiso and San Antonio), a measure of exposure to externalities (the number of plots upstream to the farm), and 1x1-degree cell fixed effects. Standard errors clustered by county.

Table X: Crop Choice: Instrumental Variables estimation at the plot level.

Panel A: Peak after December (dummy)

	OLS, Peak after Dec.			IV, Peak after Dec.		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	0.0863	0.0502	-0.118	0.666	0.923	-0.255
	(0.0296)***	(0.0263)*	(0.0318)***	(0.226)***	(0.641)	(0.0688)***
Plot level controls	Yes	Yes	Yes	Yes	Yes	Yes
1x1 degree cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	26,792	26,138	25,539	26,792	26,138	25,539
R-squared	0.279	0.212	0.285	0.128	-0.190	0.274
Mean Dependent Var.	0.503	0.679	0.587	0.503	0.679	0.587
Effective F-stat				16.840	2.473	59.704
AR test CI				[.2395, 1.26]	$(-\infty, \infty)$	[-.4062, -.1265]

Panel B: Season Length (months)

	OLS, Season length			IV, Season length		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	0.139	0.102	-0.0586	1.171	2.344	-0.214
	(0.0778)*	(0.0665)	(0.0740)	(0.759)	(1.738)	(0.176)
Plot level controls	Yes	Yes	Yes	Yes	Yes	Yes
1x1 degree cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	26,792	26,138	25,539	26,792	26,138	25,539
R-squared	0.228	0.190	0.234	0.180	-0.124	0.233
Mean Dependent Var.	7.323	7.850	7.536	7.323	7.850	7.536
Effective F-stat				16.840	2.473	59.704
AR test CI				[-.3886, 3.002]	$(-\infty, \infty)$	[-.6031, .113]

Notes: This table presents estimates of equation 9 and 10 for parcels located within a 1km buffer around canals in the area of study. The outcome variable in Panel A is the average between years 2000 to 2005 of a dummy variable equal to 1 if a plot reached its maximum value of EVI in the season in Summer (December or after), and 0 otherwise. The outcome variable in Panel B is the average between years 2000 to 2005 of the number of months between May (first month of the agricultural year) and peak of EVI within the corresponding year. Distance to the coast was measured through the river network. Plot level controls include a quadratic polynomial of plot area, county precipitation during the year, county number of days above 29 Celsius degrees ("killing days"), and plot precipitation during the summer; dummies for 5 categories of soil quality, market access measures (distance to Santiago, Valparaiso and San Antonio), a measure of exposure to externalities (the number of plots upstream to the farm), and 1x1-degree cell fixed effects. Standard errors clustered by county.

Table XI: Inequality and Crop Choice: Instrumental Variables estimation at the parcel level.

Panel A: Peak after December (dummy)

	Smaller Farms, Peak after Dec.			Larger Farms, Peak after Dec.		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	0.748	1.338	-0.294	0.889	0.505	-0.115
	(0.273)***	(1.373)	(0.0685)***	(0.329)***	(0.261)*	(0.0704)
Plot level controls	Yes	Yes	Yes	Yes	Yes	Yes
1x1 degree cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	14,571	12,021	11,386	6,270	7,427	7,447
R-squared	0.092	-0.566	0.262	-0.007	0.064	0.320
Mean Dependent Var.	0.441	0.641	0.555	0.613	0.735	0.625
Effective F-stat	11.286	1.286	55.629	8.796	3.767	61.049
AR test CI	[.2556, 1.626]	$(-\infty, \infty)$	[-.4383, -.16]	[.4041, 2.393]	$[-8.959, \infty)$	[-.2661, .01938]

Panel B: Season Length (months)

	Smaller Farms, Season length			Larger Farms, Season length		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	0.905	3.473	-0.308	2.416	1.302	-0.0600
	(0.860)	(3.566)	(0.144)**	(1.157)**	(0.929)	(0.216)
Plot level controls	Yes	Yes	Yes	Yes	Yes	Yes
1x1 degree cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	14,571	12,021	11,386	6,270	7,427	7,447
R-squared	0.218	-0.501	0.228	-0.006	0.069	0.263
Mean Dependent Var.	7.134	7.762	7.449	7.658	7.986	7.658
Effective F-stat	11.286	1.286	55.629	8.796	3.767	61.049
AR test CI	[-1.236, 2.901]	$(-\infty, \infty)$	[-.5923, -.008238]	[.6186, 7.43]	$[-35.78, \infty)$	[-.5463, .3331]

Notes: This table presents estimates of equation 9 and 10 for parcels located within a 1km buffer around canals in the area of study. The outcome variable in Panel A is the average between years 2000 to 2005 of a dummy variable equal to 1 if a plot reached its maximum value of EVI in the season in Summer (December or after), and 0 otherwise. The outcome variable in Panel B is the average between years 2000 to 2005 of the number of months between May (first month of the agricultural year) and peak of EVI within the corresponding year. Distance to the coast was measured through the river network. Plot level controls include a quadratic polynomial of plot area, county precipitation during the year, county number of days above 29 Celsius degrees ("killing days"), and plot precipitation during the summer; dummies for 5 categories of soil quality, market access measures (distance to Santiago, Valparaiso and San Antonio), a measure of exposure to externalities (the number of plots upstream to the farm), and 1x1-degree cell fixed effects. Standard errors clustered by county.

Table XII: Inequality and Season Length: Instrumental Variables estimation at the parcel level.

Panel A: Peak after December (dummy)

	Smaller Farms, Peak after Dec.			Larger Farms, Peak after Dec.		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	0.748	1.338	-0.294	0.889	0.505	-0.115
	(0.273)***	(1.373)	(0.0685)***	(0.329)***	(0.261)*	(0.0704)
Plot level controls	Yes	Yes	Yes	Yes	Yes	Yes
1x1 degree cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	14,571	12,021	11,386	6,270	7,427	7,447
R-squared	0.092	-0.566	0.262	-0.007	0.064	0.320
Mean Dependent Var.	0.441	0.641	0.555	0.613	0.735	0.625
Effective F-stat	11.286	1.286	55.629	8.796	3.767	61.049
AR test CI	[.2556, 1.626]	$(-\infty, \infty)$	[-.4383, -.16]	[.4041, 2.393]	$[-8.959, \infty)$	[-.2661, .01938]

Panel B: Season length (months)

	Smaller Farms, Season length			Larger Farms, Season length		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	0.905	3.473	-0.308	2.416	1.302	-0.0600
	(0.860)	(3.566)	(0.144)**	(1.157)**	(0.929)	(0.216)
Plot level controls	Yes	Yes	Yes	Yes	Yes	Yes
1x1 degree cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	14,571	12,021	11,386	6,270	7,427	7,447
R-squared	0.218	-0.501	0.228	-0.006	0.069	0.263
Mean Dependent Var.	7.134	7.762	7.449	7.658	7.986	7.658
Effective F-stat	11.286	1.286	55.629	8.796	3.767	61.049
AR test CI	[-1.236, 2.901]	$(-\infty, \infty)$	[-.5923, -.008238]	[.6186, 7.43]	$[-35.78, \infty)$	[-.5463, .3331]

Notes: This table presents estimates of equations 9 and 10 for parcels located within a 1km buffer around canals in the area of study. Distance to the coast measured through the river network. Plot level controls include a quadratic polynomial of plot area, county precipitation during the year, county number of days above 29 Celsius degrees ("killing days"), and plot precipitation during the summer; dummies for 5 categories of soil quality, market access measures (distance to Santiago, Valparaiso and San Antonio), a measure of exposure to externalities (the number of plots upstream to the farm), and 1x1-degree cell fixed effects. Standard errors clustered by county.

Table XIII: Irrigation Technology: Instrumental Variables estimation at the farm level.

Outcome is Irrigation Technology

Panel A: Full Sample

	Traditional Irrigation (Furrow)				Micro Irrigation			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Water Board	-0.00	-0.03	-0.12	-0.00	-0.02	0.01	0.08	0.05
	(0.03)	(0.02)*	(0.07)*	(0.05)	(0.02)	(0.01)	(0.06)	(0.05)
Observations	21,157	14,081	21,157	14,081	21,157	14,081	21,157	14,081
R-squared	0.277	0.326	0.269	0.326	0.258	0.256	0.252	0.254
Sample	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream
Method	OLS	OLS	2SLS	2SLS	OLS	OLS	2SLS	2SLS
Mean Dependent Var.	0.882	0.920	0.882	0.920	0.079	0.021	0.079	0.021
Effective F-stat			4.884	1.578			4.884	1.578
AR test CI			[-.4795, -.0311]	(-∞, ∞)			[-.0281, .4113]	(-∞, ∞)

Panel B: Large Farms

	Traditional Irrigation (Furrow)				Micro Irrigation			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Water Board	0.02	-0.03	-0.20	0.03	-0.02	0.01	0.21	0.05
	(0.02)	(0.03)	(0.10)*	(0.10)	(0.02)	(0.02)	(0.10)**	(0.08)
Observations	11,331	8,592	11,331	8,592	11,331	8,592	11,331	8,592
R-squared	0.373	0.360	0.351	0.358	0.340	0.285	0.311	0.283
Sample	Down., L	Up., L	Down., L	Up., L	Down., L	Up., L	Down., L	Up., L
Method	OLS	OLS	2SLS	2SLS	OLS	OLS	2SLS	2SLS
Mean Dependent Var.	0.891	0.868	0.891	0.876	0.088	0.032	0.088	0.077
Effective F-stat			3.753	1.729			3.753	1.729
AR test CI			[-.8577, -.09626]	(-∞, ∞)			[.09749, .8081]	(-∞, ∞)

Panel C: Small Farms

	Traditional Irrigation (Furrow)				Micro Irrigation			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Water Board	0.03	-0.03	0.05	-0.12	-0.03	0.02	-0.09	0.10
	(0.04)	(0.02)	(0.10)	(0.15)	(0.03)	(0.02)	(0.10)	(0.14)
Observations	2,480	1,110	2,480	1,110	2,480	1,110	2,480	1,110
R-squared	0.134	0.110	0.134	0.079	0.135	0.125	0.133	0.101
Sample	Down., S	Up., S	Down., S	Up., S	Down., S	Up., S	Down., S	Up., S
Method	OLS	OLS	2SLS	2SLS	OLS	OLS	2SLS	2SLS
Mean Dependent Var.	0.856	0.990	0.856	0.990	0.087	0.005	0.087	0.005
Effective F-stat			6.290	0.685			6.290	0.685
AR test CI			[-.2952, .316]	(-∞, ∞)			[-.3621, .2486]	(-∞, ∞)

Notes: This table presents estimates of equation 9 and 10 for farms reporting the use of irrigation in the Agricultural Census of 2007. The outcome variable in columns 1-4 (5-8) are dummies equal to 1 if a farm reports the use of traditional irrigation techniques (micro-irrigation techniques); the base category is the use of macro-irrigation. Panel A includes all farms, Panel B only those classified as large (being in the 5th quintile of farm size, among all farms), and Panel C those classified as small (being below the median of farm size). Odd (even) columns include farms in the first (third) decile of distance to the coast, measured through the river network to the centroid of each county. All models include farm-level controls (logarithm of labor input, dummies for education of the operation manager, being organized as a firm, and deciles of farm area), county-level controls (number of days above 29 Celsius degrees ("killing days"), average soil quality, market access (distance to Santiago and the main ports), dummies for climate zone), and 1x1-degree cell fixed effects. Standard errors are clustered by county.

Table XIV: Number of river segments and Board establishment year

	(1) Full sample			(2) Event Study sample		
	N segments	%	cum %	N segments	%	cum %
1983	2	1.26	1.26	2	3.23	3.23
1985	8	5.03	6.29	8	12.90	16.13
1992	2	1.26	7.55	2	3.23	19.35
1993	5	3.14	10.69	5	8.06	27.42
1995	16	10.06	20.75	14	22.58	50.00
1998	16	10.06	30.82	12	19.35	69.35
2018	27	16.98	47.80	19	30.65	100.00
No Board	83	52.20	100.00			
Total	159	100.00		62	100.00	
Observations	159			62		

Table XV: Effect of Water Boards on creation of new water rights within their jurisdictions (Poisson)

	Surface WR		Groundwater WR	
	(1) Water Rights (m3/s)	(2) Surface WR/Area	(3) Groundwater Rights (m3/s)	(4) Groundwater WR/Area
Board established	-0.450	-0.461	0.449	0.452
	(0.122)***	(0.0696)***	(0.0329)***	(0.143)***
Climatic controls	Yes	Yes	Yes	Yes
Segment FE	Yes	Yes	Yes	Yes
Year x Event FE	Yes	Yes	Yes	Yes
Observations	1,248	1,248	1,248	1,248
Outcome mean	0.192	0.015	0.067	0.003
Outcome SD	0.709	0.066	0.176	0.008

Notes: This table presents estimates of equation 11 using Poisson regression. Implemented using Stacked DID design by Cengiz et al. (2019) design, considering *segment* $\times$ *event* and *year* $\times$ *event* fixed effects, climatic controls for January and February and also including 8 lags of precipitation and precipitation squared. Standard errors clustered at the river-segment level.

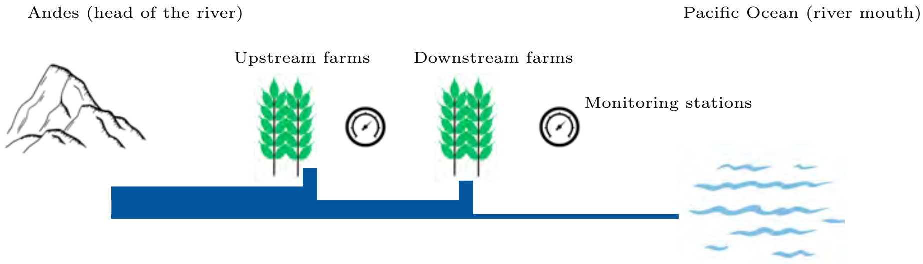
Table XVI: Effect of Water Boards on streamflows

	Full Year				Dry Season			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Board established	3.217	3.091	2.515	2.553	1.290	0.986	0.934	0.924
	(1.479)**	(1.393)**	(1.228)**	(1.202)**	(0.316)***	(0.280)***	(0.285)***	(0.284)***
Upstream river level (m3/s)			0.967	0.969			0.224	0.223
			(0.181)***	(0.178)***			(0.155)	(0.155)
Water Rights (m3/s)				0.0486				-0.0177
				(0.107)				(0.0404)
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Precipitation lags	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Segment FE	Yes	No	No	No	Yes	No	No	No
Segment x Month FE	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	11,016	11,008	11,008	11,008	1,823	1,823	1,823	1,823
R-squared	0.887	0.921	0.932	0.932	0.806	0.839	0.842	0.842
Outcome mean	21.626	21.640	21.640	21.640	5.877	5.877	5.877	5.877
Outcome SD	61.543	61.564	61.564	61.564	8.127	8.127	8.127	8.127

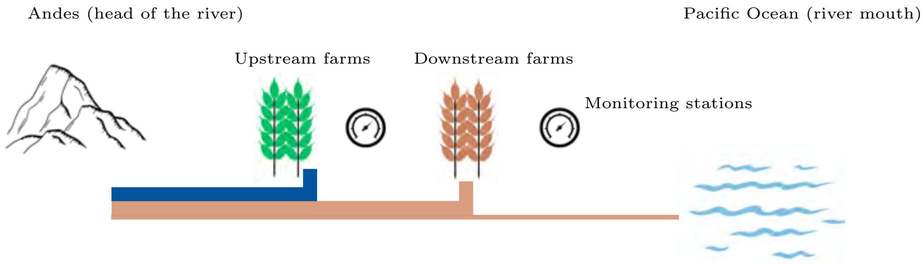
Notes: This table present impact estimates of water boards on streamflows during the Dry Season (January and February). Stacked DID design by Cengiz et al. (2019). Controlling for contemporaneous temperature, precipitation and evapotranspiration, and 8 lags of precipitation and precipitation squared. Standard Errors clustered at the River Segment level.

Figures

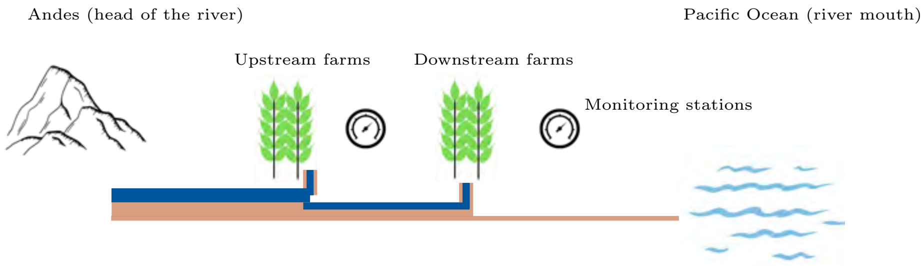
Figure I: Illustration: how property rights enforcement affects water allocation and agricultural outcomes.



(a) No drought

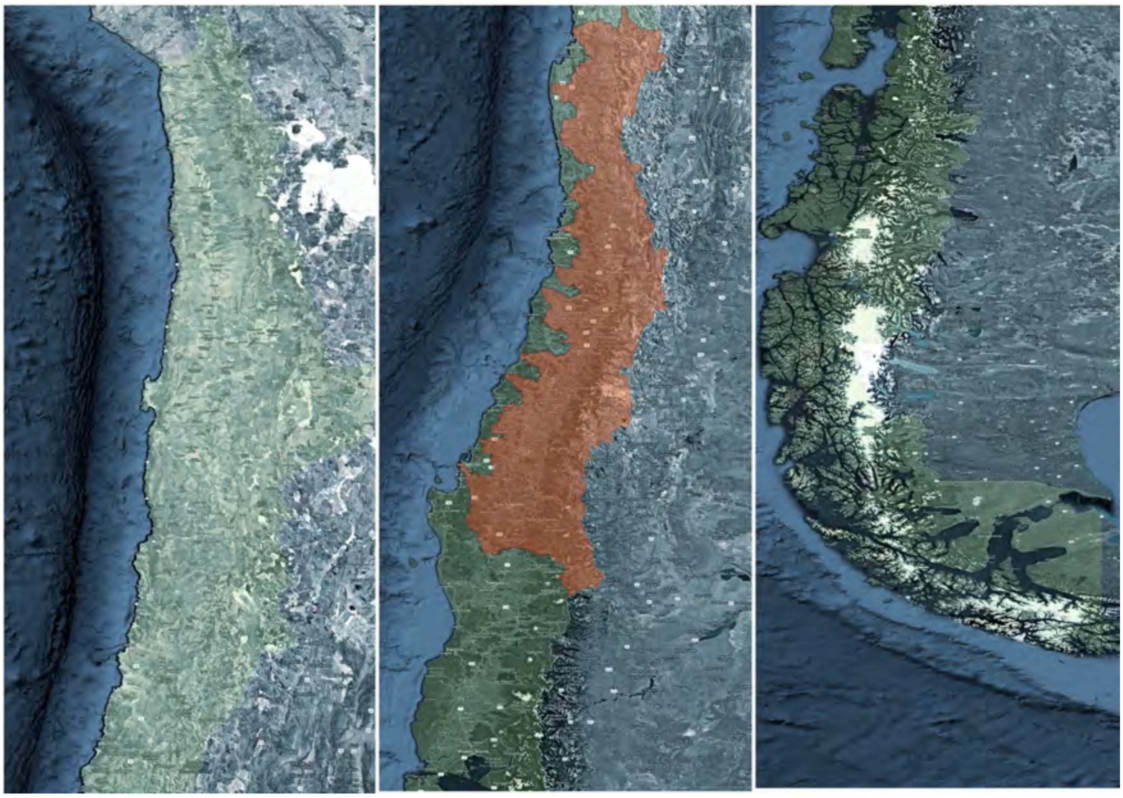


(b) Drought, and no enforcement of water rights



(c) Drought, and Water Boards enforce water rights

Figure II: Area of Study

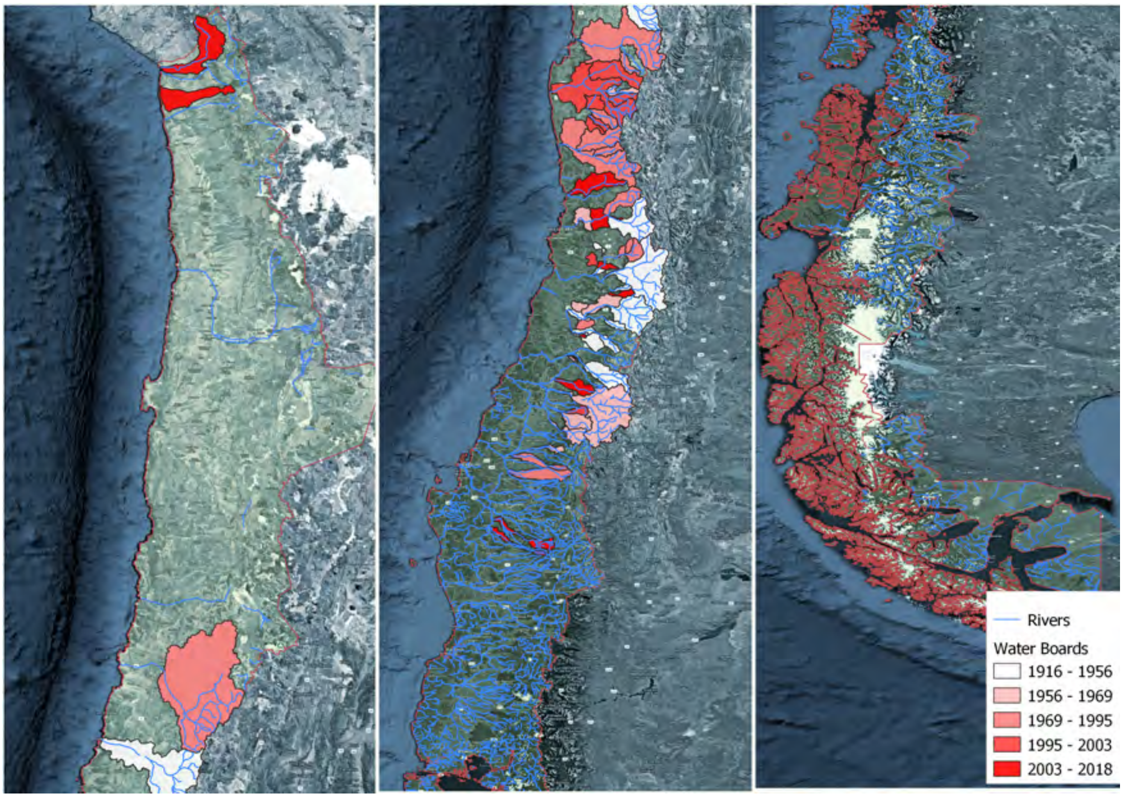


Notes: Left, center, and right panels correspond to the northern, central, and southern areas of Chile. The colored region represents the total area of study.

Figure III: Basins and Rivers in Area of Study

Notes: This map zooms into the colored area of map II. Blue lines represent rivers and orange lines represent their corresponding basin boundaries.

Figure IV: Water Boards Jurisdictions



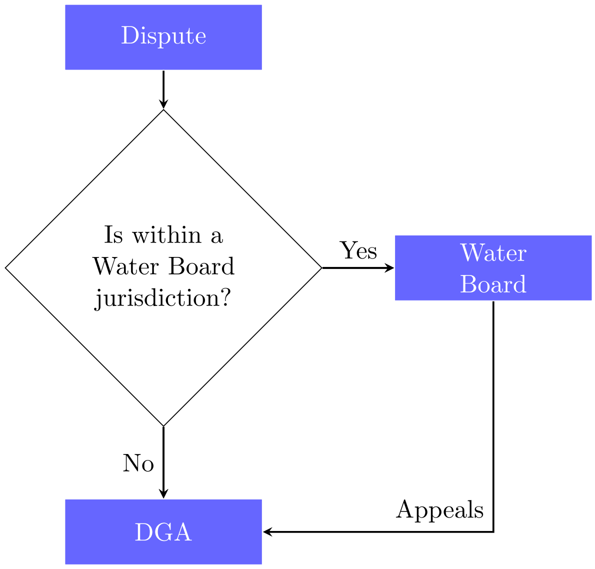
Notes: Left, center, and right panels correspond to the northern, central, and southern areas of Chile. The colored areas represent the boundaries of existing Water Boards jurisdictions and their year of establishment.

Figure V: Example of Canal Gate

Notes: This picture shows a canal gate. Water Boards have the legal right to open and close them with locks during droughts, to implement a system of irrigation shifts as a water allocation enforcement mechanism.

Figure VI: Administrative and legal hierarchy of institutions over water rights issues.

(a) Administrative



(b) Legal

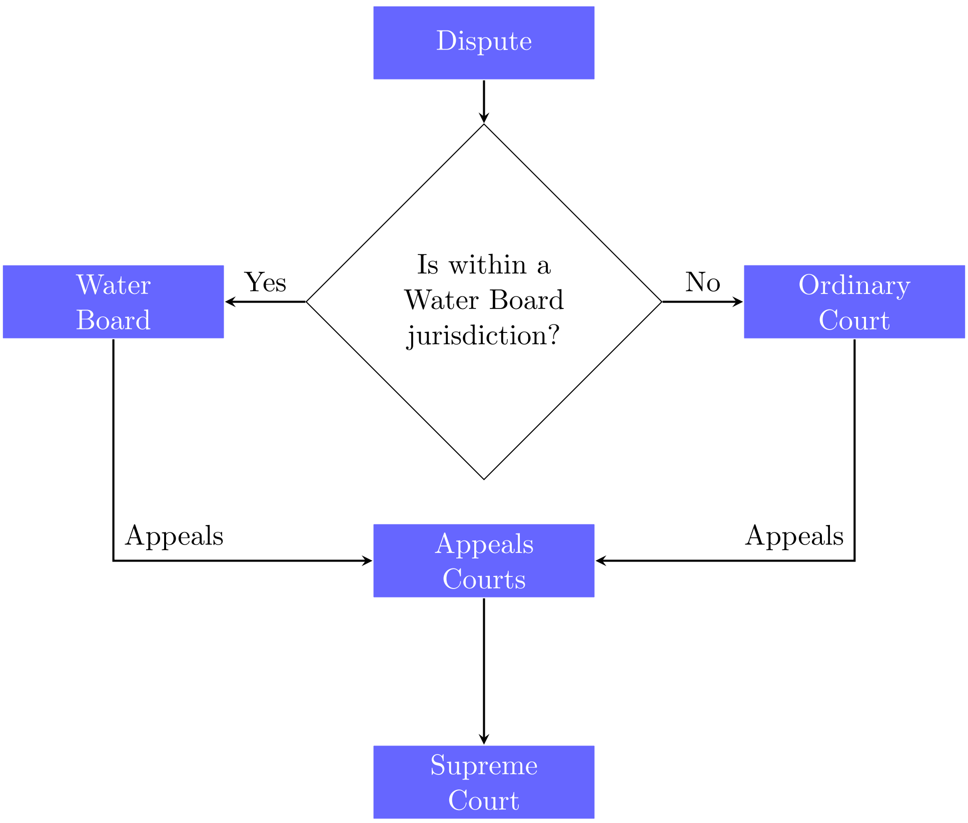
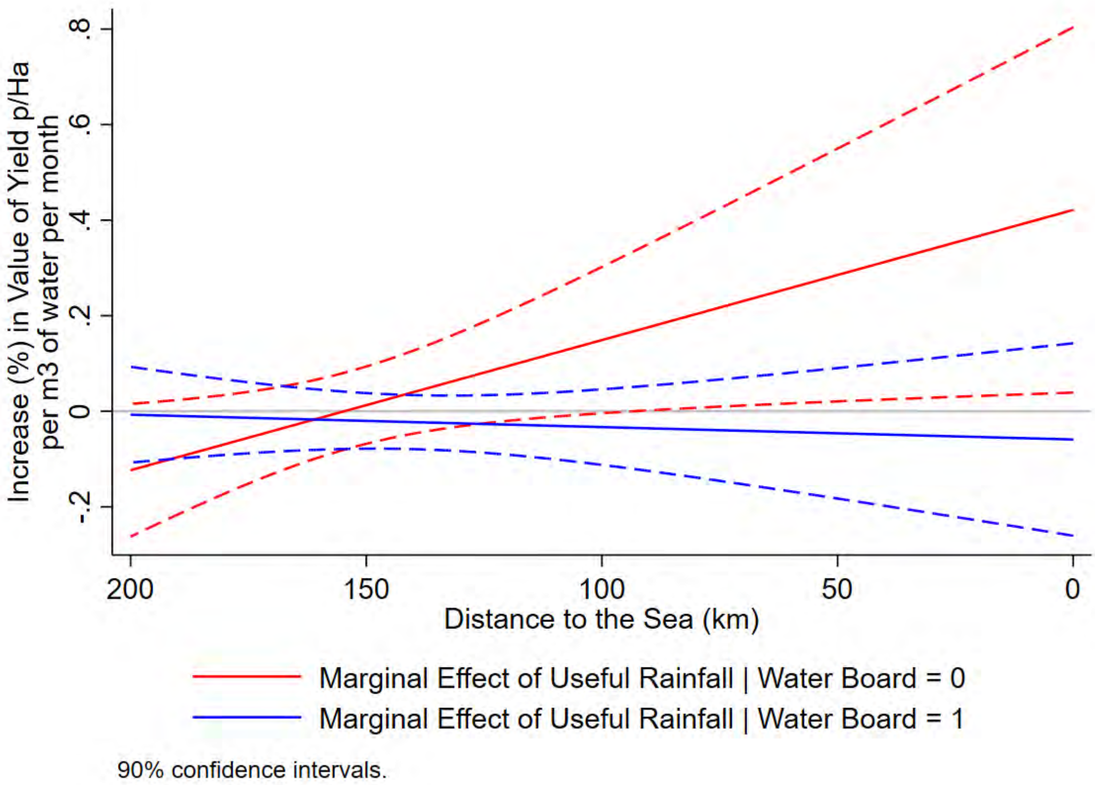
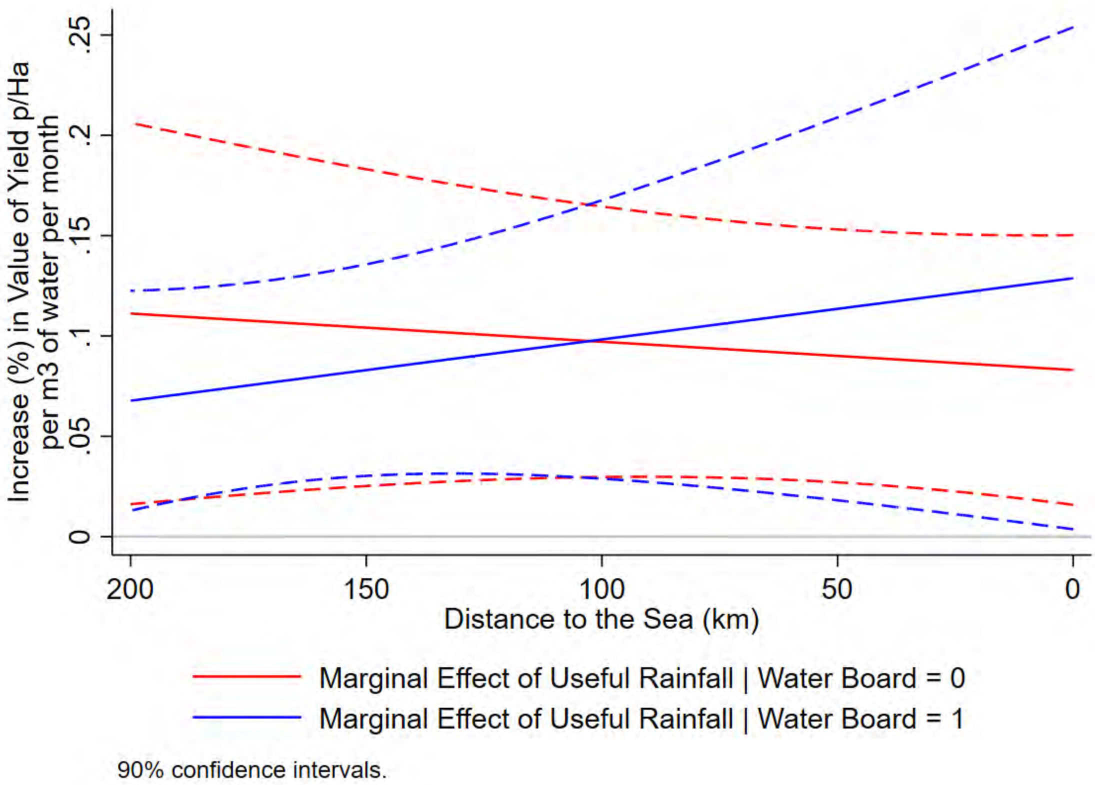


Figure VII: Main results: effect on log(Production) of rainfall during the irrigation season by longitude and treatment status for irrigated parcels registered in canal associations.



Notes: Graphical representation of results in Table II.

Figure VIII: Placebo exercise: effect on log(Production) of rainfall during the irrigation season by longitude and treatment status for rainfed parcels.



Notes: Graphical representation of results in Table III .

Figure IX: Example: water consumption and agricultural yield estimates for farms in Aconcagua Basin

(a) Water consumption

(b) Agricultural yield

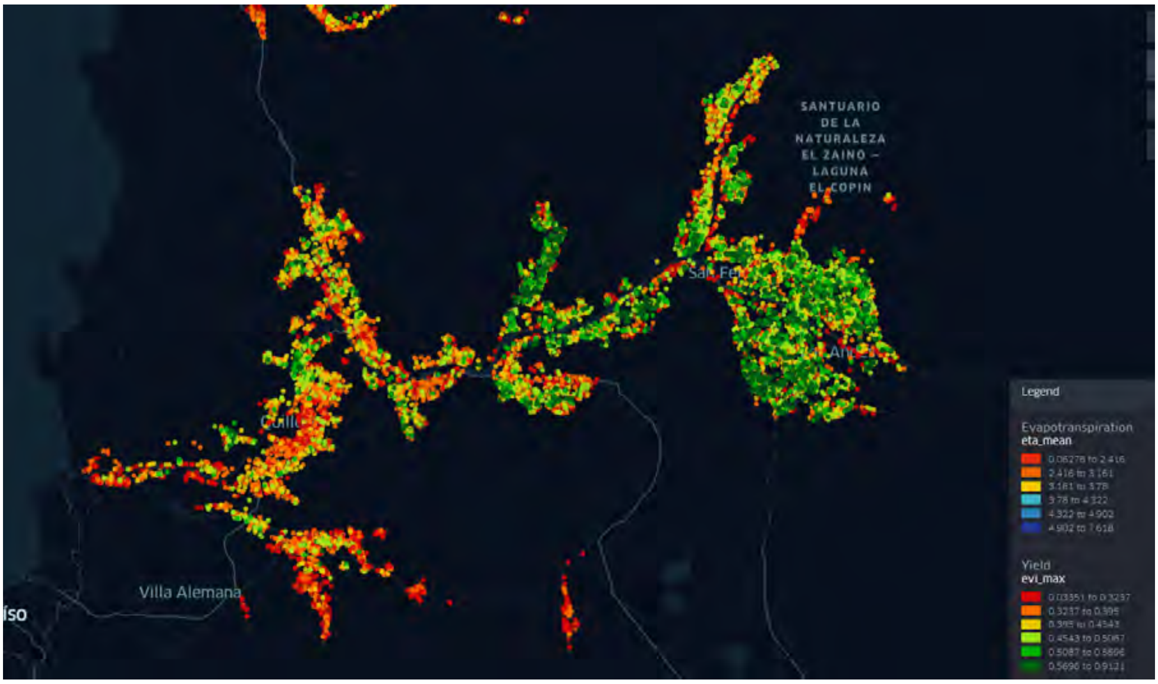
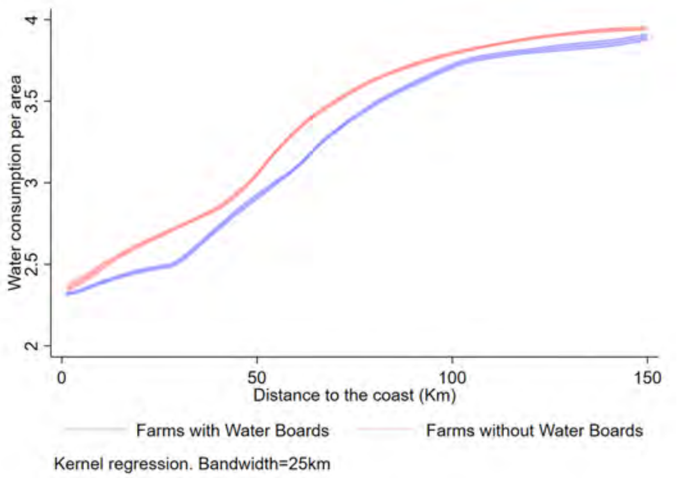
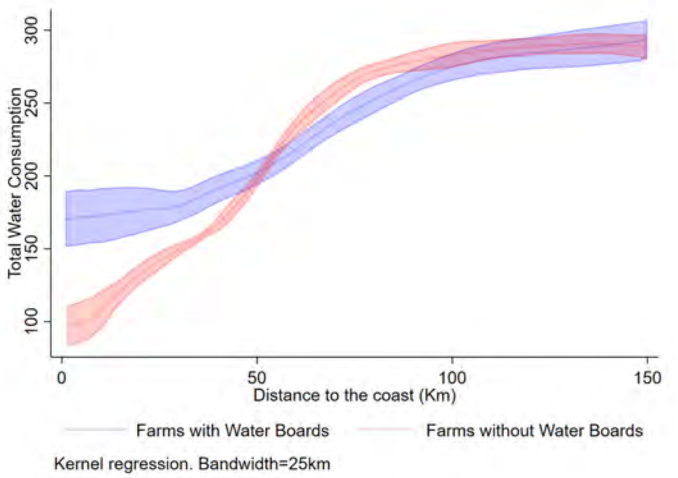


Figure X: Kernel Regressions between Water Consumption measures and location in Basin Basin Location (Distance to the Coast), by Treatment Assignment

(a) Average (per m^2) Evapotranspiration during Summer vs farm location within basin



(b) Total Evapotranspiration during Summer vs farm location within basin



(c) Water Availability Index vs farm location within basin

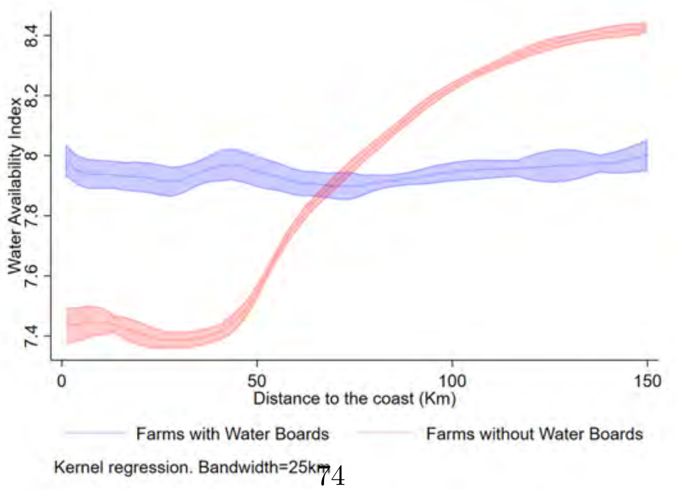
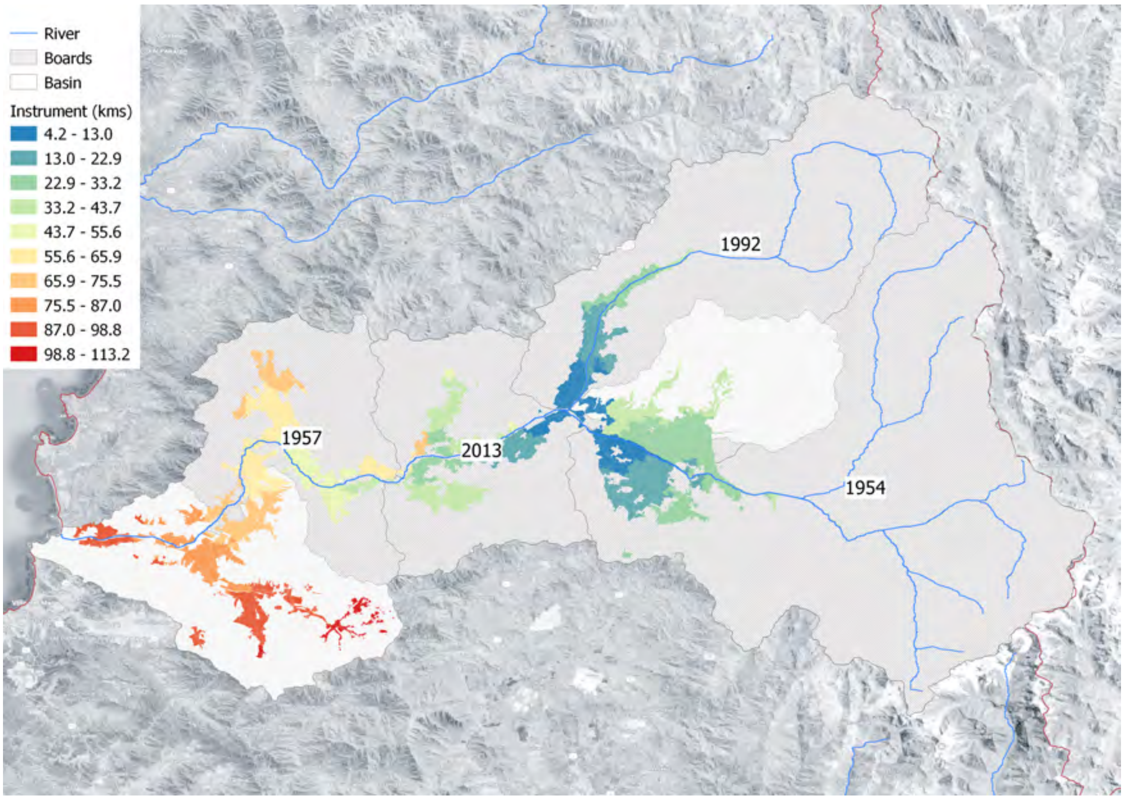


Figure XI: Illustration: farm level data and distance to most upstream capital



Notes: The map presents the Aconcagua Basin, illustrating the jurisdiction and year of Establishment of its four Water Boards, and our sample of irrigated farms. The color of each farm plot represents distance through the road network to the most upstream province capital.

Figure XII: Farm size distribution across locations

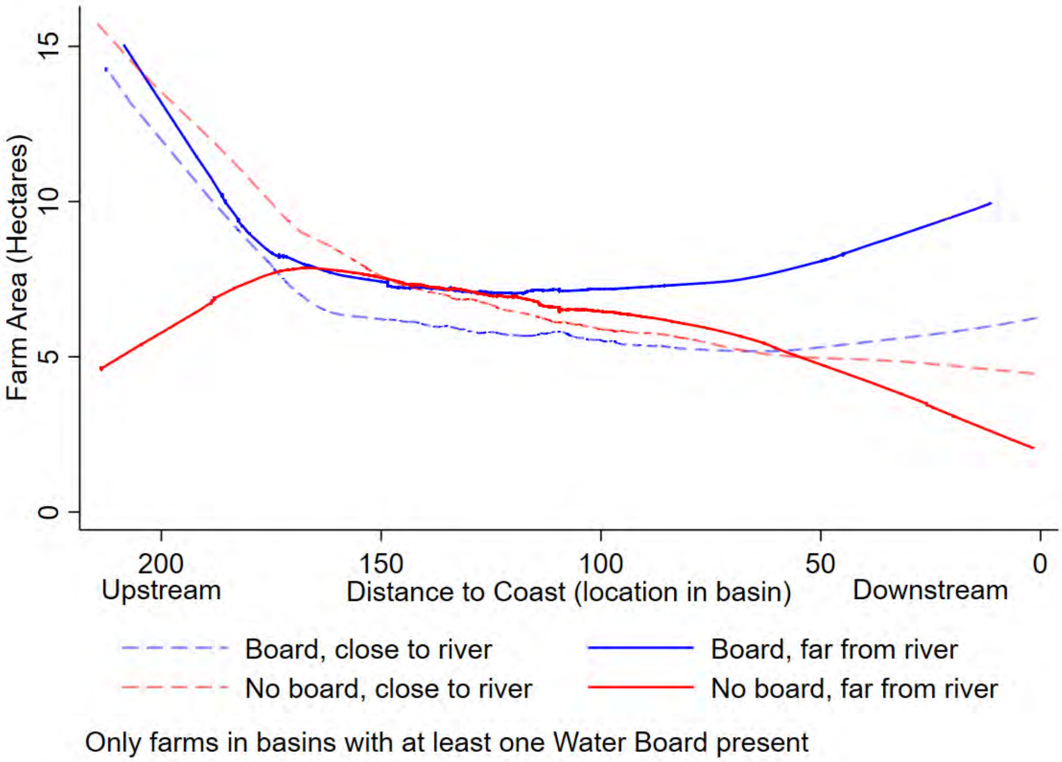
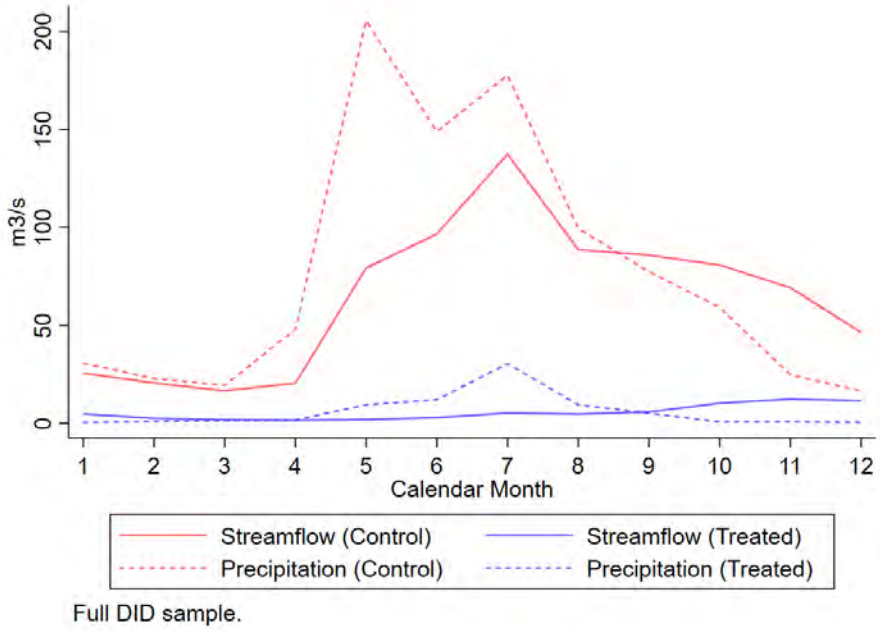
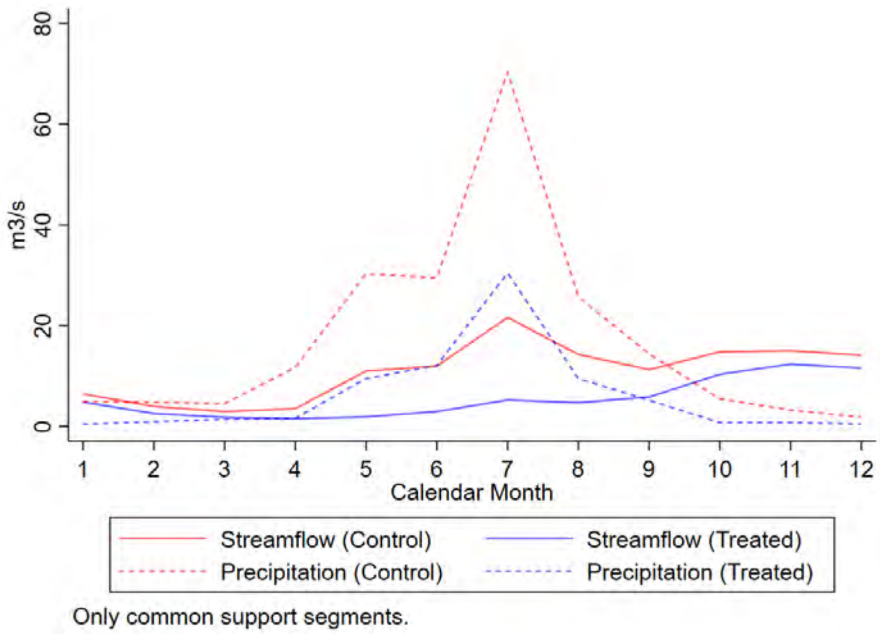


Figure XIII: Hydrological regime before 1985, by treatment assignment



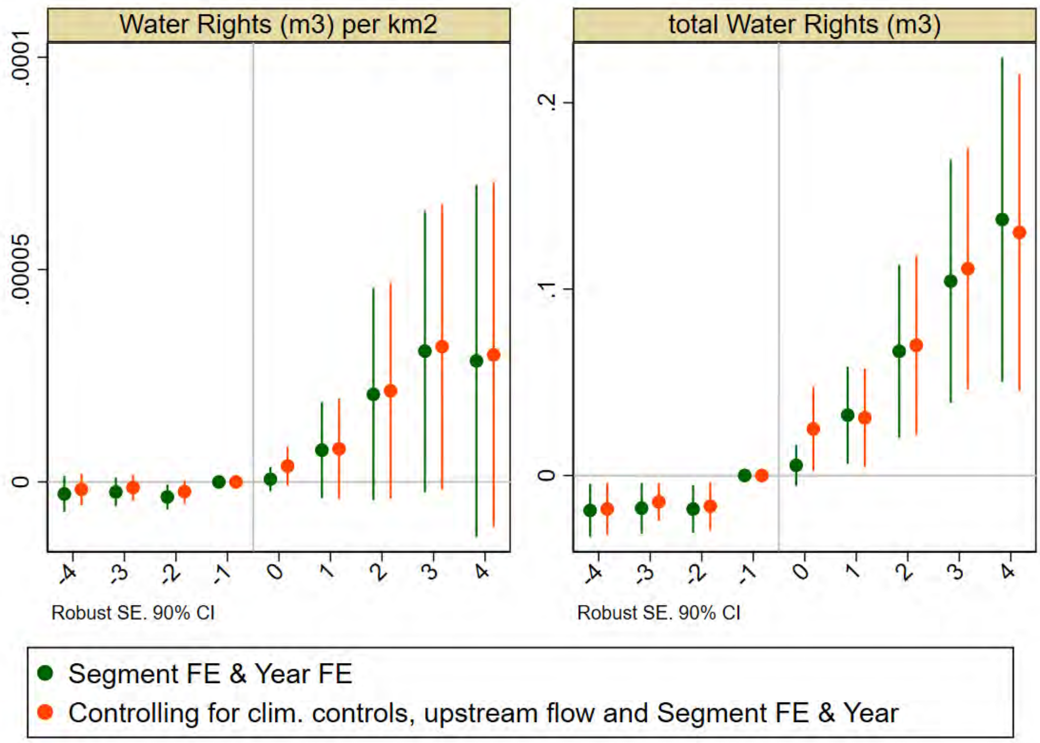
(a) Full Sample



(b) Study Sample

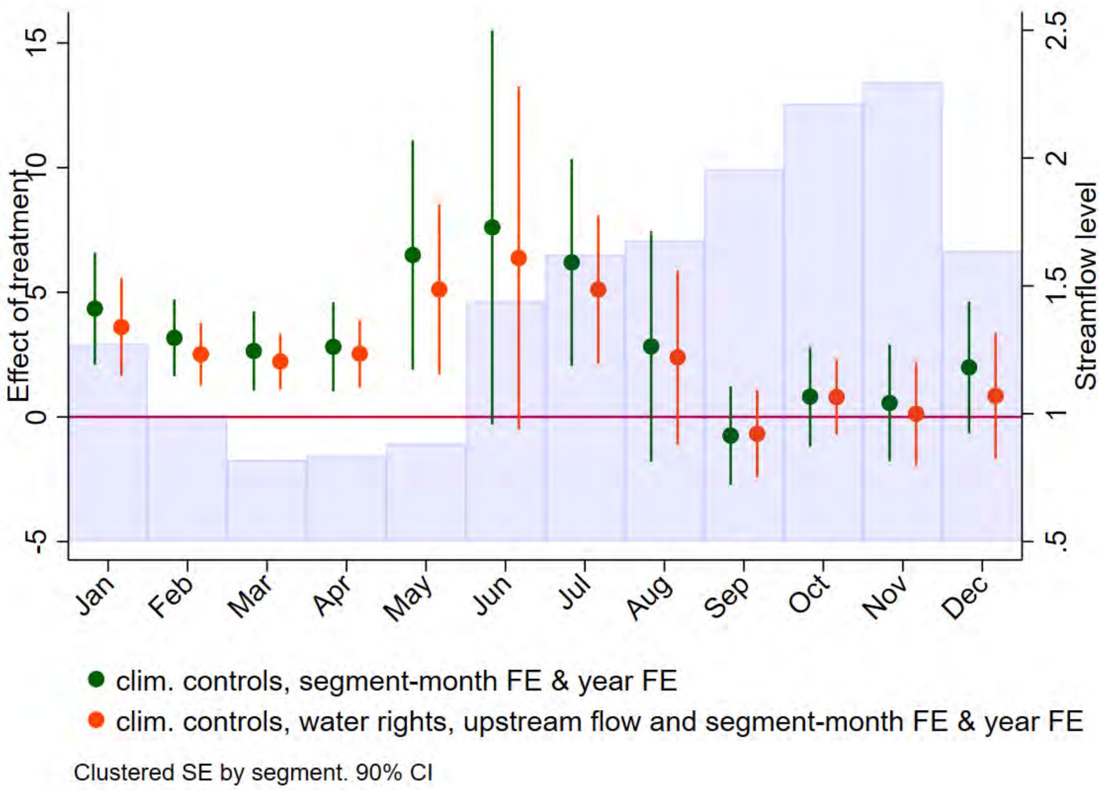
Notes: The study sample corresponds segments within the common support in average streamflow and pre-existing water rights in 1980, that eventually have Water Boards.

Figure XIV: Effect of boards establishments on Water Rights issued in their jurisdictions, by source of the water (Poisson).



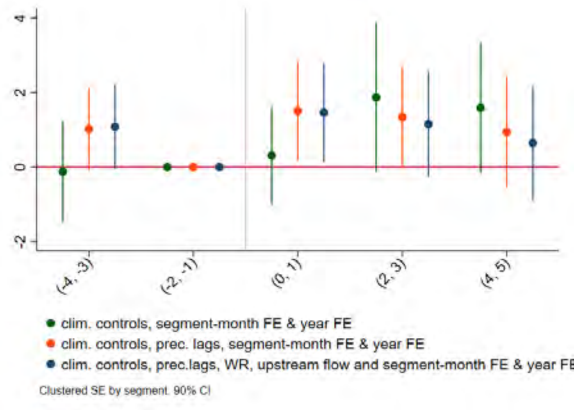
Notes: this figure present estimates of dynamic effects of water boards on water rights issued (measured in m^3/s) separately by source: in green, the effect of water boards on surface water rights; in orange, the effect of water boards on groundwater rights. Using OLS, implemented using Stacked DID design by Cengiz et al. (2019) design, considering *segment* $\times$ *event* and *year* $\times$ *event* fixed effects, climatic controls for January and February and also including 8 lags of precipitation and precipitation squared. Standard errors clustered at the river-segment level.

Figure XV: Effect of board establishments on streamflow within their jurisdiction, by month.

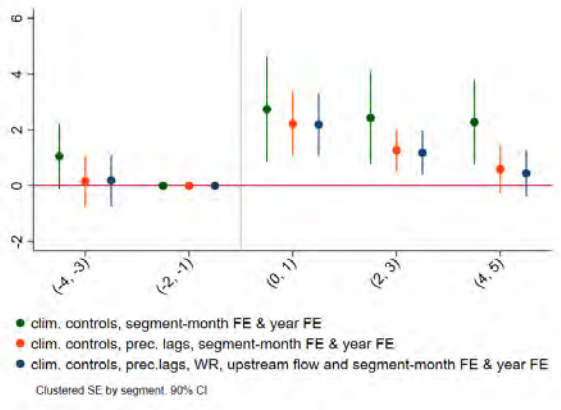


Notes: This table present heterogenous effects estimates of water boards on streamflows, by month. We interact the Board Establishment dummy variable with dummy variables indicating each month. Stacked DID design by Cengiz et al. (2019). Controlling for contemporaneous temperature, precipitation and evapotranspiration, and 8 lags of precipitation and precipitation squared. Standard Errors clustered at the River Segment level.

Figure XVI: Effect of board establishments on streamflow within their jurisdiction, by relative time (binned years) to the board establishment event.



(a) Full year.



(b) Dry season.

Notes: This table present dynamic effect estimates of water boards on streamflows, according to relative time to board establishment. We created 2-year bins, and consider the two years prior to the board establishment as the baseline period. Controlling for contemporaneous temperature, precipitation and evapotranspiration, and 8 lags of precipitation and precipitation squared, and water rights. Standard Errors clustered at the River Segment level.

A Appendix

Figure A.I: Water Right creation process.

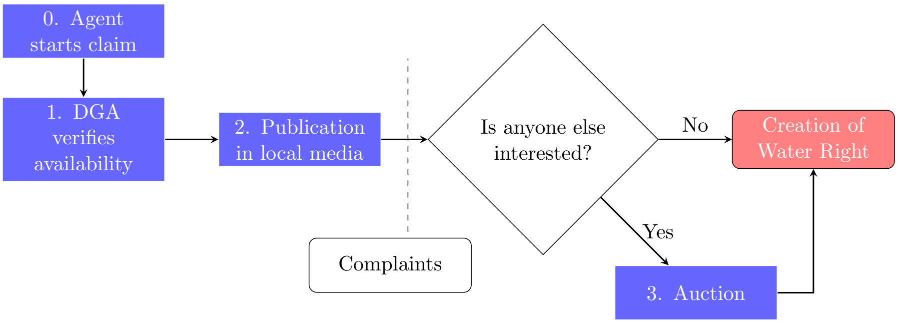
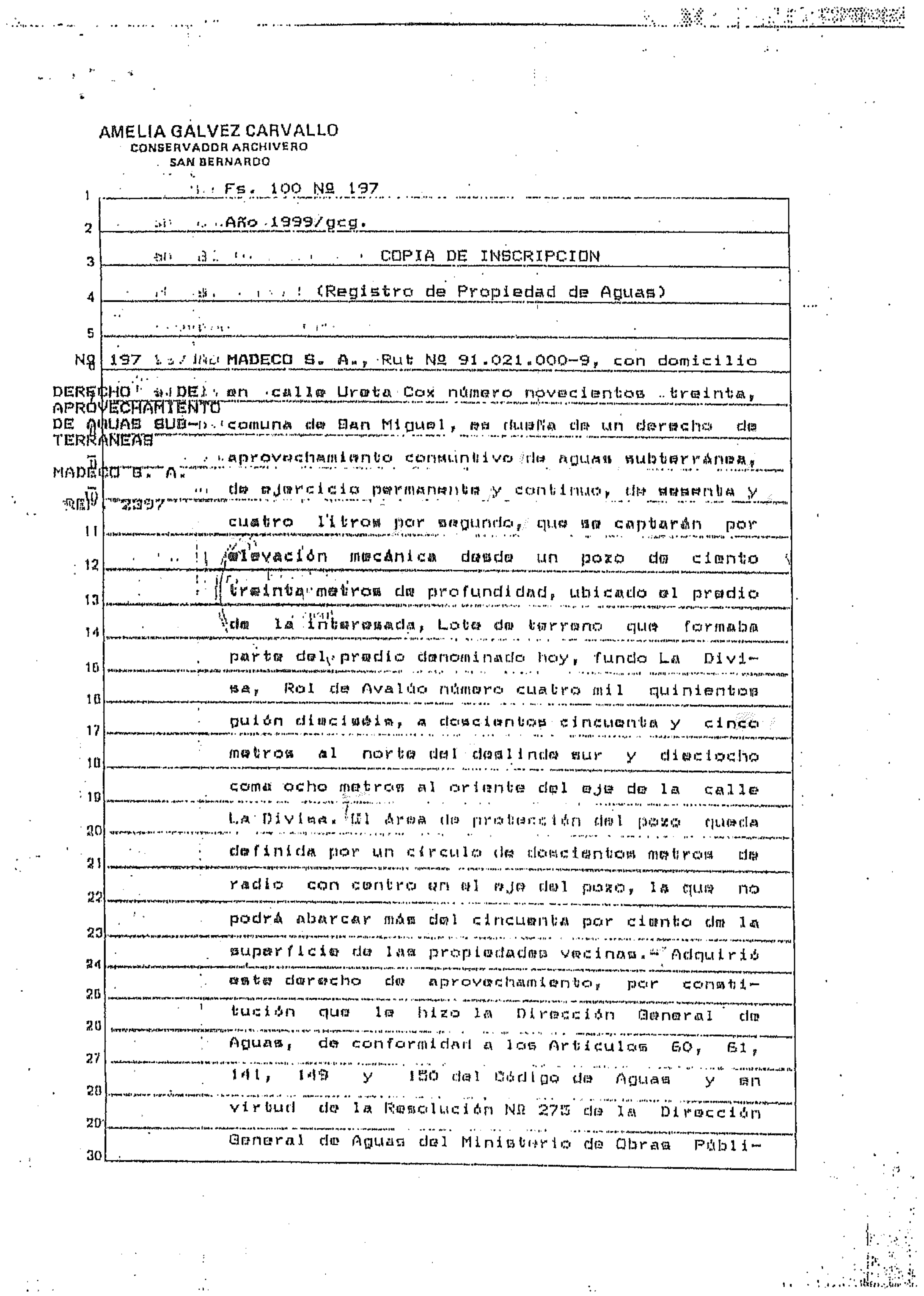


Figure A.II: Example: water right title.



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CONSERVADOR ARCHIVERO
SAN BERNARDO

Fs. 100 Nº 197

Año 1999/gcg.

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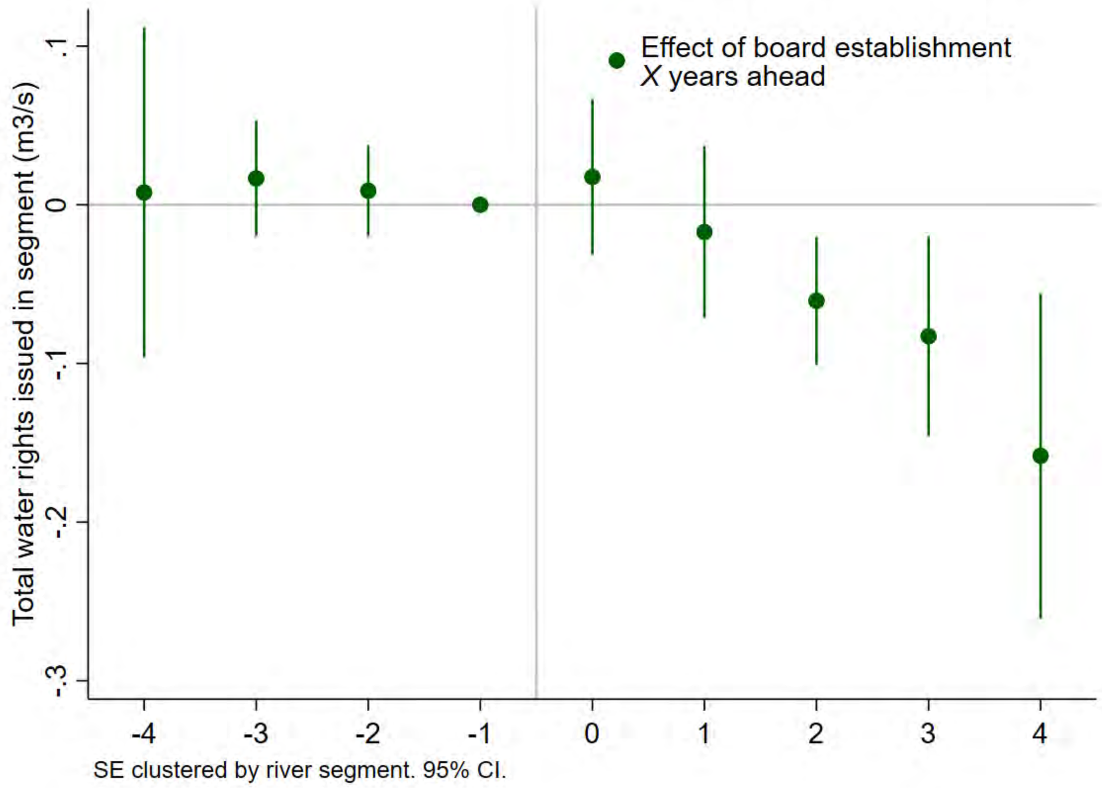
(Registro de Propiedad de Aguas)

DERECHO APROVECHAMIENTO DE AGUAS SUBTERRANEAS
MADECO S. A.
REP 2397

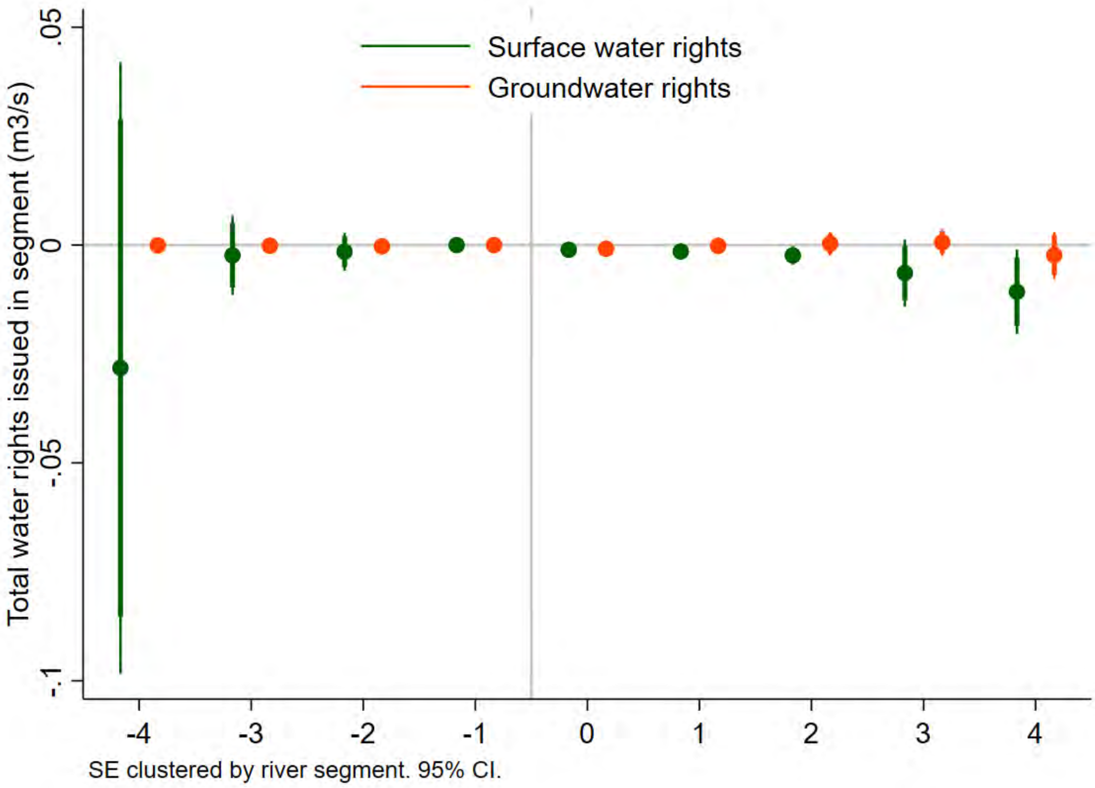
Nº 197 MADECO S. A., Rut Nº 91.021.000-9, con domicilio en calle Ureta Cox número novecientos treinta, comuna de San Miguel, es dueña de un derecho de aprovechamiento consuntivo de aguas subterráneas, de ejercicio permanente y continuo, de sesenta y cuatro litros por segundo, que se captarán por elevación mecánica desde un pozo de ciento treinta metros de profundidad, ubicado el predio de la interesada, Lote de terreno que formaba parte del predio denominado hoy, fundo La Divisa, Rol de Avalúo número cuatro mil quinientos guión dieciséis, a doscientos cincuenta y cinco metros al norte del deslinde sur y dieciocho coma ocho metros al oriente del eje de la calle La Divisa. El Area de protección del pozo queda definida por un círculo de doscientos metros de radio con centro en el eje del pozo, la que no podrá abarcar más del cincuenta por ciento de la superficie de las propiedades vecinas.- Adquirió este derecho de aprovechamiento, por constitución que le hizo la Dirección General de Aguas, de conformidad a los Artículos 60, 61, 141, 149 y 150 del Código de Aguas y en virtud de la Resolución Nº 275 de la Dirección General de Aguas del Ministerio de Obras Públi-

Figure A.III: Effect of boards establishments on Water Rights issued in their jurisdictions, by source of the water (OLS).



Notes: this figure present estimates of dynamic effects of water boards on water rights issued (measured in m^3/s) separately by source: in green, the effect of water boards on surface water rights; in orange, the effect of water boards on groundwater rights. Using OLS, implemented using Stacked DID design by Cengiz et al. (2019) design, considering *segment* $\times$ *event* and *year* $\times$ *event* fixed effects, climatic controls for January and February and also including 8 lags of precipitation and precipitation squared. Standard errors clustered at the river-segment level.

Figure A.IV: Effect of boards establishments on Water Rights issued per km^2 in their jurisdictions, by source of the water.



Notes: this figure present estimates of dynamic effects of water boards on water rights issued (measured in m^3/s,) per km^2 of surface of the basin, separately by source: in green, the effect of water boards on surface water rights; in orange, the effect of water boards on groundwater rights. Using OLS, implemented using Stacked DID design by Cengiz et al. (2019) design, considering *segment* $\times$ *event* and *year* $\times$ *event* fixed effects, climatic controls for January and February and also including 8 lags of precipitation and precipitation squared. Standard errors clustered at the river-segment level.

Figure A.V: Effects by month, estimated using Poisson Regression.

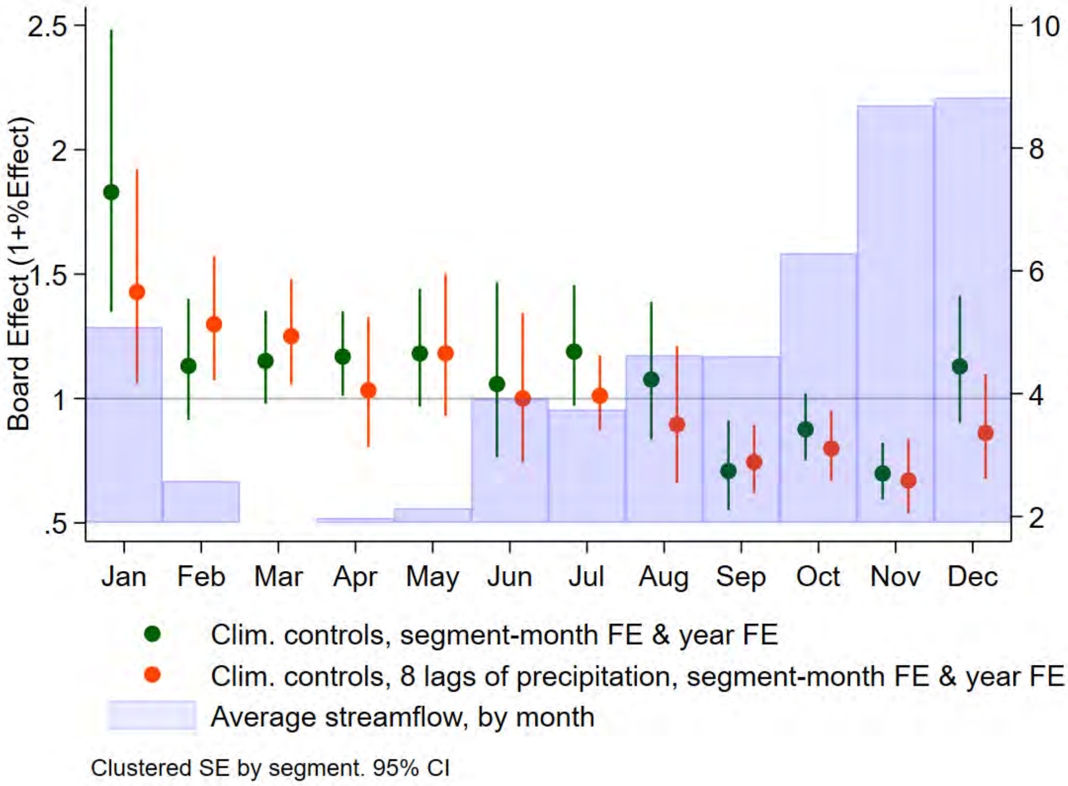


Table A.I: Balance table: outcome variable is precipitation fell during the irrigation season of the crop planted in the parcel

Rainfall during the crop irrigation season						
	Full Sample		Irrigated fields sample		Placebo sample	
	(1)	(2)	(3)	(4)	(5)	(6)
Distance to coast (100km)	0.0412	0.0469	-0.521	-0.958	0.102	0.111
	(0.0539)	(0.0610)	(0.103)***	(0.219)***	(0.0399)**	(0.0540)**
Water Board=1	-0.0814	0.0596	-0.415	-0.618	-0.413	-0.114
	(0.301)	(0.338)	(0.280)	(0.399)	(0.440)	(0.329)
Water Board=1 × Distance to coast (100km)	0.101	0.111	0.138	0.381	0.624	0.299
	(0.211)	(0.237)	(0.196)	(0.263)	(0.294)**	(0.248)
Basin FE	Yes	No	Yes	No	Yes	No
0.5 degree cell FE	No	Yes	No	Yes	No	Yes
Crop FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	79,133	79,132	15,149	15,147	63,838	63,838
R-squared	0.885	0.931	0.910	0.944	0.924	0.946
Outcome mean	0.899	0.899	0.765	0.765	0.931	0.931
Outcome SD	0.944	0.944	0.836	0.836	0.966	0.966

Table A.II: Summary Statistics: parcel level dataset, by distance to the Coast

	1					
	Mean	SD	p10	p90	Min	Max
Water Consumption per area	3.62	1.3	1.9	5.4	0.1	7.4
Total (Estimated) Water Consumption	253.81	619.1	8.9	664.5	0.2	23368.2
EVI (max over Summer)	0.45	0.1	0.3	0.6	0.1	0.9
Area (m2)	57697.51	131852.7	3494.0	146577.1	127.4	3977456.0
Latitude	-34.74	1.4	-36.8	-33.0	-37.6	-29.8
Longitude	-71.51	0.4	-72.2	-71.1	-73.0	-70.8
Precipitation (year, plot)	1939.78	790.8	979.1	2973.0	478.1	4267.5
Precipitation (Summer)	56.29	20.8	29.2	83.9	15.9	99.7
Mkt. Acc. (Santiago)	239.44	149.9	65.7	485.6	24.3	613.8
Mkt. Acc. (Valparaiso)	294.99	178.0	88.8	579.1	15.8	707.2
Mkt. Acc. (San Antonio)	236.14	156.6	59.5	493.3	20.4	621.4
Distance to Coast (location in basin)	87.61	31.9	31.7	122.8	0.9	131.8
Dist Upstream Capital	69.66	21.6	50.0	101.2	50.0	179.6
Observations	26780					

	2					
	Mean	SD	p10	p90	Min	Max
Water Consumption per area	4.04	1.1	2.6	5.4	0.3	7.0
Total (Estimated) Water Consumption	328.84	717.2	14.2	852.2	0.2	22422.0
EVI (max over Summer)	0.47	0.1	0.3	0.6	0.0	0.9
Area (m2)	70285.51	147771.5	4057.0	174246.4	47.6	4168568.5
Latitude	-34.83	1.4	-36.7	-32.8	-37.6	-29.9
Longitude	-71.30	0.5	-71.9	-70.8	-72.6	-70.6
Precipitation (year, plot)	1578.97	741.1	793.3	2792.3	449.3	3274.8
Precipitation (Summer)	46.19	15.7	28.8	68.7	16.5	93.1
Mkt. Acc. (Santiago)	236.86	155.8	48.9	475.5	9.4	596.1
Mkt. Acc. (Valparaiso)	315.74	164.8	124.9	548.4	44.6	689.6
Mkt. Acc. (San Antonio)	257.33	142.7	100.9	483.2	73.2	603.8
Distance to Coast (location in basin)	123.26	27.3	81.2	150.3	11.4	159.9
Dist Upstream Capital	70.01	13.0	56.4	88.2	50.0	88.2
Observations	26138					

	3					
	Mean	SD	p10	p90	Min	Max
Water Consumption per area	3.66	1.1	2.1	5.0	0.1	6.7
Total (Estimated) Water Consumption	294.48	656.3	14.4	758.8	0.3	23274.3
EVI (max over Summer)	0.44	0.1	0.3	0.6	0.1	0.9
Area (m2)	68699.35	145405.0	4746.7	165233.6	129.6	5350225.5
Latitude	-34.88	1.6	-36.9	-32.8	-37.8	-29.9
Longitude	-71.23	0.5	-72.0	-70.6	-72.9	-70.5
Precipitation (year, plot)	1350.98	557.7	770.2	2038.9	0.0	2881.2
Precipitation (Summer)	41.03	14.2	24.2	58.4	2.6	74.8
Mkt. Acc. (Santiago)	247.92	179.9	33.3	515.9	9.4	616.5
Mkt. Acc. (Valparaiso)	334.72	181.2	124.9	609.3	33.2	709.9
Mkt. Acc. (San Antonio)	284.51	153.5	124.5	523.6	72.8	624.1
Distance to Coast (location in basin)	157.06	27.1	120.7	188.4	31.1	219.8
Dist Upstream Capital	70.05	13.1	56.4	88.2	50.0	88.2
Observations	25539					

Table A.III: Boards and redistribution of water across locations

	Average ETa			log(total ETa)		
	(1)	(2)	(3)	(4)	(5)	(6)
Board x Downstream	0.138	0.131	0.236	0.186	0.202	0.197
	(0.111)	(0.105)	(0.119)**	(0.0999)*	(0.0961)**	(0.0823)**
Board x Midsection	0.0151	-0.0488	0.0940	0.0437	0.0592	0.109
	(0.0697)	(0.0658)	(0.0778)	(0.0938)	(0.0952)	(0.0992)
Board x Upstream	-0.150	-0.396	-0.359	0.0793	0.00508	0.000482
	(0.121)	(0.136)***	(0.0687)***	(0.0713)	(0.0729)	(0.0730)
Downstream	-	-	-	-	-	-
	-	-	-	-	-	-
Midsection	0.272	0.318	0.0897	0.246	0.262	0.164
	(0.0862)***	(0.0957)***	(0.0916)	(0.0844)***	(0.0878)***	(0.0906)*
Upstream	0.0209	0.277	-0.0258	0.257	0.352	0.237
	(0.127)	(0.120)**	(0.0880)	(0.0937)***	(0.0917)***	(0.0902)***
Area (polynomial)	Yes	Yes	Yes	Yes	Yes	Yes
Precipitation (pol.)	Yes	Yes	Yes	Yes	Yes	Yes
Prec. Summer (pol.)	Yes	Yes	Yes	Yes	Yes	Yes
Soil quality	Yes	Yes	Yes	Yes	Yes	Yes
Market Access	Yes	Yes	Yes	Yes	Yes	Yes
Basin FE	Yes	No	No	Yes	No	No
(lat, lon) grid FE	No	Yes	No	No	Yes	No
Sub-basin FE	No	No	Yes	No	No	Yes
Observations	78,457	78,457	78,456	78,457	78,457	78,456
R-squared	0.456	0.462	0.528	0.564	0.564	0.571
Mean Dependent Var.	3.771	3.771	3.771	4.417	4.417	4.417

Table A.IV: Boards and redistribution of Agricultural Production

	Yield (peak EVI)			log(total yield)		
	(1)	(2)	(3)	(4)	(5)	(6)
Board x Downstream	0.0179	0.0199	0.0182	0.190	0.206	0.178
	(0.0113)	(0.0110)*	(0.00887)**	(0.0899)**	(0.0925)**	(0.0695)**
Board x Midsection	-0.000572	-0.0000164	0.00689	0.0435	0.0726	0.0959
	(0.00907)	(0.00716)	(0.00815)	(0.0902)	(0.0928)	(0.0918)
Board x Upstream	0.00219	-0.00372	-0.00811	0.143	0.144	0.111
	(0.00783)	(0.00767)	(0.00635)	(0.0687)**	(0.0674)**	(0.0700)
Downstream	-	-	-	-	-	-
	-	-	-	-	-	-
Midsection	0.00956	0.0125	-0.00369	0.170	0.183	0.123
	(0.00776)	(0.00864)	(0.00760)	(0.0783)**	(0.0818)**	(0.0815)
Upstream	-0.00513	0.000119	-0.0178	0.217	0.252	0.194
	(0.0125)	(0.0118)	(0.0101)*	(0.0858)**	(0.0840)***	(0.0839)**
Area (polynomial)	Yes	Yes	Yes	Yes	Yes	Yes
Precipitation (pol.)	Yes	Yes	Yes	Yes	Yes	Yes
Prec. Summer (pol.)	Yes	Yes	Yes	Yes	Yes	Yes
Soil quality	Yes	Yes	Yes	Yes	Yes	Yes
Market Access	Yes	Yes	Yes	Yes	Yes	Yes
Basin FE	Yes	No	No	Yes	No	No
(lat, lon) grid FE	No	Yes	No	No	Yes	No
Sub-basin FE	No	No	Yes	No	No	Yes
Observations	78,469	78,469	78,468	78,469	78,469	78,468
R-squared	0.279	0.288	0.323	0.559	0.560	0.566
Mean Dependent Var.	0.510	0.510	0.510	0.253	0.253	0.253

Table A.V: Monitoring Stations by Year of Board Establishment

Year	N segments	percent	Cumulative perc.
1916	4	0.78	0.78
1927	4	0.78	1.55
1952	6	1.16	2.71
1953	3	0.58	3.29
1954	43	8.33	11.63
1956	7	1.36	12.98
1957	38	7.36	20.35
1959	12	2.33	22.67
1963	3	0.58	23.26
1964	1	0.19	23.45
1966	7	1.36	24.81
1976	7	1.36	26.16
1982	11	2.13	28.29
1983	2	0.39	28.68
1985	8	1.55	30.23
1992	2	0.39	30.62
1993	5	0.97	31.59
1995	16	3.10	34.69
1998	16	3.10	37.79
2018	27	5.23	43.02
No Board	294	56.98	100.00
Total	516		

Notes: This table shows the total number of monitoring stations available, and the establishment date of a water board (in case the river segment associated with a monitoring station is within a water board jurisdiction). Stations above the dashed line are excluded from the study, as the creation of their water boards took place under a different institutional regime.

Table A.VI: Dynamic effects of Water Boards on water rights. Baseline period correspond to the last two years before the boards establishment.

Water Rights created

Panel A: OLS

	Surface WR (m3/s)		Groundwater WR (m3/s)	
	(1)	(2)	(3)	(4)
-4	-0.0118	-0.00571	-0.0142	-0.0125
	[-0.241, 0.117]	[-0.252, 0.116]	[-0.0250, -0.00276]	[-0.0271, 0.00212]
	0.923	0.947	0.0450	0.203
			**	*
-3	0.0249	0.00803	-0.0149	-0.0127
	[-0.0202, 0.0731]	[-0.0271, 0.0617]	[-0.0256, -0.00416]	[-0.0288, 0.00179]
	0.442	0.692	0.0190	0.109
			**	
-2	-0.00436	-0.00358	-0.0150	-0.0147
	[-0.0172, 0.00350]	[-0.0264, 0.0157]	[-0.0246, -0.00488]	[-0.0284, -0.00528]
	0.432	0.635	0.0480	0.00100
			***	**
0	-0.00352	-0.0254	-0.0217	-0.0123
	[-0.0110, 0.00113]	[-0.0581, 0.0246]	[-0.0722, 0.0263]	[-0.0591, 0.0306]
	0.183	0.473	0.588	0.728
1	-0.00438	0.00480	0.00248	0.00153
	[-0.0126, 0.00345]	[-0.0231, 0.0272]	[-0.0805, 0.0716]	[-0.0640, 0.0719]
	0.311	0.706	0.936	0.968
2	-0.00835	-0.0229	0.0207	0.0245
	[-0.0163, 0.000501]	[-0.0295, -0.0134]	[-0.0670, 0.112]	[-0.0589, 0.113]
	0.112	0	0.613	0.605
	*	***		
3	-0.0356	-0.0252	0.0544	0.0562
	[-0.106, 0.0174]	[-0.100, 0.0224]	[-0.0850, 0.200]	[-0.0603, 0.200]
	0.278	0.539	0.431	0.356
4	-0.0803	-0.0786	0.0729	0.0680
	[-0.133, -0.0378]	[-0.171, 0.00387]	[-0.0761, 0.226]	[-0.0629, 0.215]
	0.0300	0.134	0.273	0.321
	**			
Climatic controls	No	Yes	No	Yes
Segment FE	Yes	Yes	Yes	Yes
Year x experiment FE	Yes	Yes	Yes	Yes
Observations	1,404	1,404	1,404	1,404
R-squared	0.893	0.896	0.751	0.753
Outcome mean	0.180	0.180	0.062	0.062
Outcome SD	0.686	0.686	0.170	0.170

Panel B: Poisson

	Surface WR (m3/s)		Groundwater WR (m3/s)	
	(1)	(2)	(3)	(4)
main				
-4	0.158	0.184	-0.158	-0.101
	,	,	,	,
	0.548	0.499	0.0721	0.248
			*	
-3	0.209	0.147	-0.204	-0.164
	,	,	,	,
	0.154	0.400	0.0511	0.236
			***	***
-2	0.00204	0.0691	-0.215	-0.154
	,	,	,	,
	0.853	0.366	0.0350	0.133
			***	***
0	-0.0391	-0.0103	0.0467	0.0959
	,	,	,	,
	0.227	0.890	0.0501	0.474
	*		***	
1	-0.109	-0.0774	0.306	0.341
	,	,	,	,
	0.0310	0.338	0.0210	0.0651
	**		***	***
2	-0.158	-0.110	0.426	0.412
	,	,	,	,
	0.00801	0.418	0.0420	0.0891
	***		***	***
3	-0.725	-0.676	0.543	0.480
	,	,	,	,
	0.0811	0.0731	0.0490	0.105
	***	***	***	***
4	-0.790	-0.823	0.350	0.435
	,	,	,	,
	0.0270	0.0340	0.395	0.0631
	***	***	*	***
Climatic controls	No	Yes	No	Yes
Segment FE	Yes	Yes	Yes	Yes
Year x experiment FE	Yes	Yes	Yes	Yes
Observations	1,404	1,404	1,404	1,404
R-squared				
Outcome mean	0.180	0.180	0.062	0.062
Outcome SD	0.686	0.686	0.170	0.170

Table A.VII: Dynamic effects of Water Boards on water rights per unit of area. Baseline period correspond to the last two years before the boards establishment.

Water Rights per squared Kilometer

Panel A: OLS

	Surface WR per Area		Groundwater WR per Area	
	(1)	(2)	(3)	(4)
-4	-0.0282 [-0.126, 0.0110] 0.952	-0.0284 [-0.126, 0.0111] 0.929	-0.0000869 [-0.000757, 0.000806] 0.768	0.0000348 [-0.000538, 0.00107] 0.926
-3	-0.00237 [-0.0140, 0.00336] 0.983	-0.00252 [-0.0143, 0.00484] 0.861	-0.000141 [-0.000518, 0.000412] 0.493	-0.0000798 [-0.000517, 0.000549] 0.691
-2	-0.00153 [-0.00706, 0.00100] 0.837	-0.00162 [-0.00798, 0.00157] 0.553	-0.000289 [-0.000462, -0.0000499] 0.0410 **	-0.000166 [-0.000412, 0.000130] 0.338
0	-0.00108 [-0.00313, 0.0000582] 0.133	-0.000222 [-0.00185, 0.00208] 0.872	-0.000842 [-0.00221, 0.000616] 0.408	-0.000866 [-0.00271, 0.000690] 0.467
1	-0.00147 [-0.00384, 0.000301] 0.227	-0.00207 [-0.00537, 0.000137] 0.101 *	-0.000172 [-0.00222, 0.00157] 0.803	-0.000114 [-0.00213, 0.00179] 0.897
2	-0.00237 [-0.00541, -0.000689] 0.0470 **	-0.00137 [-0.00364, 0.00157] 0.322	0.000325 [-0.00322, 0.00299] 0.846	0.000279 [-0.00261, 0.00273] 0.829
3	-0.00641 [-0.0146, 0.000119] 0.0951	-0.00662 [-0.0147, -0.000537] 0.0671 *	0.000637 [-0.00307, 0.00367] 0.662	0.000656 [-0.00333, 0.00360] 0.673
4	-0.0107 [-0.0200, -0.00504] 0 **	-0.0126 [-0.0219, -0.00618] 0.00200 **	-0.00231 [-0.00892, 0.00310] 0.464	-0.00191 [-0.00747, 0.00285] 0.498
Climatic controls	No	Yes	No	Yes
Segment FE	Yes	Yes	Yes	Yes
Year x experiment FE	Yes	Yes	Yes	Yes
Observations	1,404	1,404	1,404	1,404
R-squared	0.882	0.882	0.666	0.667
Outcome mean	0.014	0.014	0.003	0.003
Outcome SD	0.062	0.062	0.008	0.008

Panel B: Poisson

	Surface WR per Area		Groundwater WR per Area	
	(1)	(2)	(3)	(4)
main				
-4	0.158 , 0.515	0.184 , 0.519	-0.158 , 0.0761 *	-0.101 , 0.230
-3	0.209 , 0.162	0.147 , 0.429	-0.204 , 0.0420 ***	-0.164 , 0.232 ***
-2	0.00204 , 0.858	0.0691 , 0.405	-0.215 , 0.0400 ***	-0.154 , 0.140 ***
0	-0.0391 , 0.192 *	-0.0103 , 0.881	0.0467 , 0.0440 ***	0.0959 , 0.501
1	-0.109 , 0.0581 **	-0.0774 , 0.333	0.306 , 0.0100 ***	0.341 , 0.0591 ***
2	-0.158 , 0.00901 ***	-0.110 , 0.425	0.426 , 0.0400 ***	0.412 , 0.0861 ***
3	-0.725 , 0.0931 ***	-0.676 , 0.0641 ***	0.543 , 0.0591 ***	0.480 , 0.0931 ***
4	-0.790 , 0.0270 ***	-0.823 , 0.0200 ***	0.350 , 0.402 *	0.435 , 0.0671 ***
Climatic controls	No	Yes	No	Yes
Segment FE	Yes	Yes	Yes	Yes
Year x experiment FE	Yes	Yes	Yes	Yes
Observations	1,404	1,404	1,404	1,404
R-squared				
Outcome mean	0.180	0.180	0.062	0.062
Outcome SD	0.686	0.686	0.170	0.170

Table A.VIII: Dynamic effects of Water Boards on streamflows. Baseline period correspond to the last two years before the boards establishment.

	Streamflows					
	Full year			Dry season		
	(1)	(2)	(3)	(4)	(5)	(6)
(-4, -3)	-0.117	1.016	1.081	1.055	0.156	0.190
	(0.814)	(0.667)	(0.675)	(0.703)	(0.552)	(0.565)
(-2, -1)						
(0, 1)	0.309	1.512	1.460	2.742	2.222	2.194
	(0.786)	(0.802)*	(0.795)*	(1.137)**	(0.687)***	(0.678)***
(2, 3)	1.873	1.350	1.157	2.430	1.279	1.184
	(1.201)	(0.814)	(0.843)	(0.993)**	(0.454)***	(0.467)**
(4, 5)	1.587	0.945	0.644	2.280	0.583	0.443
	(1.047)	(0.891)	(0.914)	(0.922)**	(0.515)	(0.496)
Water Rights (m3/s)			-0.637			-0.299
			(0.290)**			(0.308)
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes
Precipitation lags	No	Yes	Yes	No	Yes	Yes
Segment FE	No	No	No	Yes	Yes	Yes
Segment x Month FE	Yes	Yes	Yes	No	No	No
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	14,926	13,922	13,922	2,476	2,234	2,234
R-squared	0.680	0.763	0.763	0.448	0.705	0.706
Outcome mean	10.249	10.361	10.361	4.508	4.419	4.419
Outcome SD	20.575	20.684	20.684	9.220	9.206	9.206

B Appendix: Basin level analysis

B.1 Identification Strategy

Water Boards are a permanent institution, implying permanent monetary costs (in the form of organization fees) and expected loss of control under foreseeable circumstances, such as future droughts, making it inappropriate to deal with temporary shocks. Anecdotal evidence suggests that establishing a Water Board is a slow process even in the case of agreement among users (Andres Arriagada Puentes et al., 2018), it does not seem appropriate as a tool to deal with temporary shocks, such as a short-lasting drought. In particular, droughts in Chile are frequent but not long-lasting (Fernández and Gironás, 2021): while 45 years during XX century can be classified as dry, the longest critical meteorological drought event between 1940 and 1988 lasted only 22 months (Fernández, Bonifacio et al., 1990).

To support this argument, we present different characteristics of the different areas adopting water boards by year of adoption in figures B.I, B.II and B.III in the Appendix. Figure B.I presents three different measures of water availability before 1985: precipitations (B.Ia), river streamflow B.Ib and glacier surface in the basin B.Ic. We separate the figures for areas where the board was established before 1981 -when the Water Code of 1981 was passed- and after; the distinction is relevant, as it was the Water Code of 1981 that opened the reclamation of rivers and established the water markets we are studying.

Figure B.Ia shows that even though the average precipitation was higher in areas that established boards before 1981 -areas where agriculture developed earlier-, we can see that for those boards established after[36], there is a trend: higher precipitation in areas where boards were established later. This is consistent with boards facing dryer long-term conditions adopted boards earlier. In figure B.Ib we see that the average streamflows increase with the year of establishment, too. Finally, we consider the share of the basin that is covered by glaciers at the head of the rivers, in the Andes. This is a measure of the natural availability of water during the Summer: glaciers smooth the relationship of precipitations and streamflows, by accumulating snow during the winters, and slowing down the melting

[36]Except for those boards established in 1982, which establishment process was probably started before the passing of the Water Code of 1981.

process, allowing solid water to melt and flow downstream during the Spring and Summer. Figure B.Ic shows that except for the years 1982 and 1983, it seems that the presence of glaciers increases as the year of establishment increases. This is consistent with boards being adopted earlier in places with less natural water availability during Summer when water is most needed for irrigation.

Figure B.II presents similar figures for the average minimum and maximum temperatures, latitude and longitude of monitoring stations. For basins that adopted boards after the passing of the Water Code of 1981, minimum and maximum temperatures seem to increase with the year of establishment of boards. Latitude and longitude do not display any distinctive pattern. Finally, in figure B.III we present some measures of long-term agricultural activity: agricultural land surface between 1980 and 2010, and water rights established before 1985. While agricultural activity is endogenous to water governance -as we show later in this paper-, most of the increases in water demand and changes in agriculture are a result of intensification and technological change in a fixed agricultural area (Meza et al., 2021). Basins that adopt boards earlier actually have a lower agricultural land share -at odds with the idea that early adopters might be facing stronger demand driven by extensive agriculture-; and there is no clear pattern regarding the early (i.e. before 1985) creation of water rights.

B.2 Redistribution within the Basin.

Increases in streamflow reflect more water flowing downstream from a given point where we measure water. If there are no lawful users downstream of a location, then there is no incentive nor (non-environmental) reason to keep water flowing after that point. Therefore, we expect to find a stronger effect upstream, as river segments located downstream will have relatively fewer lawful users located below them.

Figures Ia, Ib and Ic illustrate why we expect higher streamflow increases in upstream locations: in normal times (figure Ia), the infrastructure itself restricts users from over-extracting water. In a drought, the total streamflow available for distribution is reduced, and so the law established proportional reductions for all users. Figure Ib presents this case when no board is in charge of enforcing water rights: as the infrastructure is not binding anymore, the users upstream are able to over-extract, leaving not enough water for downstream users. Figure Ic shows how this situation changes in the presence of water boards: enforcement by the water boards implies increased streamflows between upstream and downstream locations. The increase in streamflow will be captured by the monitoring stations located between the users that would over-extract in the absence of a board, and those who receive water thanks to the board.

Table B.I presents estimates of heterogeneous effects, by interacting the treatment variable with dummy variables for river segments closer to the coast (below the median of the distribution of distances to the coast, in degrees) or farther away from the coast. Columns 1 and 2 consider the full year, while columns 2 and 4 only include the dry season.

The results show that the coefficients are higher for upstream locations in the full year, and for the dry season when we control for precipitation lags. Also, the coefficients are strongly significant for the dry season only for upstream locations, while for downstream locations are significant only at the 10% when controlling for precipitation lags. Finally, the table reaffirms the previous results that the effect is economically and statistically significant only for the dry season.

B.2.1 Water Boards and Land Inequality at the Basin Level

Water boards allocate power according to property: each water rights owner have a vote that is proportional to their streamflow ownership. This is a departure from conventional democratic rules that may imply improved economic outcomes (e.g Alesina and Rodrik, 1994), but also could reinforce elite capture dynamics (Bardhan and Mookherjee, 2000; Banerjee et al., 2001).

In table B.II we compare the impacts of the establishment of Water Boards in basins with higher versus lower land concentration. Using 2013 data on farm size, we measure land concentration for all the river segments under analysis[37].

Our results suggest that most of the observed impacts of Water Boards are driven by

[37]In principle we could directly measure water rights ownership concentration. In practice, this was not possible due to the low quality of the geolocation of water rights in the period under study.

areas with higher land concentration. Columns 1 and 2 show that the reduction in the creation of water rights is similar for areas with low and high land concentration (although the effect is not significant in areas with higher land concentration due to higher standard errors). Columns 3 and 4, instead, show that all the increase in groundwater rights (i.e. the displacement of the demand) happens in basins with higher land concentration. Finally, columns 5 and 6 show that the streamflow increase in the irrigation season is significant and higher for areas with higher land concentration, while for lower land concentration this does not happen.

One interpretation for the former results is that the presence of local elites -associated with higher land concentration- enhances the performance of water boards: local elites may be able to discipline more effectively the team managing the river[38]. It is possible, too, that these aggregate results hide heterogeneous distributional impacts, and so these improvements in property rights enforcement are beneficial only for local elites.

B.2.2 Monitoring and Enforcement.

So far, we have argued that water boards affect the allocation of water through two main mechanisms:

> **Monitoring:** water boards, by keeping track of the creation of water rights, are in a better position than both the state and the water users to identify interference by new water rights, and so introduce more complaints to stop the creation of rights.
>
> **Enforcement:** water boards reallocate water according to the legal mandate to enforce the existing water rights.

Our results in sections 6.2 and 6.2 suggest that both mechanisms are working, opening the question of their relative roles in shaping the allocation of water in the space.

[38] In a simple agency model with liquidity constraints (available upon request), the presence of agents with enough resources to start litigation against a "shirking" Water Board is a necessary condition for an equilibrium where water boards effectively enforce property rights, as the board is disciplined by the threat of a lawsuit by water rights users affected by over-extraction. The Water Board does not exert effort (and so, property rights are not enforced in equilibrium) if lawsuits are unaffordable for all users that do not have water access as a consequence of over-extraction in an equilibrium without enforcement.

In order to disentangle the relative roles of both mechanisms, we apply a statistical mediation argument (Baron and Kenny, 1986; Valeri and VanderWeele, 2013) to estimate the direct causal effect of water boards on streamflows, and their indirect effect, mediated by their effect on water rights. Statistical mediation exercises rely on several assumptions, but the Difference-in-difference design already assumes part of them[39].

To formalize the argument, let's consider a simplified version of equation 12 i.e. our models for water rights:

$$\text{WR}_{gst} = \beta_1 \text{Board}_{gst} + \beta_2 X_{gst} + \mu_t + \eta_g + \varepsilon_{gst} \tag{15}$$

With this definition, we can define the counterfactual expected water rights under water boards and without water boards as respectively:

$$\begin{aligned} \text{WR}(\text{Board} = 1) = \mathbb{E}\left[\text{WR}_{gst} | \text{Board} = 1\right] = &\quad \beta_1 + \beta_2 X_{gst} + \mu_t + \eta_g \\ \text{WR}(\text{Board} = 0) = \mathbb{E}\left[\text{WR}_{gst} | \text{Board} = 0\right] = &\qquad\quad \beta_2 X_{gst} + \mu_t + \eta_g \end{aligned}$$

Now, we can extend our model for streamflows, allowing water boards to affect also the relationship between water rights and streamflows:

$$\begin{aligned} \text{Stream}_{gmt} = &\alpha_1 \text{Board}_{gt} + \alpha_2 \text{WR}_{gmt} + \alpha_3 \text{Board}_{gt} \times \text{WR}_{gmt} \\ &+ \alpha_4 \text{X}_{gsmt} + \mu_t + \eta_{gm} + \varepsilon_{gmt} \end{aligned} \tag{16}$$

Then, from estimates of equations 15 and 16, we can recover the effect of water boards on streamflows, mediated by water rights. Following Baron and Kenny (1986) and Valeri and VanderWeele (2013), we define

[39]Statistical mediation exercises in a causal environment rely on four assumptions: (1) no unmeasured treatment-outcome confounding, (2) no unmeasured mediator-outcome confounding; (3) no unmeasured treatment-mediator confounding, and (4) no mediator-outcome confounder affected by treatment (Valeri and VanderWeele, 2013). While assumptions (1) and (3) were already assumed on running the Difference-in-difference analysis, assumptions (2) and (4) are non-standard, and imply in this setting a causal interpretation to the relationship between streamflows and water rights claimed, conditional on the set of fixed effects and controls. Providing evidence of such a causal relationship is currently under development, but the results so far do not contradict this assumption: the coefficient of water rights on streamflow is negative and in the same order of magnitude, as expected.

1. Natural Direct Effect of Water Boards on Streamflows:

$$\mathbb{E}\left[\text{Stream}|\text{Board}=1,\text{WR}(\text{Board}=0)\right]-\mathbb{E}\left[\text{Stream}|\text{Board}=0,\text{WR}(\text{Board}=0)\right]$$
$$=\alpha_1+\alpha_3\mathbb{E}\left[\text{WR}|\text{Board}=0\right]$$

2. Natural Indirect Effect of Water Boards on Streamflows, mediated by Water Rights

$$\mathbb{E}\left[\text{Stream}|\text{Board}=1,\text{WR}(\text{Board}=1)\right]-\mathbb{E}\left[\text{Stream}|\text{Board}=1,\text{WR}(\text{Board}=0)\right]$$
$$=(\alpha_2+\alpha_3)\times\left(\mathbb{E}\left[\text{WR}|\text{Board}=1\right]-\mathbb{E}\left[\text{WR}|\text{Board}=0\right]\right)=(\alpha_2+\alpha_3)\times\beta_1$$

The Natural Indirect Effect will be our estimate of the effect of Monitoring over streamflows. If water boards affect streamflows only through these two channels, then the Natural Direct Effect reflects the role of Enforcement.

In table B.III we present the results of the mediation exercise. The Natural Indirect Effect of water boards mediated by water rights is an increase of just $0.097m^3/s$; the Natural Direct effect is $0.842m^3/s$. Taken together, these results imply that just 10.3% of the total effect of water boards on streamflows is mediated by water rights. This suggests a limited role of Monitoring in increasing streamflows, compared to the effects of Enforcement.

B.3 Tables and Figures

Table B.I: Heterogeneous effects, by distance to the coast.

	Streamflow			
	Full Year		Dry Season	
	(1)	(2)	(3)	(4)
Board × segment close to coast	0.680	0.607	1.049	0.858
	(0.642)	(0.543)	(0.638)	(0.476)*
Board × segment far from coast	0.890	0.404	1.040	1.297
	(0.669)	(0.560)	(0.527)*	(0.431)***
Water Rights (m3/s)	-1.069	-0.440	-1.398	-0.00176
	(0.360)***	(0.306)	(0.975)	(0.286)
Climatic controls	Yes	Yes	Yes	Yes
Precipitation lags	No	Yes	No	Yes
Segment FE	No	No	Yes	Yes
Segment x Month FE	Yes	Yes	No	No
Year x Experiment FE	Yes	Yes	Yes	Yes
Observations	13,792	12,759	2,285	2,037
R-squared	0.702	0.776	0.454	0.681
Outcome mean	10.105	10.237	4.150	4.021
Outcome SD	20.402	20.527	8.345	8.222

Notes: This table present heterogenous effects estimates of water boards on streamflows, according to the relative distance to the coast. We interact the Board Establishment dummy variable with dummy variables indicating if a river segment is below or above the median of the longitude distance to the coast (0.3 longitude degrees). Stacked DID design by Cengiz et al. (2019). Standard Errors clustered at the River Segment level.

Table B.III: Monitoring vs Enforcement

	Mediation exercise: indirect effect of water boards	
	(1)	(2)
	Water Rights (m3/s)	River level (m3/s)
Board established	-0.199	1.349
	(0.112)*	(0.412)***
Water Rights (m3/s)		-0.239
		(0.292)
Board $\times$ Water Rights (m3/s)		-0.625
		(0.649)
Climatic controls	Yes	Yes
Precipitation lags	Yes	Yes
Segment FE	Yes	No
Segment x Month FE	No	Yes
Year FE	Yes	Yes
Observations	1,818	2,222
R-squared	0.829	0.721
Natural Direct Effect		1.044
Natural Indirect Effect		0.172

Notes: Notes: This table presents the results of a Mediation exercise. We implement Valeri and VanderWeele (2013) results on Statistical Mediation to estimate the indirect effect of water boards on water rights mediated by water rights (i.e. the increase in streamflows attributable to the effect of water boards on reducing the creation of water rights).

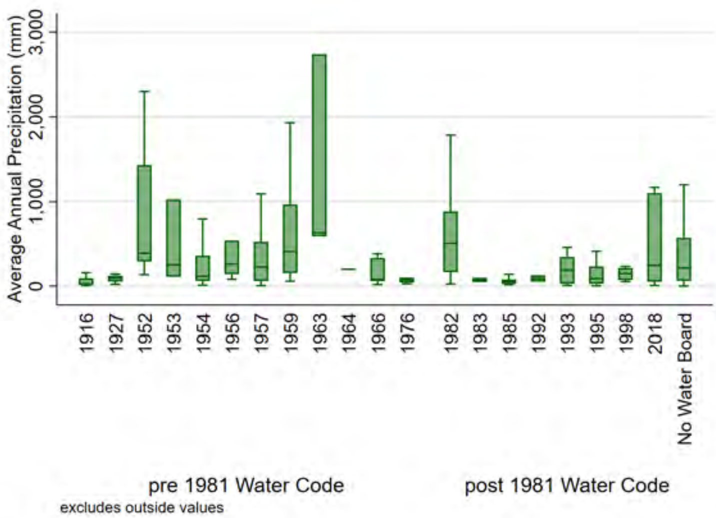
Table B.II: Water Board effects and Land Concentration

	Surface water rights		Groundwater rights		Streamflow	
	(1)	(2)	(3)	(4)	(5)	(6)
Board Est. × high land concentration	-0.210	-0.152	0.119	0.105	1.828	1.081
	(0.135)	(0.0983)	(0.0549)**	(0.0520)**	(0.660)***	(0.375)***
Board Est. × low land concentration	-0.195	-0.162	-0.00999	-0.00925	0.500	0.849
	(0.0954)**	(0.0845)*	(0.0198)	(0.0150)	(0.638)	(0.677)
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes
Precipitation lags	No	Yes	No	Yes	No	Yes
Segment FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,917	1,704	1,917	1,704	2,285	2,037
R-squared	0.827	0.868	0.731	0.773	0.451	0.681
Outcome mean						
Outcome SD						

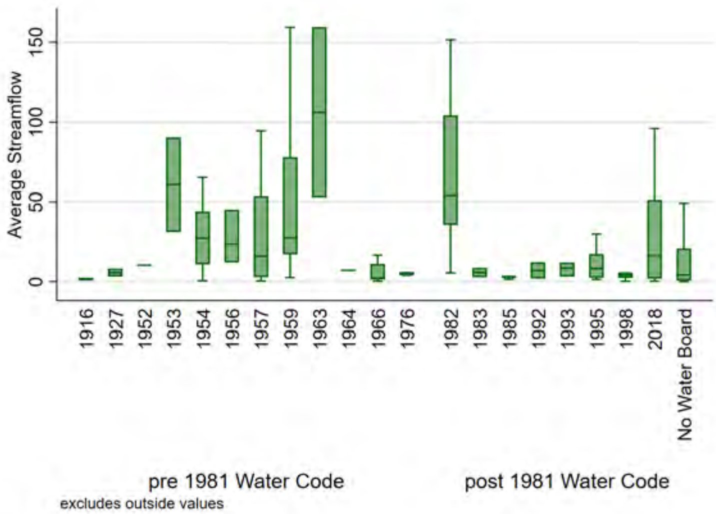
Notes:Notes: This table present heterogenous effects estimates of water boards on streamflows, according to the land concentration within the basin. We interact the Board Establishment dummy variable with dummy variables indicating if a river segment is below or above the median of the Gini Coefficient of land concentration. Stacked DID design by Cengiz et al. (2019). Standard Errors clustered at the River Segment level.

Figure B.I: Climatic and geographic characteristics, by year of establishment

(a) Average Precipitation



(b) Streamflow



(c) Glacier surface

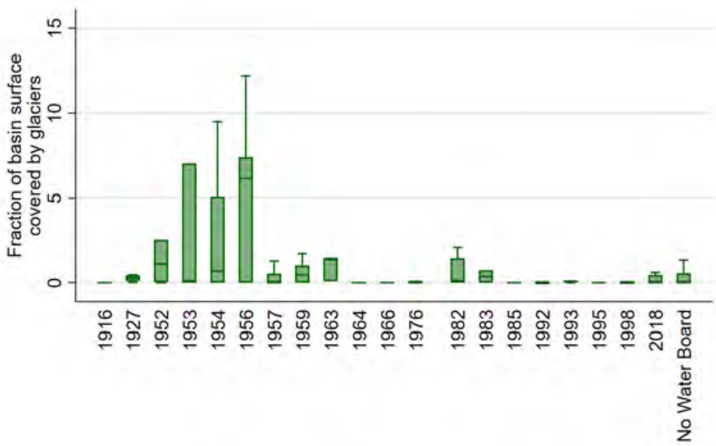
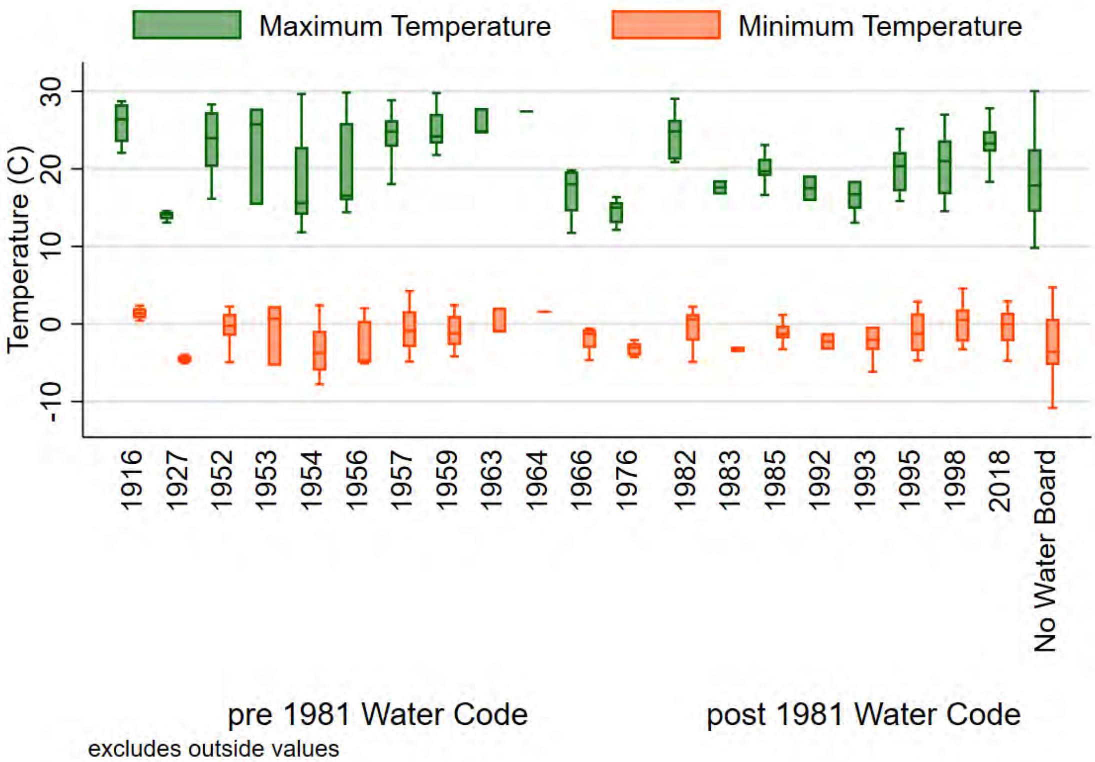


Figure B.II: Climatic and geographic characteristics, by year of establishment (cont.)



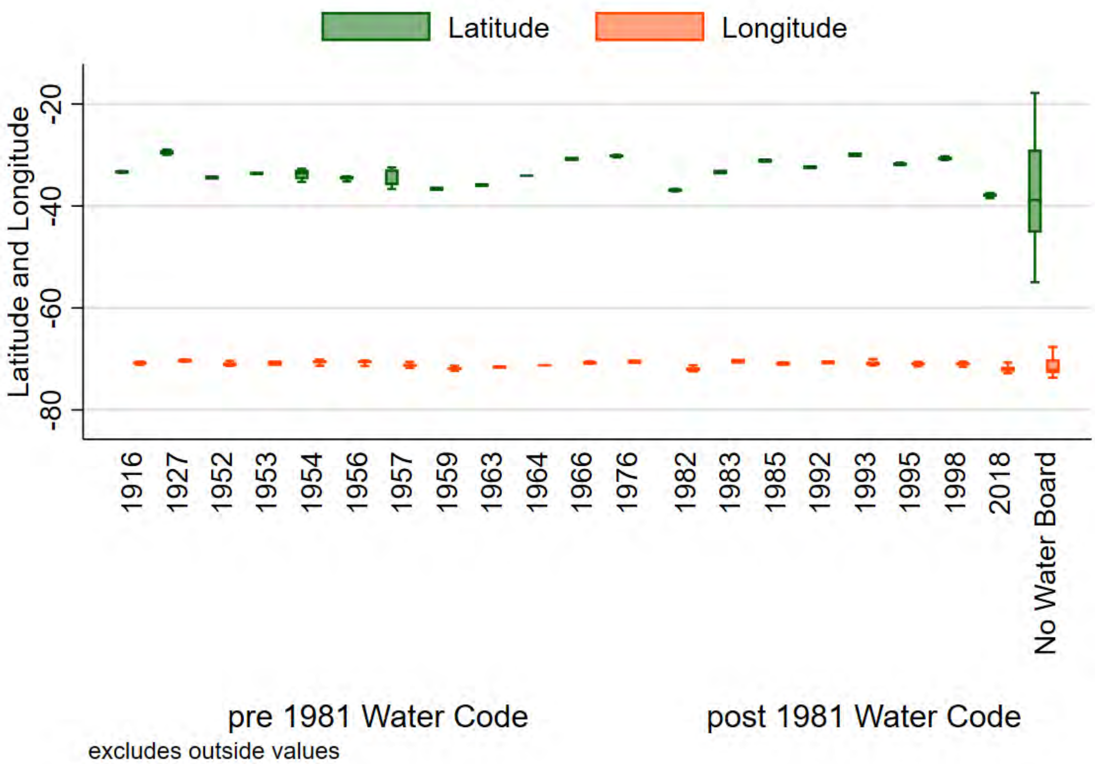
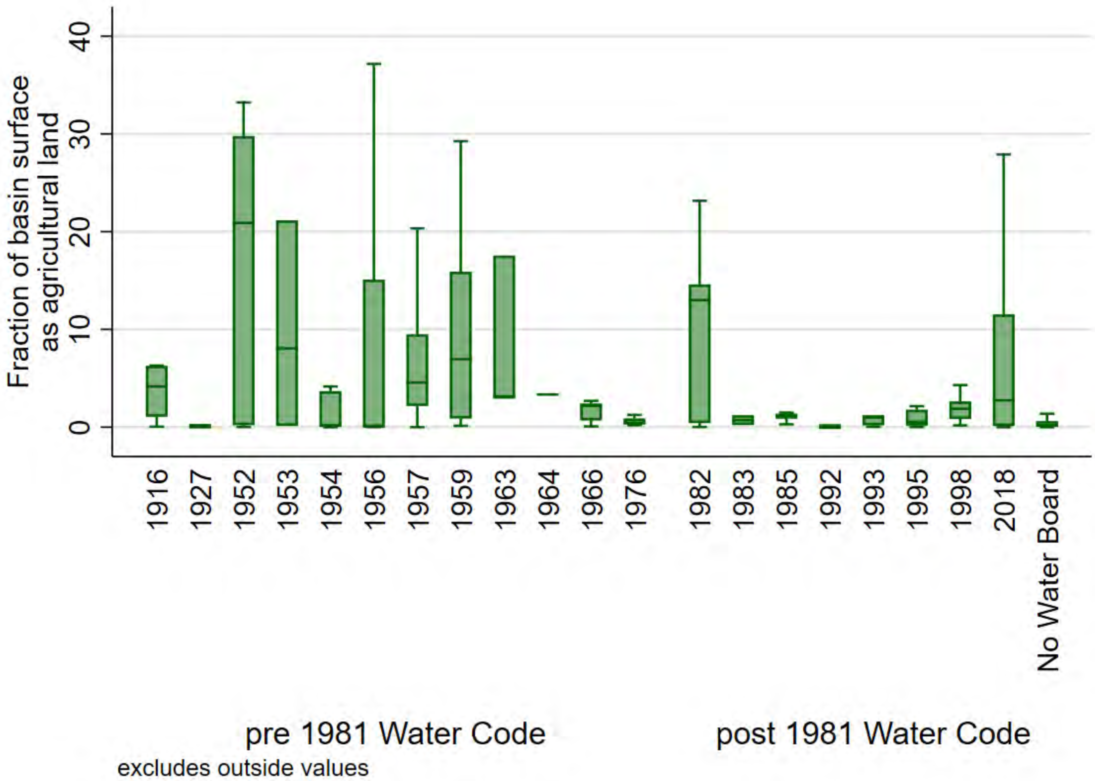
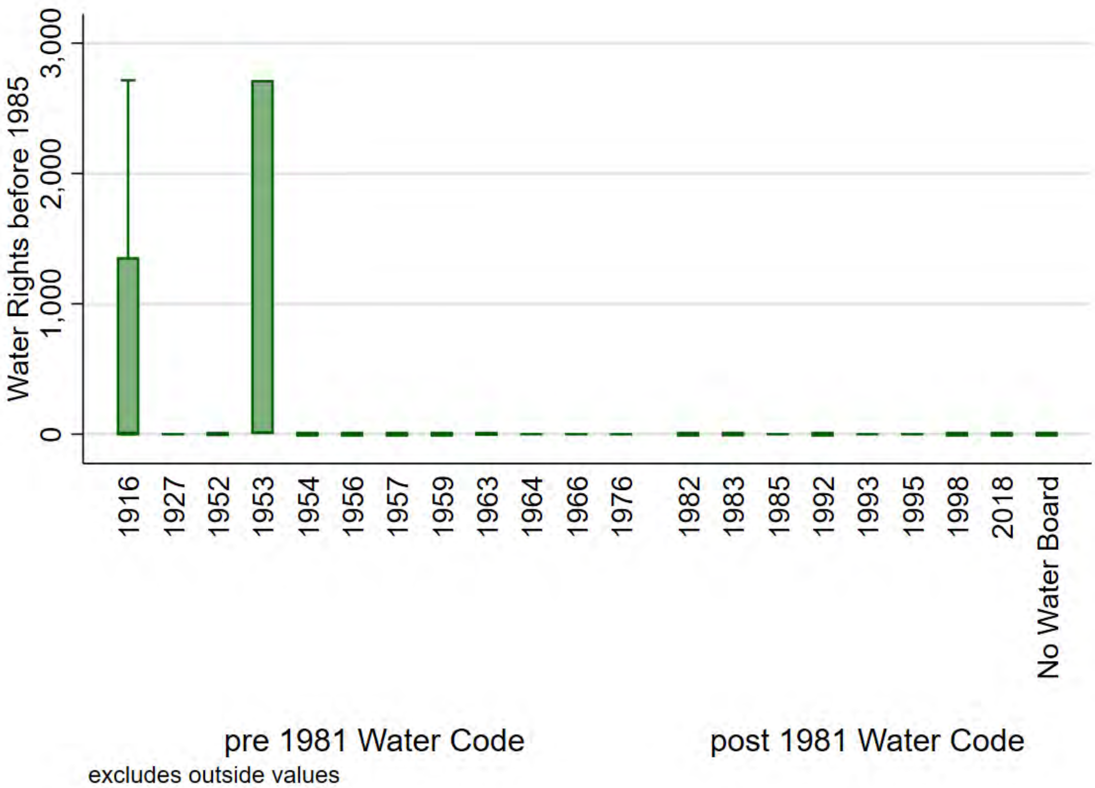


Figure B.III: Climatic and geographic characteristics, by year of establishment





C Appendix: Measuring Distances

This appendix details the calculations developed to determine spatial relationships between various entities (e.g., gauges, municipality irrigated areas, farms) along a river system, which we use to determine relative positions along rivers, i.e. downstream and upstream locations. It also describe measures of distance along road networks used to control for market access and create instrumental variable.

C.1 Distance to the River Mouth

This algorithm estimates how far each entity is from the river mouth, measured along the river's path. This measure is used later as in input to determine the relative position of entities in the river network. Along the way, it provides a first order approximation of the relative position of each entity in the river system: places close to the river mouth can be roughly said to be downstream while places far from the mouth can roughly said to be upstream.

C.1.1 Inputs

- A set of georeferenced points of interest. This is straightforward when the object of interest is approximately a point (e.g. a gauge). If the object of interest has a non-negligible area (e.g. farm, municipality's irrigated area), we use its point of inaccessibility as reference point.
- River network layer.
- River mouth coordinate.

C.1.2 Steps

1. Convert the river network into a set of points.
2. For each point of interest, find the closest point in the river. Call each of these points a river connecting point (rcp).

3. Rasterize the river. In the resulting raster, every pixel crossed by the river has a value of 1. The rest of the raster has null values.

4. Estimate the least cost path connecting each rcp to the mouth of the river, over the rasterized version of the river.

5. For each rcp, recover the length of its corresponding least cost path.

6. For each object of interest, assign the distance to the outfall from its corresponding rcp.

C.1.3 Output

For each object of interest we have its distance to the river mouth over the river network. This corresponds to the distance to the outfall from the point of the river that is closest to the object of interest. This process is illustated in figure C.I.

C.2 Distance Calculation over Road Network

This algorithm estimates distances between a set of points (e.g., farms) and key locations such as the upstream provincial capital within the basin, ports, and the national capital. The calculation is performed using the built-in least-cost-path tool in QGIS. The road network is represented by a rasterized layer of paved roads from 2014. To reflect the varying quality of road types, paved roads are assigned half the travel cost of other road types (e.g., dirt roads, stabilized roads, gravel roads). The algorithm then calculates the shortest path over the road network, ensuring that distances reflect actual travel paths rather than straight-line distances.

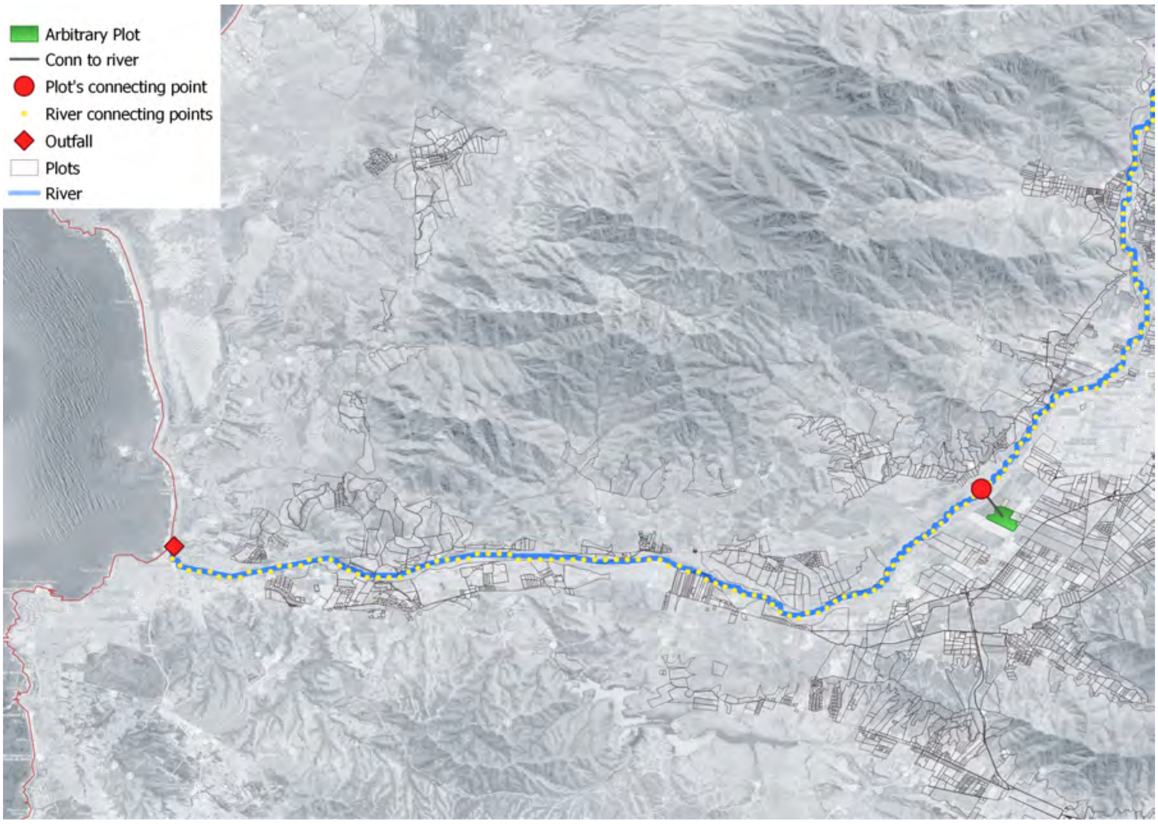


Figure C.I: Altorithm Illustratgion. An arbitrary area—shown in green—is connected to the closest point in the river, marked by a red circle. The distance assigned to this arbitrary object will be the distance along the river from the connecting point (red circle) to the river mouth or outfall (red square).