# Governing Environmental Markets: Evidence From Irrigation In Water Markets*

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March 28, 2025

**Abstract**

Water resources present a classic tragedy of the commons that is of increasing relevance due to 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 capacity of upstream users to over-extract. We show that these efficiency gains are a result of both water redistribution and individual adaptation, as 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 the analyzed property rights institution. Meanwhile, although upstream farmers reduce their water consumption, their productive outcomes remain unchanged. We also document increases in river streamflow during the irrigation season, concentrated in basins with higher agricultural activity. 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.*

*We are grateful to Ray Fisman, Martin Fiszbein, Dilip Mookherjee, Kevin Lang, Pedro Dal Bo, Stelios Michalopoulos, and Oded Galor for their invaluable guidance and support. We also thank Elias Cisneros and Xinming Du for their extensive comments and feedback. For helpful discussions and comments at different stages of this project, we thank Kelsey Jack, Matthew Turner, Wolfram Schlenker, Jonathan Colmer, Gemma Dipoppa, Kyle Emerick, Douglas Gollin, Ujjayant Chakravorty, Andrew Foster, Erzo F.P. Luttmer, Marc Rysman, Jihye Jeon, David Atkin, Amit Khandelwal, Kevin Donovan, Rocco Machiavello, Veronica Rappoport, Edward Rubin, Yanos Zylberberg, Francisco Gallego, Maximiliano Molina, Jorge Gironas, Pablo Mendoza, and many others. The paper benefited from comments by seminar participants at Boston University and Brown University, and conference participants at the RIDGE Long Run Growth and Environmental Economics 2023 workshops, the Chilean Economic Society 2023, the Econometric Society NASM 2024, NEUDC 2024, and the EAERE Summer School 2024. We are grateful to Juan F. Baquedano for excellent research assistance. The views expressed herein are entirely those of the authors and do not necessarily reflect the views of the Inter-American Development Bank, its Board of Directors, or the countries they represent.

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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 challenges around other common pool resources, 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 negative 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 further study how specialized enforcement institutions can improve their operation.

We study water allocation in 12 large-scale river basins in Chile, which share a unique institutional setting that 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., land, see 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 between users.

Our analysis shows 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 in-

dicating a Pareto inefficient allocation. To empirically assess whether this condition holds and where, 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 boards, 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 use census data alongside remote sensing-based estimates of water consumption, agricultural yields, and growing season length, all 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 simultaneously accounting for their relative position within the basin. To our knowledge, we are the first paper exploring the extent of redistribution caused by property rights enforcement explicitly.

To address endogeneity in Water Board formation, we construct an instrumental variable (IV) based on the cost of reaching the specific courts of competent jurisdiction to initiate Board establishment, which are irrelevant for other legal matters affecting downstream users. Our IV estimates reveal that property rights enforcement substantially impacts 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 ordinary least squares (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 enables 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 25% in the dry season, when incentives to over-extract are strongest. This effect is concentrated in areas where we expect more redistribution associated with enforcement.

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 this 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 its 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 the less discussed condition of enforcement, a consequence of Chile's 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 boards' 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 a 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 and the rivalry over its consumption (Ostrom and Gardner, 1993). This implies 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

[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

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 study, 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. According to Ostrom, this is achieved by introducing locally managed monitoring, enforcement and decision-making.[2] Most of the related literature has focused on testing the aforementioned 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). However, in the environment we are studying –distribution of water within basins encompassing several local communities–, these conditions do not apply.[3] This paper, therefore, empirically tests one of Ostrom'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, such as 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. Existing studies closest to our own include Rafey (2023), which 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), which estimates the efficiency losses from rationing groundwater relative to a counterfactual Pigouvian allocation, and Donna and Espín-Sánchez (2023), which studies how liquidity constraints may imply that markets are less efficient than a quota system for allocating water in Spain. This body

[2] 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.

[3] 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".

of work investigates 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 (e.g. Colmer et al., 2024; Greenstone et al., 2025). Our work complements this literature 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, which have prevented conventional methods to estimate productivity (e.g. Levinsohn and Petrin, 2003, used by Rafey (2023)) from being 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 impacts of water infrastructure. Duflo and Pande (2007) estimates the productivity and distributional impacts of dams using an instrumental variable approach, showing that although 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. (2023), using different identification strategies based on 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 to use 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), which use different methods

to characterize the extent to which adaptation can mitigate the agricultural costs of climate shocks. More recent contributions include Hagerty (2021), which studies farmers'short and long-term adaptations to water availability changes through crop and operation decisions. Our contribution is to document the complementarity of private investments and public goods, like property rights enforcement.

We additionally contribute to the literature on the economic consequences of natural resource 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 specifically rights over water. Most of the related work identifies misallocation caused by legal limits to the exercise of property rights, that translate into market frictions. Instead, 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 (e.g. Bauer, 2004).

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. Chari et al. (2021) shows that a property rights reform allowing farmers to lease out their land increases productivity and output by reallocating land towards more efficient producers. Manysheva (2022) quantifies the efficiency gains of land privatization in the presence of credit constraints. Our work shows that a necessary condition for realizing such efficiency gains is the proper enforcement of property rights under trade.

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 impacts vary by farm size. Section 6 further explores the water redistribution mechanisms by studying the impact of Water Boards on river streamflows. Section 7 presents our conclusions.

## 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 directly 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 its 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). The rugged topography makes the construction of infrastructure connecting basins extremely costly. In our analysis, 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 characterized as Mediterranean, with rainfall increasing in a North-South gradient; and a dry season extending from November to March. Rivers in this area are mostly fed by both rainfall and snowmelt (Varas and Varas, 2021; CNR, 2018a). This implies that rivers reach their maximum stream levels in the boreal winter and spring, then decline to reach 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 legally considered real estate, such that a water rights purchase is legally equivalent to a purchase of land (CNR, 2018a)[4]. 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; each of these attributes are defined during the creation of each water right. Figure A.I in Appendix A presents an example of a water right.

Water 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 regulatory agency in charge of assessing water resources and enforcing laws governing water issues. These rights can be generated 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. Water rights can be freely traded among both individuals and firms, without any interference by the government, and they are legally considered real estate (Biblioteca del Congreso Nacional, 1981).

The legal body that regulates water matters is the Water Code of 1981. Enforcement in principle relies on the DGA, which is supposed to address water stealing and over-extraction. However, Chile's higher courts have overruled and systematically limited the scope of DGA's enforcement capacities (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, 2018a). This coarse measure limits over-extraction in normal times by limiting the maximum water intake, but it does not during droughts: 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 cannot adapt accordingly.

[4]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, 2018a).

***Background on Water Boards.*** Droughts reduce the total stream flow, and Chilean law establishes that these reductions should be prorated proportionally among all users, such that a reduction of 50% of the total river streamflow should imply a 50% reduction in 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 20$^{\text{th}}$ century agricultural users created Water Boards as a representative body of water users (Peña, 2021). With the passing of the Water Code of 1981, Water Boards gained 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, while defining its own funding sources.

Water Boards enforce water allocations during droughts by implementing a system of irrigation shifts, in which the Boards calculate the number of days or hours of unrestricted irrigation that correspond to each farmer, given each farmer's water allotment and the total water available for distribution. The Boards enforce this delineated 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, pg. 77).

During their 2 or 3-year tenure, Water Boards report only to their constituents, who elect them with votes weighted by their Water Rights streamflow property. Water Boards are further subject to regulation by the DGA, but courts have curtailed the DGA's ability to intervene (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 by a lawsuit from 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.[5] 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.[6]. Figure VI presents flowcharts of how Water Boards relate to Chilean administrative (Figure VIa) and legal institutions (Figure VIb) on water matters. Administrative measures, such as cutting allotments in the context of drought, are decided by each Water Board, for water rights within their jurisdiction.[7] If any user wants to dispute a given 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 water source in question. [8] Part of the duties of a Water Board is to appoint a "Judge of Waters," who is usually part of the board or an employee of the Board. This judge has full authority to solve legal disputes and to enforce their rulings with the authority of the Water Board. In the absence of a Water Board, instead, the only option available to users is to initiate legal action through 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, and eventually can be escalated to the Supreme Court. Bauer (2004) discusses how higher courts lacked water-specific knowledge and how their rulings

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

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

[7] 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.

[8] 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.

have ignored substantive water issues, instead 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., 2015a) 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., 2015a). 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 maintains a network of 803 monitoring stations in rivers and canals across the country since 1913. Our main sample is composed by 306 of these stations that have been created before 1980 in the Study Area. $CR^2$ has identified the drainage areas of each monitoring station and their characteristics. These characteristics include the cultivated surface within the drainage area, and also the amount

of water rights created in the area each year.

# 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[9].

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

[9]We focus on the allocation of water rights instead of effective water because our setting has limited short-term (i.e. intra-seasonal) trading due to limited storage capacity in most basins (Bauer, 2004; Hadjigeorgalis and Lillywhite, 2004). Hence, most trading decisions happen when there is still uncertainty about how much water will be effectively available. Nevertheless, this analysis is equivalent to a first-order approximation to a similar analysis for the allocation of water itself.

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 $\theta$. 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:

**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[10].

[10] 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

***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 crop: The fixed inputs are chosen based on

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

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

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.

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 $\dfrac{\partial \bar{\pi}_i}{\partial \bar{w}_i} = \dfrac{\partial \bar{\pi}_j}{\partial \bar{w}_j}$, $\forall i, j \in N$[11]. 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

[11] 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.

of the Envelope Theorem.[12] 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 $\theta$ to be equal to 1.048 for annual irrigated crops, which is approximately equal to 1.[13]

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 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,

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

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

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.[14]

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.[15] $\mathbb{X}_i^{2007}$ 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

[14] 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.

[15] 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 B.

choices and the irrigated surface. $\text{Board}_c$ equals 1 if the farms belong to a county whose centroid falls inside the jurisdiction of a water board. Finally, $\mu_c$ is a county fixed effect, and $\mu_r$ 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 controls: basin fixed effects, $0.5 \times 0.5$-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 $0.5 \times 0.5$-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:

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

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

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

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 ($\beta_6$) 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[16].

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%

[16]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.

per extra cubic meter of water per hectare per month), which is approximately the same for farms located 200$km$ 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 find no effect of Water Boards on these farms.[17].

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 219$km$) 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

[17] 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

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 and irrigation technology choices.

Our analysis relies on a novel database, containing more than $75,000$ land 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, 2015a; Boser et al., 2024). In addition, we also estimate agricultural yield and crop choice using Enhanced Vegetation Index (EVI) estimates from LANDSAT 7. 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]

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. (2015a), 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

[18] The unit used corresponds to $mm$ of water evaporated per pixel, with pixels measuring $30m^2$.

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

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

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

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). $\mu_g$ is a basin fixed effect; in our implementation, we estimate equation 8 considering basin, sub-basin and sub-sub-basin fixed effects. 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. 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[20]. 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.

[20]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.

***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 lack of enforcement[21]. 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

[21] 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.

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 the presence of heterogeneous effects, but more importantly, to mitigate potential SUTVA violations[22] .

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[23].$\eta_g$ 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.

[22] 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.

[23] 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 midsection and upstream locations, instead, our main equation is

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

where $Mean(DistanceUpstreamCapital|downstream)$ is the average instrument for downstream locations; all other terms are the same as for downstream locations. We also control 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)[24].

***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[25].

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

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

[25] 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.

for farms located downstream, but a reduction of just 4% among upstream farms[26]. 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 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.

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

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[27]. To address concerns regarding the scale of each operation, we consider the average consumption of water per unit of area as our outcome measure.

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 from the river will be among the first ones to lose water access if water supply is insufficient. 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

[27] 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.

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 to demand the creation of a Water Board (from the perspective of downstream users). At the same time, large far-from-the-river downstream farms 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 successfully sue to establish 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. Under this interpretation, downstream elites are key to successfully establish Water Boards, and also to keep the river manager accountable for 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 X 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 XI 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[28]).

The outcome variable in Columns 1 to 4 of Table XII 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[29]. 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 $3pp$ less likely to use furrow technology. Our IV estimates, instead, show a reduction of $12pp$ in the use of traditional irrigation technologies. There is a statistically insignificant increase of $8pp$ in the use of micro-irrigation. Our IV estimates in Panel B, instead, show a significant reduction ($20pp$, statistically significant at 10%) in the use of traditional irrigation techniques among downstream large farms, accompanied by an equal increase ($21pp$, 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 irriga-

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

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

tion 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.

# 6 Basin Level Analysis

In this section, we show that Water Boards reallocate water at the basin scale. Using a Difference-in-differences design that leverages the staggered adoption of Water Boards across basins, we estimate the impacts of their introduction on river streamflows. Figures Ib and Ic illustrate the mechanism: when property rights are enforced during the dry season, water is redistributed from upstream to downstream users. This redistribution pattern implies that streamflow increases will be stronger 1) at upstream monitoring stations (those positioned between the upstream water diverters and downstream water users), compared to downstream monitoring stations (those positioned after most water users), and 2) in basins with more cultivated surface, where irrigation demand is higher and redistribution more valuable. In turn, we expect to find smaller or no impacts on streamflows the rest of the year, in downstream locations, and in areas with lower agricultural activity. Our empirical results are consistent with these predictions.

## 6.1 Identification

Our identification strategy exploits the staggered adoption of Water Boards across basins to estimate the causal impact of property rights enforcement on the spatial allocation of water. Table XIII presents the year of establishment of Water Boards for the monitoring stations within our area of study. Given the data available and the institutions in place, we focus our analysis on the boards established after 1981.

The first challenge in building counterfactual streamflows is to identify a proper set of control river segments. Two key features of rivers that may determine conflict around them are total streamflow and hydrologic regime. While the first is linked directly to water scarcity, the second attribute is linked to the temporal availability of water over the agricultural cycle. Figure XIIIa presents monthly averages of precipitation and streamflow before

1985 for rivers that eventually will host Water Boards, versus those rivers that will not: Water Boards are more likely to emerge in rivers with lower streamflow and precipitation, but relatively high Summer streamflow[30]. This season is when water is more needed for irrigation, especially for high-value crops and fruits that need year-round water input, as illustrated by Table A.I. Figure XIIIb confirms this seasonal demand pattern, showing that water deliveries by one Water Board to canals within its jurisdiction peak during Summer months. Given these long-run systematic differences between rivers with and without Water Boards, we provide estimates for the full sample of monitoring stations in the area, and also for our Event Study sample, which includes only monitoring stations located in areas that eventually adopt Water Boards, thereby relying on the timing of adoption for identification.

Our identification strategy assumes 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 counterfactual water demand, and so the differences in adoption timing are driven by long-term water availability. We do not expect them to be driven by short-term (e.g. 1 year) shocks, given the characteristics of this institution –permanent, coercive, and complex to establish[31].

One concern is that, if the establishment of a Water Board is triggered by drier conditions during a medium-run climatic cycles, we could observe spurious increases in streamflow after the establishment event due to mean reversion in precipitation. We explore explicitly the dynamic of precipitation around the establishment event in Figure XIV. Figures XIVa and XIVb show that this is not the case for the dry season–if anything, precipitations are *lower* after a Board establishment, ruling out this situation.

[30] This is the case of rivers with a nivo-glacial regime: their streamflow is at least partially fed by snow melting, and so, they will have relatively more water available in the Summer

[31] In a case of a Board establishment in 2015, just the lawsuit that created the Water Board took at least one year. This happened after undocumented conversations among irrigators organizations and attempts to solve basin-level conflicts with other economics sectors CNR (2018b). Moreover, all these processes would have taken longer in the 1990s, where most of the Board establishment events took place, due to improvements in telecommunications and transportation infrastructure.

***Difference-in-Differences design for River Streamflows.*** Our main equation is:

$$\begin{aligned} \text{Stream}_{gmt} = \sum_{i=-3}^{3} \delta_i \text{Board Establishment}_{gst} \times 1\left[t - t^* = i\right] \\ + \beta \text{X}_{gmt} + \gamma \text{WR}_{gmt} + \mu_t + \eta_{gm} + \varepsilon_{gmt} \end{aligned} \tag{11}$$

where $\text{Stream}_{gmt}$ is the streamflow at monitoring station $g$ in month $m$ and year $t$, and $\text{Board}_{gt}$ equals 1 if segment $g$ is under Water Board jurisdiction in year $t$. $t^*$ denotes the Water Board establishment year with jurisdiction over $g$. $\text{X}_{gsmt}$ is a vector of monthly climatic characteristics, including linear and quadratic terms for rainfall and average maximum temperature, average minimum temperature, and potential evapotranspiration. $\text{WR}_{gmt}$ corresponds to total Water Rights claimed in the area draining towards $g$. $\mu_t$ and $\eta_{gm}$ are year and station-month fixed effects, accounting for seasonality at the station level[32].

One challenge is the potential endogeneity of water rights: Water Boards can provide better monitoring, and so to stop the creation of new water rights that may interfere with preexisting ones[33]. We address this concern by reporting estimates both including and excluding water rights. Our results are not sensitive to their inclusion.

To account for possible heterogeneous treatment effects, we use the staggered difference-in-differences estimator proposed by Borusyak et al. (2024). This approach handles heterogeneous effects in a context of staggered adoption, and provides a standard errors estimator that allows for correct coverage under clustering and small sample size.

## 6.2 Water Boards Impacts on Streamflows

Our results show that Water Boards significantly increase river streamflows during the dry season, consistent with effective water redistribution from upstream to downstream users. Figure XV presents our main estimates of the effect of Water Board establishment on summer streamflows. For our treated-only sample (Figure XVb), we observe statistically significant increases in streamflow for summers two and three years after the introduction of Water Boards. On average, these effects represent an increase of approximately 25%

[32] Equation 11 are derived from a water balance equation, where the inflows equalize outflows in a basin.
[33] In our sample, we do not find evidence of this effect.

in streamflow. When averaging across all post-establishment years (0 to 3), we find an increase of 13%. The Full Sample estimates (Figure XVa) yield similar results in both sign and magnitude: years 2 and 3 show a 27% increase in streamflow, while the average across years 0 to 3 shows a 16% increase. Importantly, we find no evidence of pre-trends in either sample, supporting our identification assumptions. These summer-specific effects contrast sharply with our estimates for the entire year (Figure A.II), where no coefficient is statistically significant, although for our Event Study sample, most pre-trend coefficients are negative while most post-event coefficients are positive.

These results reflect large scale redistribution of water in the short run. Assuming that half of the streamflow during the Summer is used for irrigation, then the 25% increase found in years 2 and 3 is consistent with an increase of 50% on water consumption among downstream farms, which aligns with our estimates in Section 5. Long-run adaptation may create differences between the redistribution implied by our DID estimates and the long-run effects, estimated in Section 5.

***Heterogeneous effects by geographical characteristics.*** To further test our predictions, we examine how impacts vary by location within the basin and by agricultural intensity. Figure XVI presents our estimates of heterogeneous effects. The upper panel shows effects by basin location, while the lower panel shows effects by cropland area. The upper left panel, (Figure XVIa) displays impacts for upstream monitoring stations, while the upper right panel (Figure XVIb) shows the board impacts for downstream monitoring stations. Our results reveal that absolute increases in streamflow for 2 and 3 years after the establishment at upstream stations are approximately double those at downstream stations. Since upstream stations have a larger streamflow, the estimates correspond to average effects at years 2 and 3 of approximately 28% at upstream areas, and 25% at downstream.

In the bottom panel of Figure XVI we compare our estimates of impacts for monitoring stations in areas with high cropland share (Figure XVIc) and low cropland share (Figure XVId). In high cropland areas areas, Water Boards have positive impacts on every year after their establishment, while for low cropland share areas the effects are negative (but not significant) in the first years, and smaller in magnitud for years 2 and 3. Since stations

in high cropland areas have lower baseline streamflows, the average increase over four years is about 28%, and over 40% for years 2 and 3. For low cropland share areas, instead, the increase is just 6% over the 4 years, and 20% for years 2 and 3.

Finally, in XVII, we present separate estimates for the four groups that can be defined by the combinations of these categories. While downstream-low cropland share group of stations do not show any increase in streamflow (Figure XVIIa), the strongest increases happened for upstream-high cropland share stations (Figure XVIIb). Monitoring stations in either downstream-high cropland share (Figure XVIIc) and upstream-low cropland share (Figure XVIId) present significant effects, too.

Our results show that Water Boards significantly increase streamflows at the basin scale, with impacts varying by location and agricultural intensity. The observed patterns–stronger effects upstream, in cropland-rich areas, and during dry seasons–support our interpretation that this reflects the spatial reallocation of water by Water Boards, to enforce property rights. This is a key mechanism to understand the spatial differences in efficiency found in Section 4, and productivity in Section 5.

## 7 Conclusions

In this paper, we examine how specialized enforcement institutions affect water markets' allocative efficiency, even in contexts with well-defined property rights that are 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. By contrast, we find evidence of misallocation in areas without such Boards, such that downstream users face higher shadow values due to upstream over-extraction. Using various identification strategies and measures, we further explore how Water Boards' enforcement creates net economic gains through extensive water redistribution that enables private investments.

Our analysis of Water Boards provides novel insights into the challenges of establishing environmental markets. The operation of these markets must overcome subtractability and

high monitoring and enforcement costs–resource attributes that lead to the Tragedy of the Commons. While water is a leading example of a resource subject to this issue, similar characteristics are present in many others, including fisheries and atmospheric emissions. Surface water offers a unique analytical advantage: the directional nature of surface water flows allows for clear identification of affected agents and precise measurement of redistribution. This directionality may explain why water boards are effective: with a single entity maintaining both accountability and authority, it creates strong incentives for downstream users to invest in basin-wide enforcement. This highlights how market design challenges differ across resources: similar decentralized institutions may prove less effective where such incentives are weak.

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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## References


Alesina, A. and Rodrik, D. (1994). Distributive politics and economic growth. *The Quarterly Journal of Economics*, 109(2):465–490.

Allen, R. G., Morton, C., Kamble, B., Kilic, A., Huntington, J., Thau, D., Gorelick, N., Erickson, T., Moore, R., Trezza, R., and others (2015a). EEFlux: A Landsat-based evapotranspiration mapping tool on the Google Earth Engine. In *2015 ASABE/IA Irrigation Symposium: Emerging Technologies for Sustainable Irrigation-A Tribute to the Career of Terry Howell, Sr. Conference Proceedings*, pages 1–11. American Society of Agricultural and Biological Engineers.

Allen, R. G., Morton, C., Kamble, B., Kilic, A., Huntington, J., Thau, D., Gorelick, N., Erickson, T., Moore, R., Trezza, R., and others (2015b). EEFlux: A Landsat-based evapotranspiration mapping tool on the Google Earth Engine. In *2015 ASABE/IA Irrigation Symposium: Emerging Technologies for Sustainable Irrigation-A Tribute to the Career of Terry Howell, Sr. Conference Proceedings*, pages 1–11. American Society of Agricultural and Biological Engineers.

Allen, R. G., Tasumi, M., and Trezza, R. (2007). Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Model. *J. Irrig. Drain Eng.*, 133(4):380–394.

Alvarez-Garreton, C., Mendoza, P., Boisier, J. P., Addor, N., Galleguillos, M., Zambrano-Bigiarini, M., Lara, A., Puelma, C., Cortes, G., Garreaud, R., McPhee, J., and Ayala, A. (2018). The CAMELS-CL dataset: Catchment attributes and meteorology for large sample studies-Chile dataset. *Hydrology and Earth System Sciences*, 22(11):5817–5846. Publisher: Copernicus GmbH.

Andrews, I., Stock, J., and Sun, L. (2019). Weak Instruments in IV Regression: Theory and Practice. *Annual Review of Economics.*, 2019(11):727–753.

Angrist, J. and Pischke, J.-S. (2009). *Mostly harmless econometrics: an empiricists guide*. Princeton University Press, Princeton.

Asher, S., Campion, A., Gollin, D., and Novosad, P. (2022). The Long-Run Development

Impacts of Agricultural Productivity Gains: Evidence from Irrigation Canals in India.

Banerjee, A., Mookherjee, D., Munshi, K., and Ray, D. (2001). Inequality, Control Rights, and Rent Seeking: Sugar Cooperatives in Maharashtra. Publication Title: Journal of Political Economy Volume: 109 Issue: 1.

Bardhan, P. and Mookherjee, D. (2000). Capture and Governance at Local and National Levels. *American Economic Review*, 90(2):135–139.

Bauer, C. J. (2004). *Siren Song Chilean Water Law As a Model for International Reform.* Resources for the Future Press. Publication Title: Siren song: Chilean water law as a model for international reform.

Besley, T. and Burgess, R. (2000). Land Reform, Poverty Reduction, and Growth: Evidence from India*. *The Quarterly Journal of Economics*, 115(2):389–430.

Biblioteca del Congreso Nacional (1981). Codigo de Aguas (DFL-1122). Publisher: Ministerio de Justicia Place: Santiago de Chile.

Blakeslee, D., Dar, A., Fishman, R., Malik, S., Pellegrina, H. S., and Bagavathinathan, K. S. (2023). Irrigation and the spatial pattern of local economic development in India. *Journal of Development Economics*, 161:102997.

Borusyak, K., Jaravel, X., and Spiess, J. (2024). Revisiting event-study designs: robust and efficient estimation. *Review of Economic Studies*, 91(6):3253–3285.

Boser, A., Caylor, K., Larsen, A., Pascolini-Campbell, M., Reager, J. T., and Carleton, T. (2024). Field-scale crop water consumption estimates reveal potential water savings in california agriculture. *Nature Communications*, 15(1):2366.

Burke, M. and Emerick, K. (2016). Adaptation to climate change: Evidence from US agriculture. *American Economic Journal: Economic Policy*, 8(3):106–140. Publisher: American Economic Association.

Cardenas, J. C. and Carpenter, J. (2008). Behavioural Development Economics: Lessons from Field Labs in the Developing World. *The Journal of Development Studies*, 44(3):311–338. Publisher: Routledge _eprint: https://doi.org/10.1080/00220380701848327.

Chari, A., Liu, E. M., Wang, S. Y., and Wang, Y. (2021). Property Rights, Land Misalloca-

tion, and Agricultural Efficiency in China. *Review of Economic Studies*, 88(4):1831–1862. Publisher: Oxford University Press.

CNR (2018a). Manual avanzado para profesionales de las organizaciones de usuarios de aguas. Technical report, CNR. Publication Title: CNR-0468.

CNR (2018b). Manual intermedio para dirigentes de organizaciones de usuarios de aguas. Technical report, Comision Nacional de Riego. Publication Title: CNR-0470.

Coase, R. H. (1960). The problem of social cost. *Journal of Law and Economics*, 4(16):1–44.

Colmer, J., Martin, R., Muûls, M., and Wagner, U. J. (2024). Does pricing carbon mitigate climate change? firm-level evidence from the european union emissions trading system. *The Review of Economic Studies*, page rdae055.

Cárdenas, J.-C. and Ostrom, E. (2004). What do people bring into the game? Experiments in the field about cooperation in the commons. *Agricultural Systems*, 82(3):307–326.

De Janvry, A., Emerick, K., Gonzalez-Navarro, M., and Sadoulet, E. (2015). Delinking land rights from land use: Certification and migration in Mexico. *American Economic Review*, 105(10):3125–3149. Publisher: American Economic Association.

Deryugina, T. and Hsiang, S. (2017). The Marginal Product of Climate. Technical report, National Bureau of Economic Research, Cambridge, MA.

Deryugina, T., Moore, F., and Tol, R. S. J. (2021). Environmental applications of the Coase Theorem. *Environmental Science and Policy*, 120:81–88.

Donna, J. and Espín-Sánchez, J. A. (2023). The Illiquidity of Water Markets. Technical report, Elsevier BV. Publication Title: SSRN Electronic Journal.

Duflo, E. and Pande, R. (2007). Dams*. *The Quarterly Journal of Economics*, 122(2):601–646.

Fernández, B. and Gironás, J. (2021). *Water Resources of Chile*, volume 8. Springer International Publishing, Cham. Series Title: World Water Resources.

Greenstone, M., Pande, R., Ryan, N., and Sudarshan, A. (2025). Can pollution markets work in developing countries? experimental evidence from india*. *The Quarterly Journal of Economics*, page qjaf009.

Hadjigeorgalis, E. and Lillywhite, J. (2004). The impact of institutional constraints on the limarí river valley water market. *Water Resources Research*, 40(5).

Hagerty, N. (2021). Adaptation to surface water scarcity in irrigated agriculture. *Working paper*.

Hardin, G. (1968). The Tragedy of the Commons. *Source: Science, New Series*, 162(3859):1243–1248.

Henrich, J., McElreath, R., Barr, A., Ensminger, J., Barrett, C., Bolyanatz, A., Cardenas, J. C., Michael, G., Edwins, G., Henrich, N., Lesorogol, C., Marlowe, F., Tracer, D., and Ziker, J. (2006). Costly Punishment Across Human Societies. *Science*, 312(5781):1767–1770.

Hsiang, S. (2016). Climate Econometrics. *Annual Review of Resource Economics*, 8(1):43–75. Publisher: Annual Reviews.

Intergovernmental Panel On Climate Change (2023). *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 1 edition.

Kala, N. (2019). Learning, Adaptation and Climate Uncertainty: Evidence from Indian Agriculture. Technical report.

Karlan, D., Osei, R., Osei-Akoto, I., and Udry, C. (2014). Agricultural Decisions after Relaxing Credit and Risk Constraints *. *The Quarterly Journal of Economics*, 129(2):597–652.

Kleibergen, F. and Paap, R. (2006). Generalized reduced rank tests using the singular value decomposition. *Journal of Econometrics*, 133(1):97–126.

Lobell, D. B., Roberts, M. J., Schlenker, W., Braun, N., Little, B. B., Rejesus, R. M., and Hammer, G. L. (2014). Greater Sensitivity to Drought Accompanies Maize Yield Increase in the U.S. Midwest. *Science*, 344(6183):516–519. Publisher: American Association for the Advancement of Science.

Manysheva, K. (2022). Land Property Rights, Financial Frictions, and Resource Allocation in Developing Countries *. Technical report.

Medema, S. G. (2020). The Coase Theorem at Sixty. *Journal of Economic Literature*,

58(4):1045–1128.

Meinzen-Dick, R. (2007). Beyond panaceas in water institutions. *Proceedings of the National Academy of Sciences*, 104(39):15200–15205. Publisher: National Academy of Sciences ISBN: 0702296104.

Olea, J. L. M. and Pflueger, C. (2013). A Robust Test for Weak Instruments. *Journal of Business & Economic Statistics*, 31(3):358–369. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/00401706.2013.806694.

Ostrom, E. (1990). *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge University Press. Publication Title: Governing the Commons.

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, 325(5939):419–422.

Ostrom, E. (2010). Beyond Markets and States: Polycentric Governance of Complex Economic Systems. *American Economic Review*, 100(3):641–72.

Ostrom, E. and Gardner, R. (1993). Coping with Asymmetries in the Commons: Self-Governing Irrigation Systems Can Work. *Journal of Economic Perspectives*, 7(4):93–112. Publisher: American Economic Association.

Peña, H. (2021). River Basin Policy and Management. pages 229–242.

Rafey, W. (2023). Droughts, Deluges, and (River) Diversions: Valuing Market-Based Water Reallocation. *American Economic Review*, 113(2):430–71.

Ryan, N. and Sudarshan, A. (2022). Rationing the Commons. *Journal of Political Economy*, 130(1):210–257.

Schlenker, W., Hanemann, W. M., and Fisher, A. C. (2005). Will U.S. Agriculture Really Benefit from Global Warming? Accounting for Irrigation in the Hedonic Approach. Technical report. Volume: 95 Issue: 1.

Tamayo, T. and Carmona, A. (2019). *El negocio del agua: Cómo Chile se convirtió en tierra seca*. Penguin Random House Grupo Editorial Chile. Google-Books-ID: VBy_DwAAQBAJ.

Varas, E. C. and Varas, E. V. (2021). Surface Water Resources. pages 61–92.

World Bank (2011a). Chile: Diagnóstico de la gestión de los recursos hídricos. Technical report, World Bank, Washington, DC.

World Bank (2011b). Chile: Diagnóstico de la gestión de los recursos hídricos. Technical report, World Bank, Washington, DC.

World Bank (2021). El agua en Chile: Elemento de desarrollo y resiliencia. Technical report, World Bank, Washington, DC.

# Tables

Table I: Balance Table for Misallocation Test

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 for Irrigated Farms, by Treatment Status

| | Outcome is log(Value Yield p/Hectare) | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| 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) m5 | (2) m6 | (3) m7 | (4) 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=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

Panel A: Parcels Not Under Water Board Jurisdiction

| | 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 | | | | | |

Panel B: Parcels Under Water Board Jurisdiction

| | 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 | | | | | |

*Notes:* This table presents summary statistics for agricultural parcels, separated by water board jurisdiction status. Panel A shows statistics for parcels not under the jurisdiction of the water board, while Panel B shows statistics for parcels under jurisdiction.

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

Panel A: Main Result

| | 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 |
| AR test CI | | | | [.5718, 4.547] | (-∞, ∞) | [-.8887, -.2858] |

Panel B: First Stage

| | (1) Downstream | (2) Mid section | (3) Upstream |
|---|---|---|---|
| inst | -0.00527 | 0.00982 | 0.0413 |
| | (0.00128)*** | (0.00624) | (0.00535)*** |
| Observations | 26,792 | 26,138 | 25,539 |
| R-squared | 0.408 | 0.423 | 0.575 |
| Effective F-stat | 16.856 | 2.473 | 59.704 |

*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

Panel A: Main Result

| | 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 |
| AR test CI | | | | [.03535, .399] | (-$\infty$, $\infty$) | [-.06594, .01147] |

Panel B: First Stage

| | (1) Downstream | (2) Mid section | (3) Upstream |
|---|---|---|---|
| inst | -0.00527 | 0.00982 | 0.0413 |
| | (0.00128)*** | (0.00624) | (0.00535)*** |
| Observations | 26,792 | 26,138 | 25,539 |
| R-squared | 0.408 | 0.423 | 0.575 |
| Effective F-stat | 16.840 | 2.473 | 59.704 |

*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

Panel A: Main Result

| | 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 |
| AR test CI | [-.1069, 4.618] | (-∞, ∞) | [-1.123, -.3446] | [1.455, 10.91] | [-30.76, ∞) | [-.5604, .04246] |

Panel B: First Stage

| | Small Farms | | | Large Farms | | |
|---|---|---|---|---|---|---|
| | (1) Downstream | (2) Mid section | (3) Upstream | (4) Downstream | (5) Mid section | (6) Upstream |
| inst | -0.00465 | 0.00706 | 0.0398 | -0.00525 | 0.0138 | 0.0453 |
| | (0.00139)*** | (0.00623) | (0.00533)*** | (0.00177)*** | (0.00713)* | (0.00580)*** |
| Observations | 14,571 | 12,021 | 11,386 | 6,270 | 7,427 | 7,447 |
| R-squared | 0.389 | 0.428 | 0.608 | 0.461 | 0.423 | 0.567 |
| Effective F-stat | 11.286 | 1.286 | 55.629 | 8.796 | 3.767 | 61.049 |

*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

Panel A: Main Result

| | 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 |
| AR test CI | [-.03417, .3998] | (-∞, ∞) | [-.07747, -.008775] | [.1157, .9683] | [-3.291, ∞) | [-.04862, .04783] |

Panel B: First Stage

| | Small Farms) | | | Large Farms | | |
|---|---|---|---|---|---|---|
| | (1) Downstream | (2) Mid section | (3) Upstream | (4) Downstream | (5) Mid section | (6) Upstream |
| inst | -0.00465 | 0.00706 | 0.0398 | -0.00525 | 0.0138 | 0.0453 |
| | (0.00139)*** | (0.00623) | (0.00533)*** | (0.00177)*** | (0.00713)* | (0.00580)*** |
| Observations | 14,571 | 12,021 | 11,386 | 6,270 | 7,427 | 7,447 |
| R-squared | 0.389 | 0.428 | 0.608 | 0.461 | 0.423 | 0.567 |
| Effective F-stat | 11.286 | 1.286 | 55.629 | 8.796 | 3.767 | 61.049 |

*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 Parcel 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] | (-∞, ∞) | [-.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] | (-∞, ∞) | [-.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 Season Length: Instrumental Variables Estimation at the Parcel Level

Panel A: Outcome is 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] | (-∞, ∞) | [-.4383, -.16] | [.4041, 2.393] | [-8.959, ∞) | [-.2661, .01938] |

Panel B: Outcome is 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] | (-∞, ∞) | [-.5923, -.008238] | [.6186, 7.43] | [-35.78, ∞) | [-.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 XII: 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.

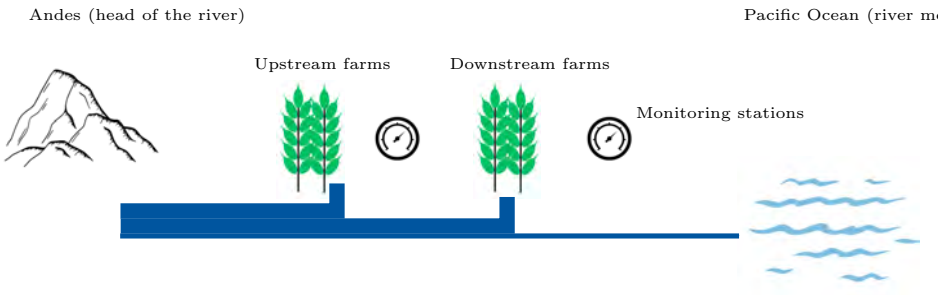
Table XIII: Monitoring Stations by Year of Board Establishment

| Year | $N$ segments | Percent | Cumulative perc. |
|---|---|---|---|
| 1974 | 1 | 0.33 | 0.33 |
| 1989 | 12 | 3.96 | 4.29 |
| 1993 | 10 | 3.30 | 7.59 |
| 1994 | 20 | 6.60 | 14.19 |
| 1995 | 4 | 1.32 | 15.51 |
| 1996 | 38 | 12.54 | 28.05 |
| 1997 | 6 | 1.98 | 30.03 |
| 1998 | 14 | 4.62 | 34.65 |
| 1999 | 62 | 20.46 | 55.12 |
| 2000 | 10 | 3.30 | 58.42 |
| 2001 | 11 | 3.63 | 62.05 |
| 2004 | 1 | 0.33 | 62.38 |
| 2005 | 3 | 0.99 | 63.37 |
| 2013 | 1 | 0.33 | 63.70 |
| 2018 | 5 | 1.65 | 65.35 |
| 2019 | 22 | 7.26 | 72.61 |
| No Board | 83 | 27.39 | 100.00 |
| Total | 303 | 100.00 | |
| Observations | 303 | | |

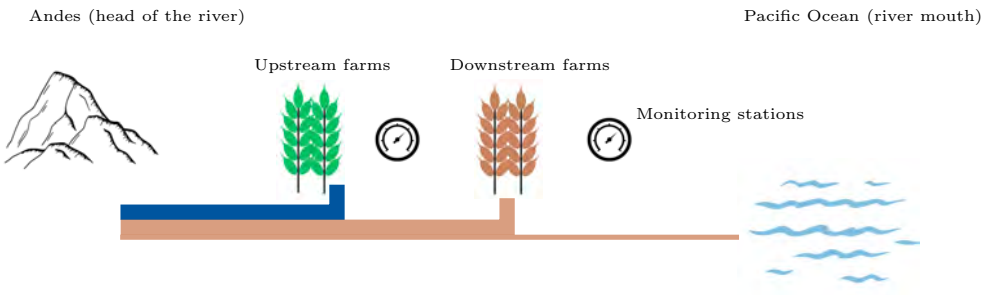
*Notes:* This table shows the total number of monitoring stations in our area of study, and the establishment date of a water board (in case the monitoring station is in a subsubbasin within the jurisdiction of a water board).

# Figures

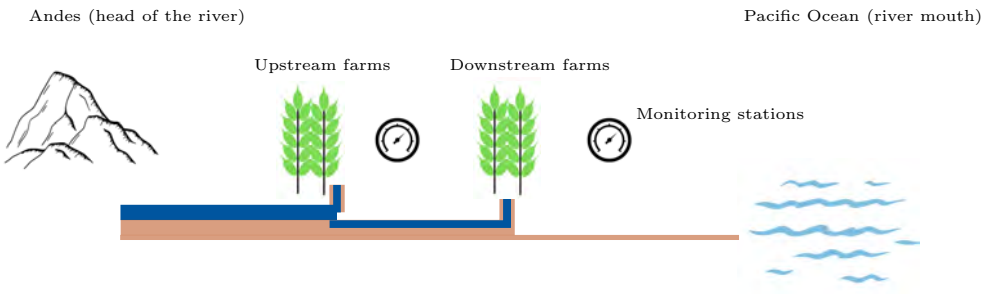
Figure I: How Property Rights Enforcement Affects Water Allocation and Agricultural Outcomes




(a) No drought

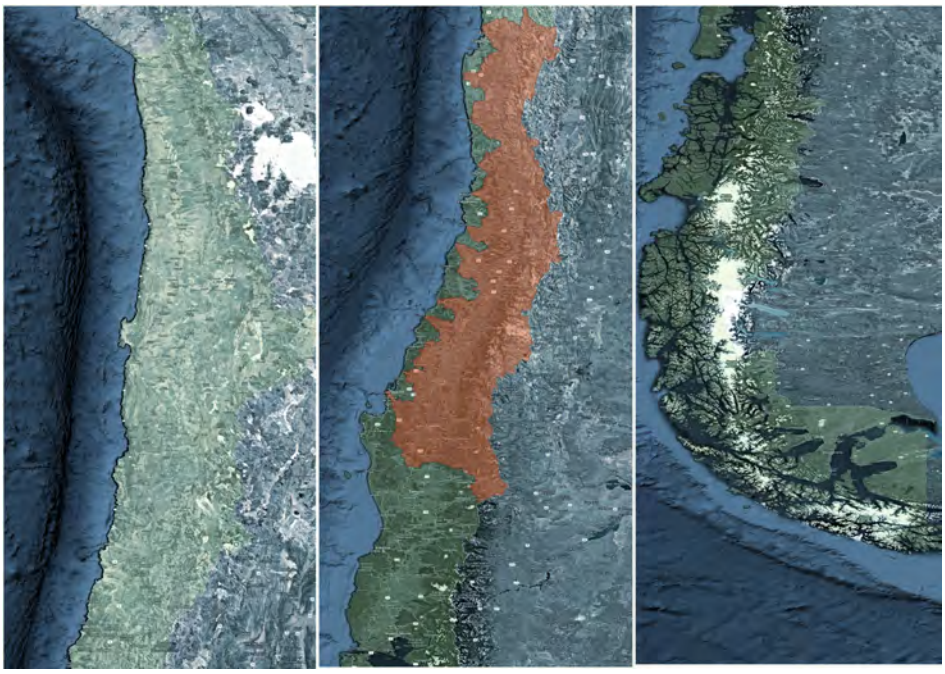



(b) Drought, and no enforcement of water rights




(c) Drought, and Water Boards enforce water rights

Figure II: Area of Study



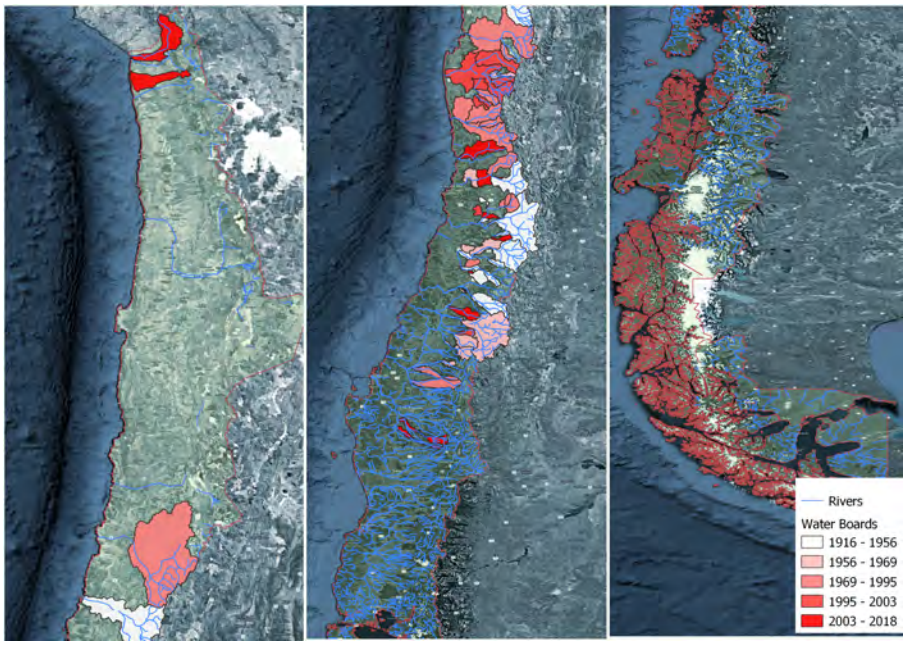
*Notes:* Left, center, and right panels correspond to the northern, central, and southern areas of Chile. The colored region represents the total area of study.

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.

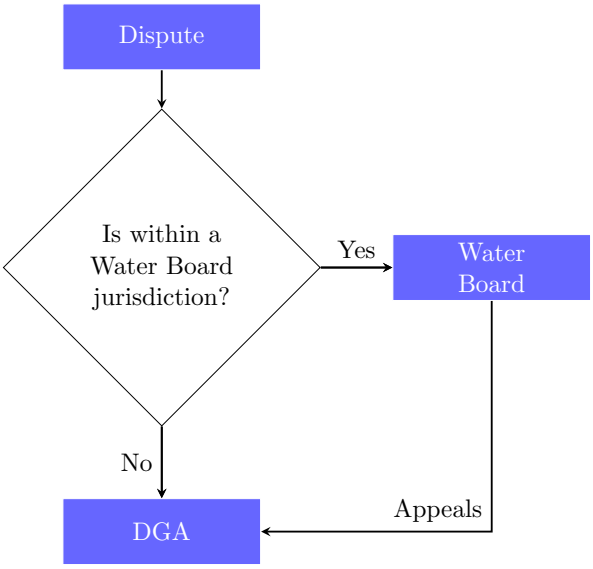
Figure V: Example of Canal Gate



*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

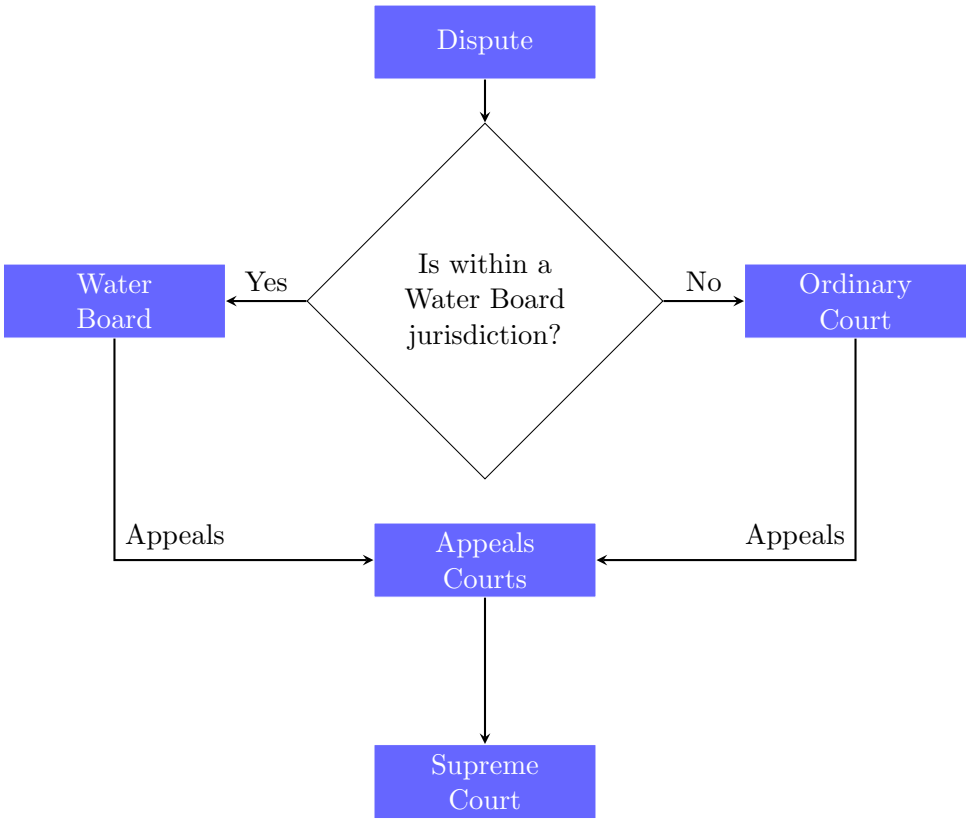
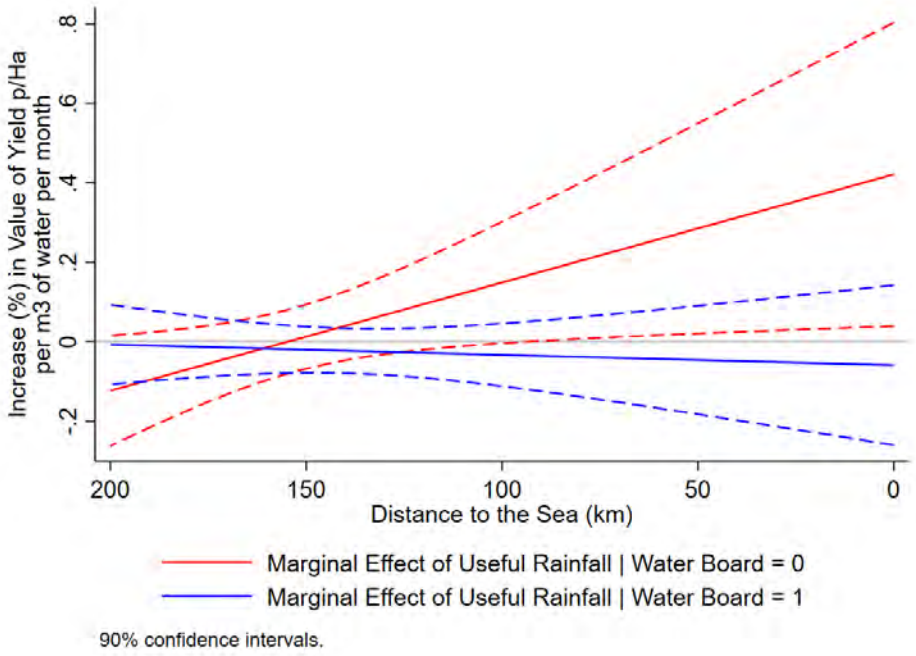
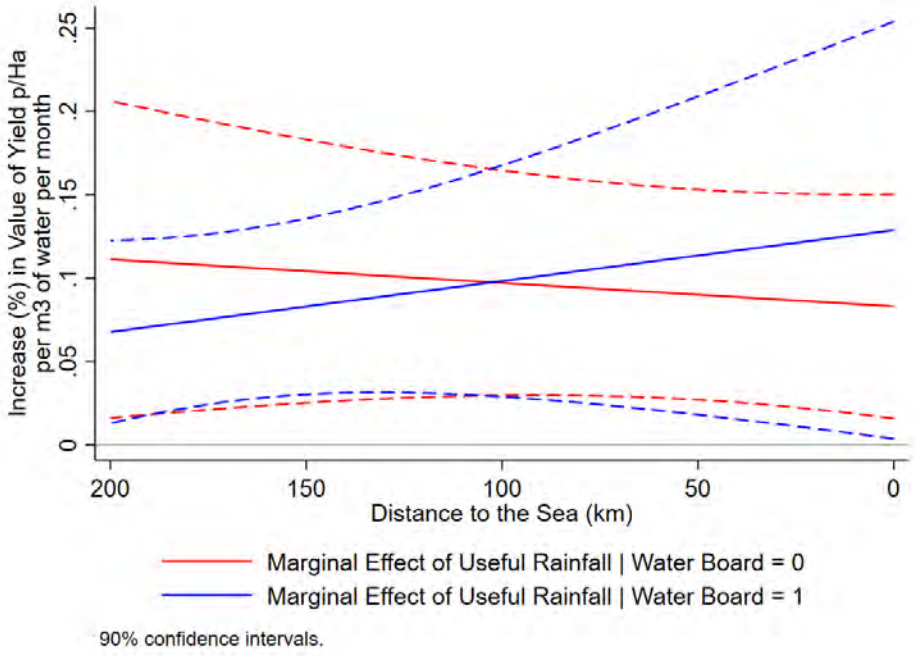


Figure VII: Main Results: Effect on log(Production) of Rainfall during the Irrigation Season by Longitude and Treatment Status for Irrigated Parcels Registered in Canal




*Notes:* Graphical representation of results in Table II.

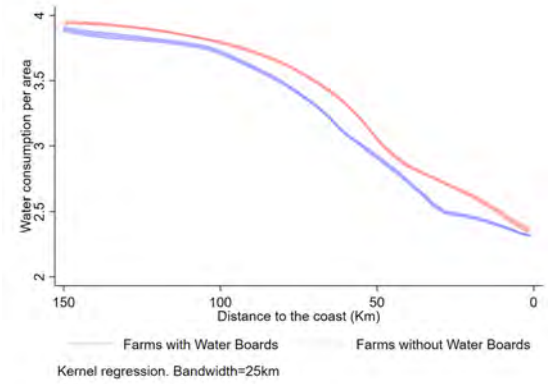
Figure VIII: Placebo Exercise: Effect on log(Production) of Rainfall during the Irrigation Season by Longitude and Treatment Status for Rainfed Parcels



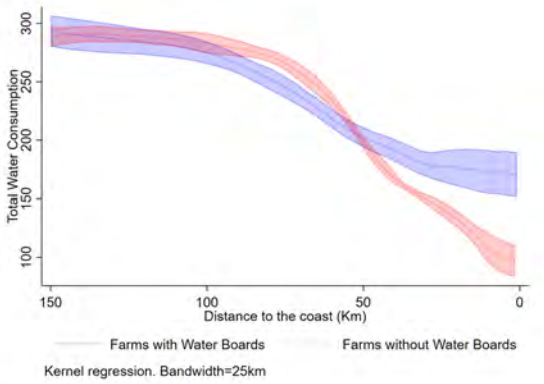

*Notes:* Graphical representation of results in Table III.

Figure X: Non-parametric Regressions of Water Consumption Measures on Distance to the Coast

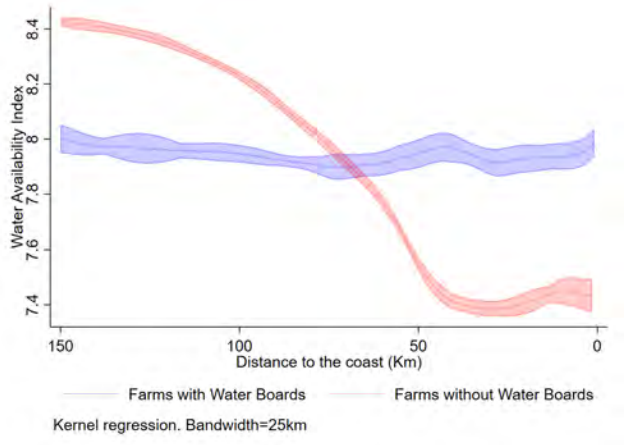
(a) Average (per $m^2$) Evapotranspiration during Summer vs Farm Location within Basin




(b) Total Evapotranspiration during Summer vs Farm Location within Basin



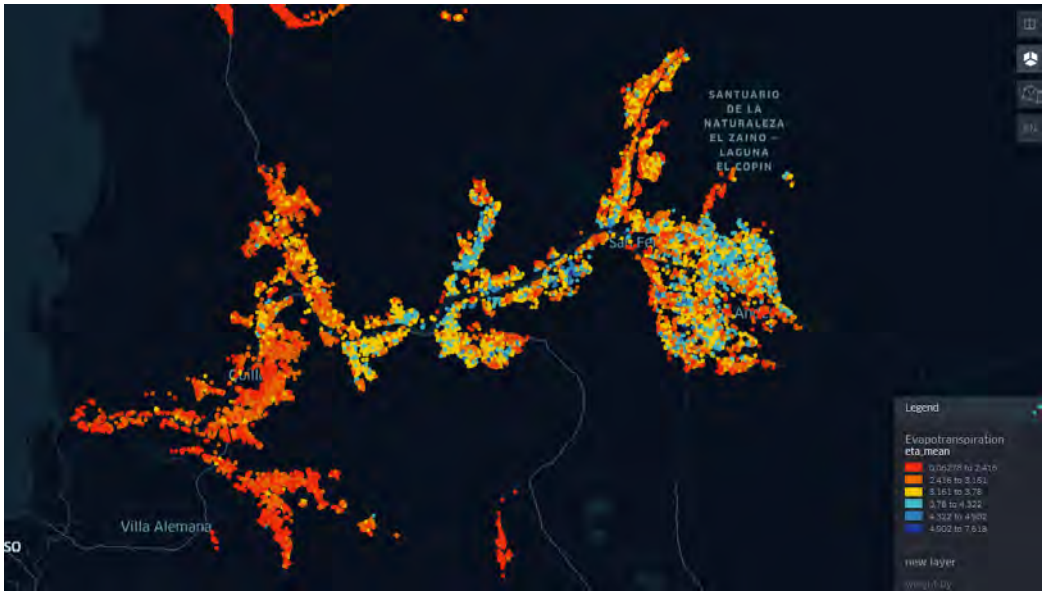

(c) Water Availability Index vs Farm Location within Basin



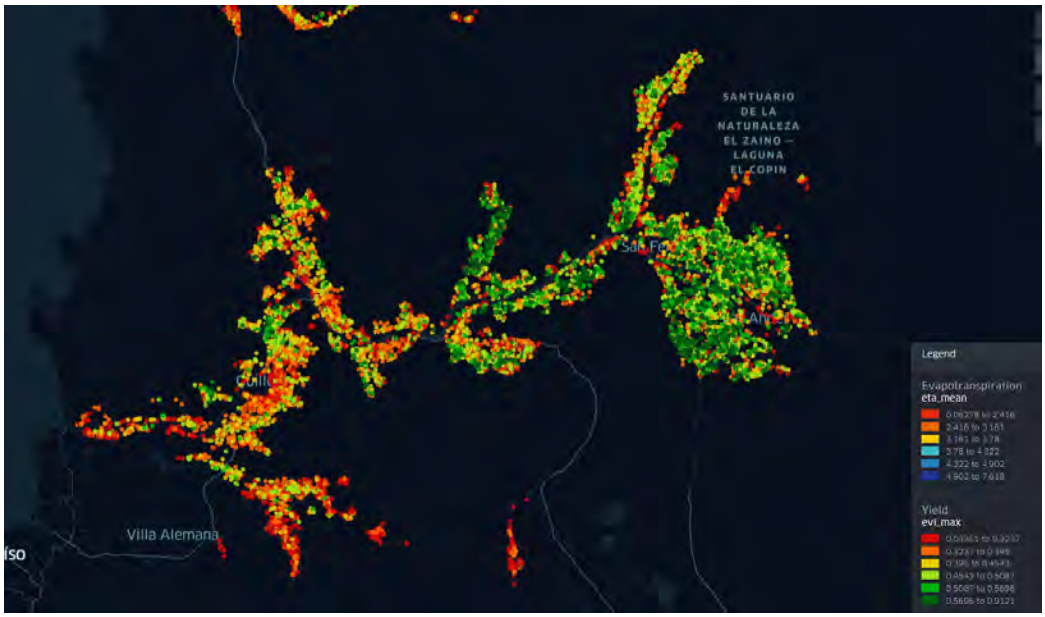

*Notes:* This figure presents local polynomial regressions of three water consumption measures on distance to the Coast, separately by treatment assignment, for farms located less than 150km from the coast. The outcome in Panel A is estimated water consumption per surface. The outcome in Panel B is the total estimated water consumption. Panel C outcome is the Water Availability Index (estimated water consumption per surface divided by NDVI during the summer; the inverse of the Hydric Stress Index presented by Allen et al. (2015b)). Epanechnikov kernel, Bandwidth of 25km, and polynomial of degree 0.

Figure IX: Example: Water Consumption and Agricultural Yield Estimates for Farms in Aconcagua Basin

(a) Water Consumption

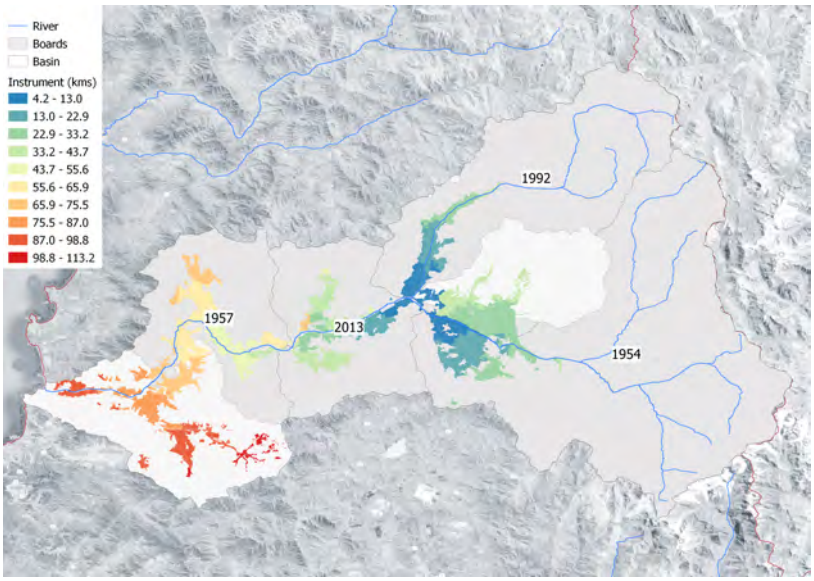



(b) Agricultural Yield



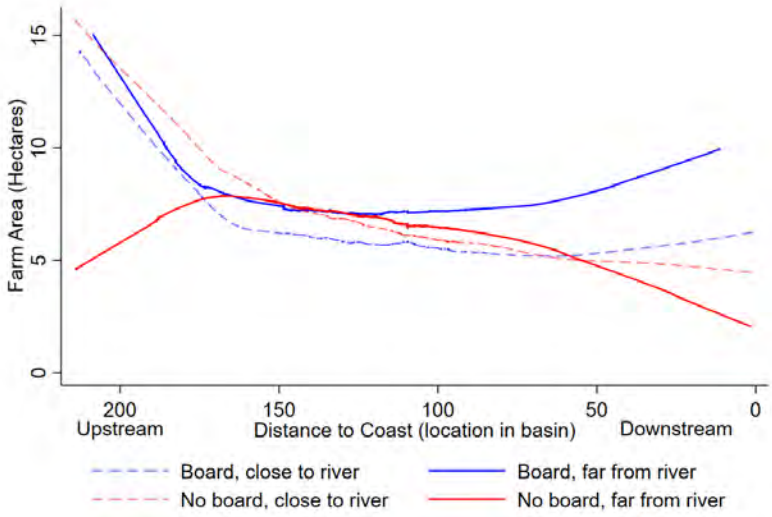

*Notes:* Panel (a) shows estimated water consumption (evapotranspiration) and panel (b) shows agricultural yield (using Enhanced Vegetation Index) for farms in the Aconcagua Basin.

Figure XI: Example: Farm Level Data and Distance to Most Upstream in Aconcagua Basin 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.

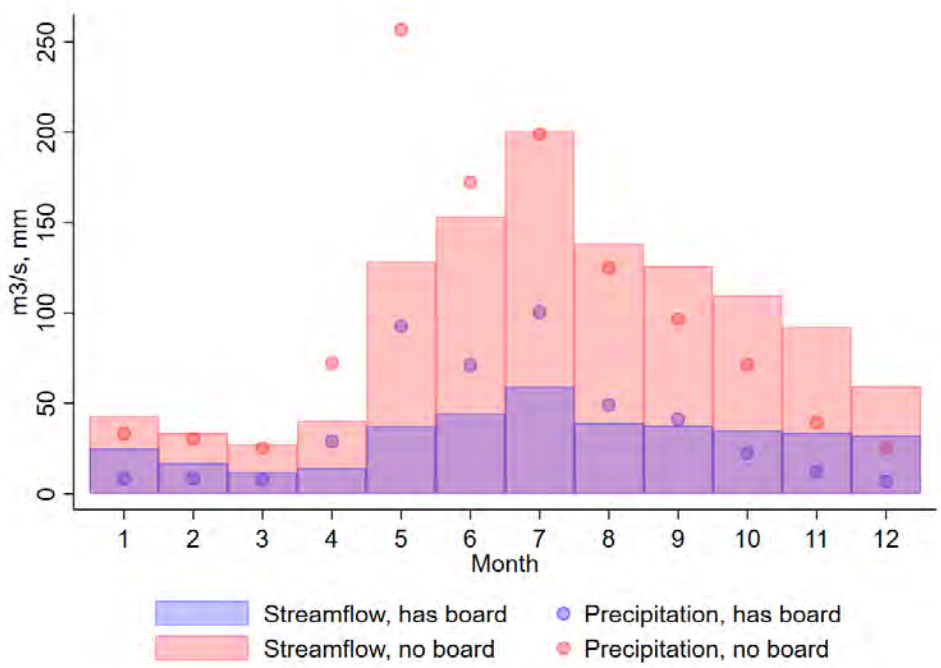
Figure XII: Farm Size Distribution across Locations



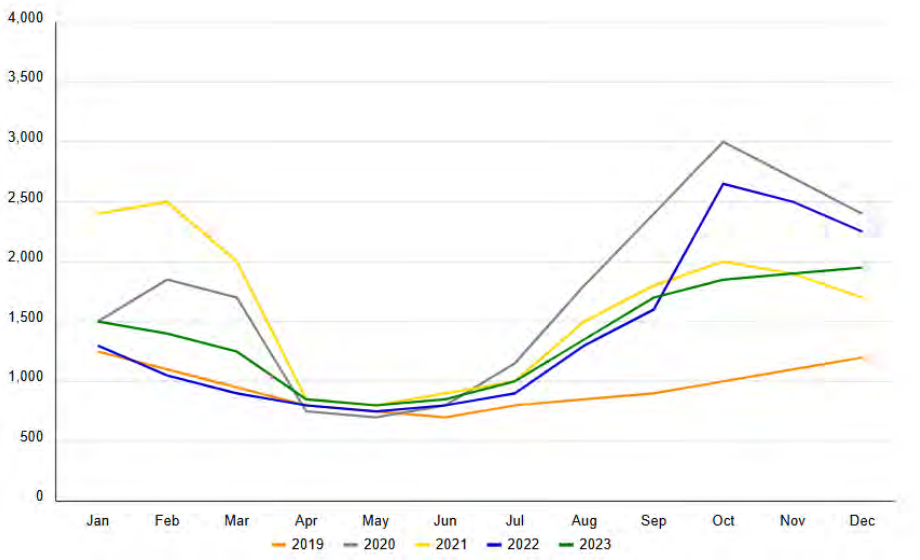

*Notes:* This figure shows average farm size by location in the basin, comparing farms close to the river ($< 3.5km$) and far from the river ($> 3.5km$). Only farms in basins with at least one water board present are included. Upstream locations are shown on the right side and downstream locations on the left.

Figure XIII: Comparing rivers with and without Water Boards

(a) Average Streamflow and Precipitation Within and Outside Water Board Jurisdictions, Pre-1985

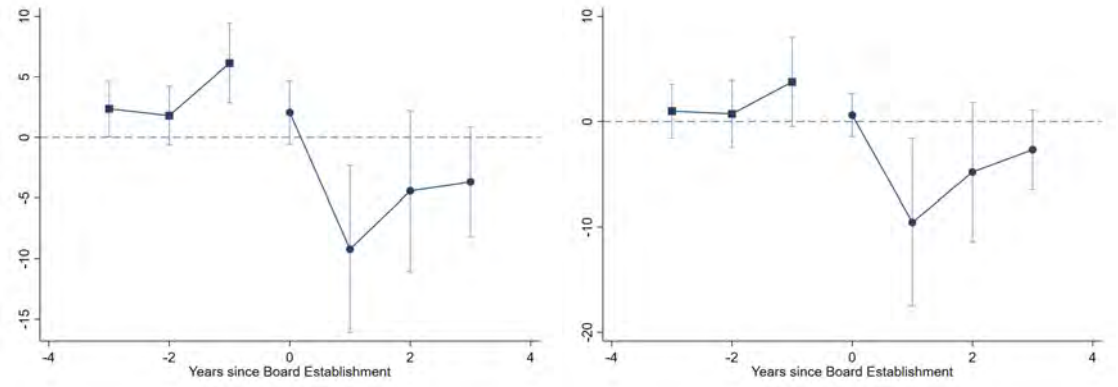



(b) Water Distribution by El Arrayan Water Board to Governed Canals, 2019-2023




*Notes:* Panel (a) shows average streamflow and precipitation in monitoring stations within and outside water board jurisdictions before 1985. Source: Authors' calculation. Panel (b) displays water distribution by El Arrayan Water Board to governed canals from 2019-2023, measured in liters per second. Source: https://jmapocho.cl/reparto-total/. Captured on November 7, 2023.

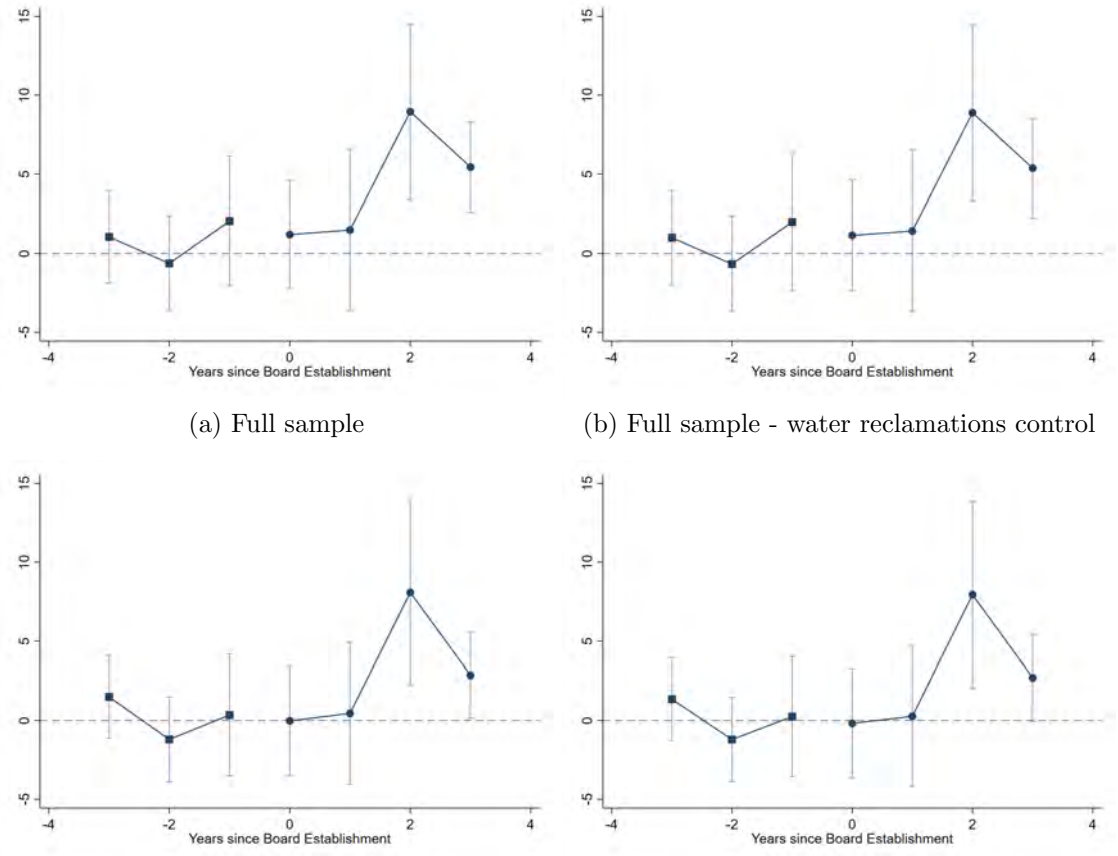
Figure XIV: Precipitations and Board Establishment Events (Placebo) Event




(a) Full sample (b) Event Study sample

*Notes:* This figure presents the dynamics of precipitation around Water Board establishment events, using the Event Study estimator by Borusyak, Jaravel and Spiess (2024). The Full Sample correspond to monitoring stations located in the Study Region, while the Event Study sample only includes eventually treated monitoring stations (i.e. monitoring stations located in subsubbasins within Water Boards jurisdictions). Controlling for monitoring station-month and year fixed effects. Standard errors estimated using Borusyak, Jaravel and Spiess (2024) leave-one-out procedure, clustering at the hydrological basin level and allowing for effects heterogeneity based on 4 groups by longitudinal distance to the coast and agricultural land share in the drainage area of each monitoring station.

Figure XV: Dynamic Effects of Board Establishment Events on Dry Season Streamflow




(a) Full sample

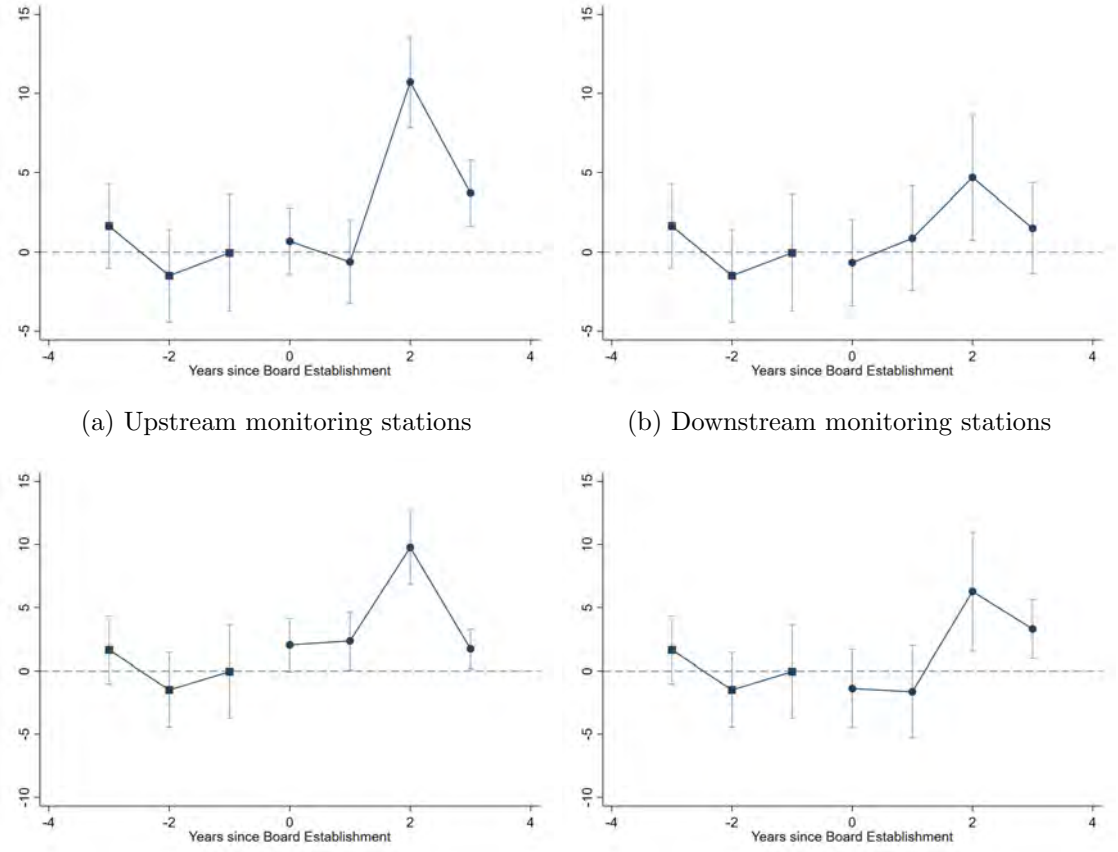
(b) Full sample - water reclamations control

(c) Event Study sample

(d) Event Study sample - water reclamations control

*Notes:* This figure presents our main estimates of the impact of Water Board establishment events on streamflows, using the Event Study estimator by Borusyak, Jaravel and Spiess (2024). The Full Sample correspond to monitoring stations located in the Study Region, while the Event Study sample only includes eventually treated monitoring stations (i.e. monitoring stations located in subsubbasins within Water Boards jurisdictions). Controlling for monthly climatic measures in the drainage area of each monitoring station (linear and squared terms for precipitation and average maximum temperature,, average minimum temperature, and potential evapotranspiration) and monitoring station-month and year fixed effects. Standard errors estimated using Borusyak, Jaravel and Spiess (2024) leave-one-out procedure, clustering at the hydrological basin level and allowing for effects heterogeneity based on 4 groups by longitudinal distance to the coast and agricultural land share in the drainage area of each monitoring station.

Figure XVI: Heterogeneous Effects on Dry Season Streamflow by Location and Cropland Share




(a) Upstream monitoring stations

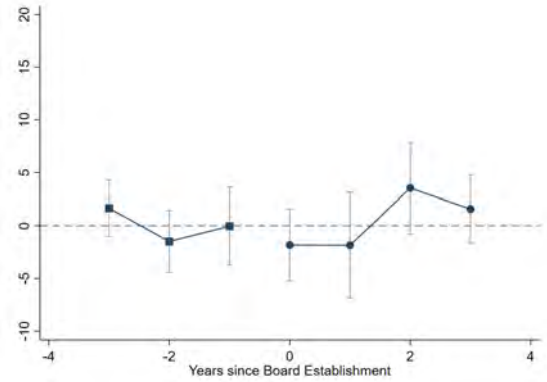
(b) Downstream monitoring stations

(c) Above median cropland share

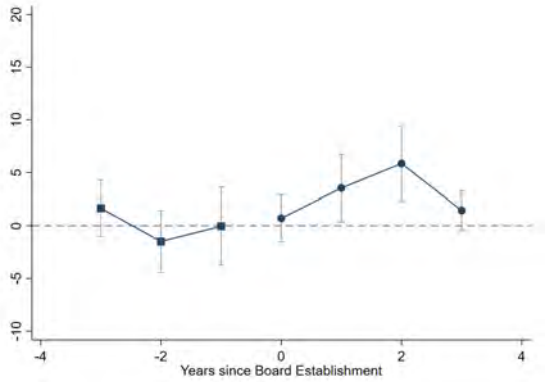
(d) Below median cropland share

*Notes:* This figure presents our heterogeneous effects estimates of the impact of Water Board establishment events on streamflows, using the Event Study estimator by Borusyak, Jaravel and Spiess (2024). All estimates correspond to the Event Study sample (eventually treated monitoring stations, i.e. monitoring stations located in subsubbasins within Water Boards jurisdictions). Upper panels present heterogeneous impacts according to longitudinal distance to the coast: upstream (Panel A) versus downstream (Panel B) monitoring stations. Lower panels present heterogeneous impacts according to share of cropland in the drainage area: monitoring stations with above median cropland share (Panel C) versus those with below median cropland share (Panel D). Controlling for monthly climatic measures in the drainage area of each monitoring station (linear and squared terms for precipitation and average maximum temperature, average minimum temperature, and potential evapotranspiration) and monitoring station-month and year fixed effects. Standard errors estimated using Borusyak, Jaravel and Spiess (2024) leave-one-out procedure, clustering at the hydrological basin level and allowing for effects heterogeneity based on 4 groups by longitudinal distance to the coast and agricultural land share in the drainage area of each monitoring station.

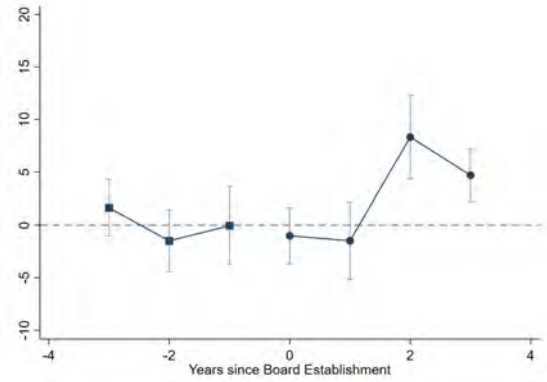
Figure XVII: Heterogeneous Effects on Dry Season Streamflow by Location-Cropland Combinations



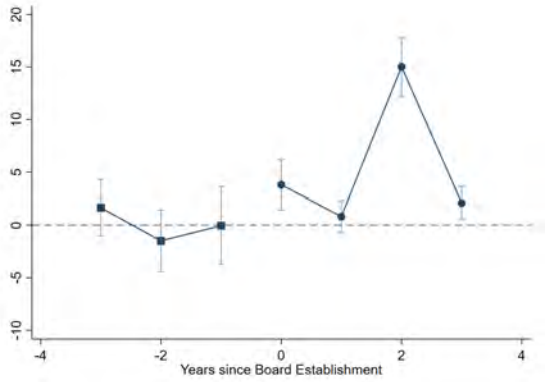

(a) Downstream farms with low cropland share




(b) Upstream farms with low cropland share




(c) Downstream farms with high cropland share

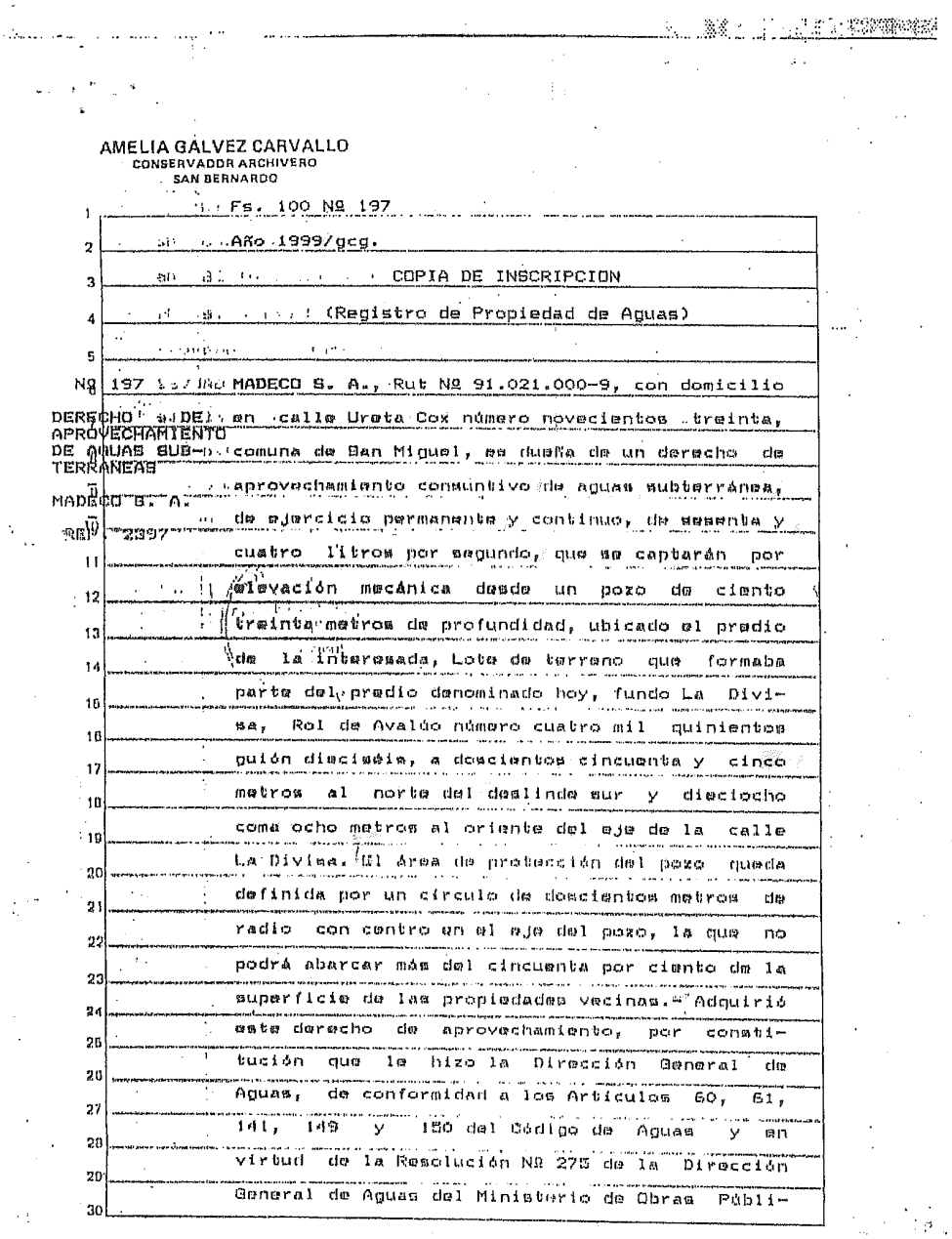



(d) Upstream farms with high cropland share

*Notes:* This figure presents our heterogeneous effects estimates of the impact of Water Board establishment events on streamflows, using the Event Study estimator by Borusyak, Jaravel and Spiess (2024). All estimates correspond to the Event Study sample (eventually treated monitoring stations, i.e. monitoring stations located in subsubbasins within Water Boards jurisdictions). The panels show the interaction between geographical location and agricultural intensity: downstream farms with low cropland share (Panel A), upstream farms with low cropland share (Panel B), downstream farms with high cropland share (Panel C), and upstream farms with high cropland share (Panel D). Controlling for monthly climatic measures in the drainage area of each monitoring station (linear and squared terms for precipitation and average maximum temperature, average minimum temperature, and potential evapotranspiration) and monitoring station-month and year fixed effects. Standard errors estimated using Borusyak, Jaravel and Spiess (2024) leave-one-out procedure, clustering at the hydrological basin level and allowing for effects heterogeneity based on 4 groups by longitudinal distance to the coast and agricultural land share in the drainage area of each monitoring station.

# A Appendix

Figure A.I: Example: Water Right Title



AMELIA GALVEZ CARVALLO
CONSERVADOR ARCHIVERO
SAN BERNARDO

Fs. 100 Nº 197

Año 1999/gcg.

COPIA DE INSCRIPCION

(Registro de Propiedad de Aguas)

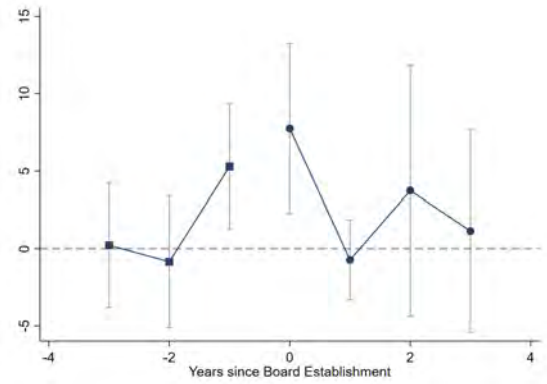
Nº 197 MADECO S. A., Rut Nº 91.021.000-9, con domicilio en calle Ureta Cox número novecientos treinta, comuna de San Miguel, es dueña de un derecho de aprovechamiento consuntivo de aguas subterránea, de ejercicio permanente y continuo, de sesenta y cuatro litros por segundo, que se captarán por elevación 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-

DERECHO DE APROVECHAMIENTO DE AGUAS SUB-TERRANEAS

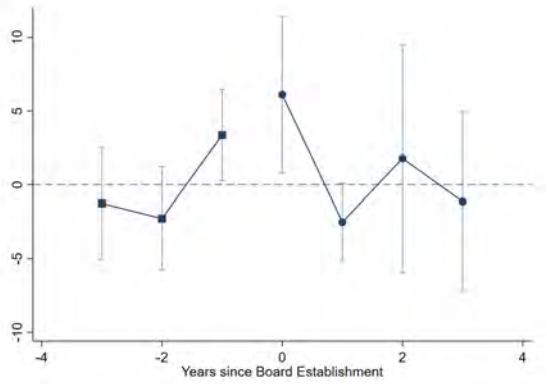
MADECO S. A.

REM 2397

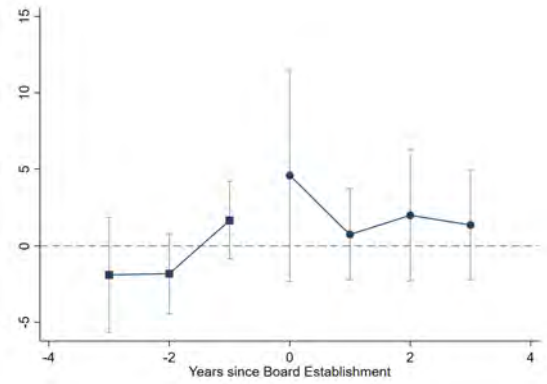
Figure A.II: Dynamic Effects of Board Establishment Events on Streamflow - Full Year



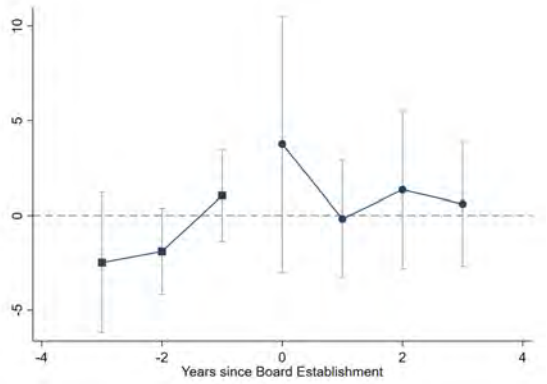

(a) Full sample




(b) Full sample - water reclamations control




(c) Event Study sample




(d) Event Study sample - water reclamations control

*Notes:* This figure presents our main estimates of the impact of Water Board establishment events on streamflows, using the Event Study estimator by Borusyak, Jaravel and Spiess (2024). The Full Sample correspond to monitoring stations located in the Study Region, while the Event Study sample only includes eventually treated monitoring stations (i.e. monitoring stations located in subsubbasins within Water Boards jurisdictions). Controlling for monthly climatic measures in the drainage area of each monitoring station (linear and squared terms for precipitation and average maximum temperature, average minimum temperature, and potential evapotranspiration) and monitoring station-month and year fixed effects. Standard errors estimated using Borusyak, Jaravel and Spiess (2024) leave-one-out procedure, clustering at the hydrological basin level and allowing for effects heterogeneity based on 4 groups by longitudinal distance to the coast and agricultural land share in the drainage area of each monitoring station.

Table A.I: Irrigation Calendar by Crop

| Irrigated crops | Crop Needs Irrigation in Month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **J** | **F** | **M** | **A** | **M** | **J** | **J** | **A** | **S** | **O** | **N** | **D** |
| Wheat | | | | | | x | x | x | x | x | x | x |
| Rice | x | x | x | | | | | | | | x | x |
| Maize | x | x | x | | | | | | | | x | x |
| Barley | | | | | | x | x | x | x | x | x | |
| Other cereals | x | x | x | | | | | | | | x | x |
| Vegetables | x | x | x | | | | | | | | x | x |
| Fruits | x | x | x | x | x | x | x | x | x | x | x | x |
| Grapes | x | x | x | x | x | x | x | x | x | x | x | x |
| Citrus | x | x | x | x | x | x | x | x | x | x | x | x |
| Oil crops | x | x | x | | | | | | | | x | x |
| Potatoes | x | x | x | | | | | | | | x | x |
| Pulses | x | x | x | | | | | | | | x | x |
| Sugar beet | x | x | x | | | | | | | x | x | x |
| Fodder temporary | | | | | | x | x | x | x | x | x | |
| Tobacco | x | x | x | | | | | | | | x | x |
| Pasture permanent | x | x | x | x | x | x | x | x | x | x | x | x |

*Source:* FAO, INE.

Table A.II: Summary Statistics: Land Parcel Level Dataset, by Distance to the Coast

Panel A: Downstream parcels.

| | 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 | | | | | |

Panel B: Middle section parcels

| | 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 | | | | | |

Panel C: Upstream parcels

| | 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 | | | | | |

*Notes:* This table presents summary statistics for agricultural parcels, separated by their location in their corresponding basin. Panel A shows statistics for plots located in Downstream locations (i.e. in the first tercile of distance to the coast), Panel B for plots located in the Middle section (second tercile), and Panel C for plots located in the Upstream section (third tercile).

# B 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.

## B.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.

### B.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.

### B.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.

### B.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 B.I.

## B.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.

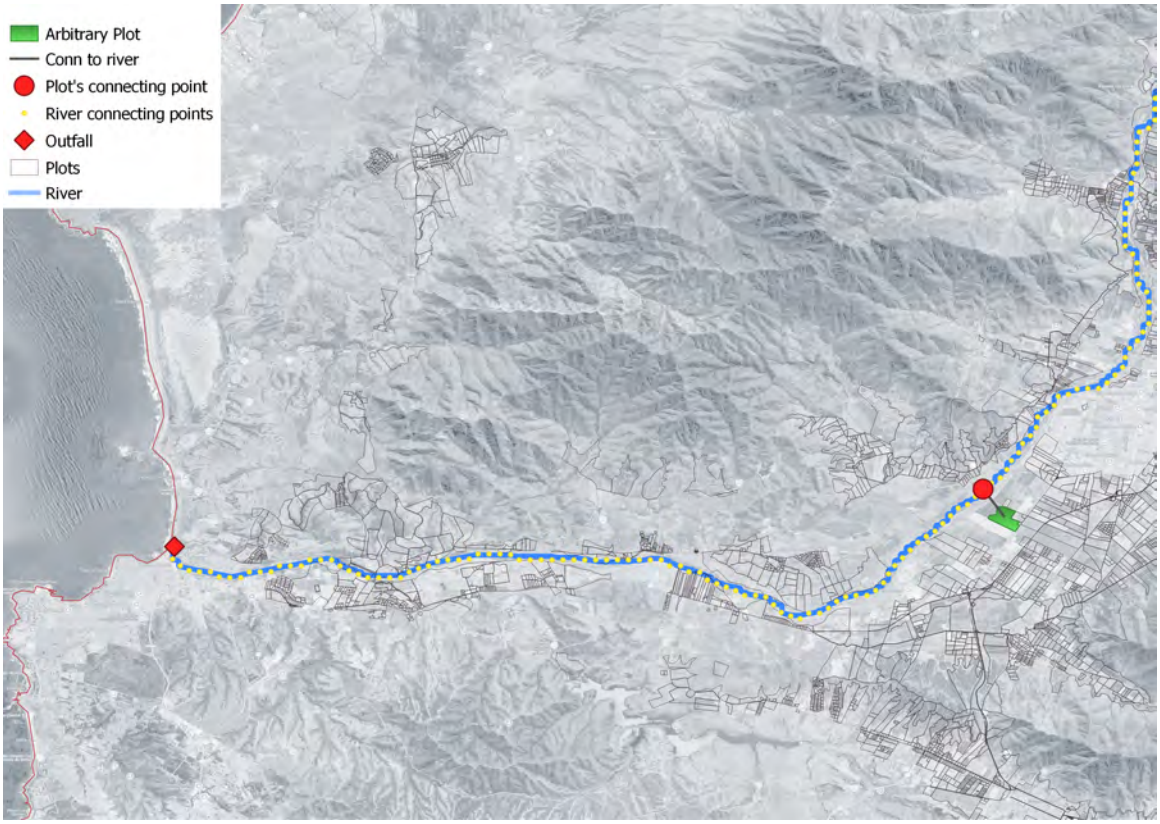



Figure B.I: Altorithm Illustratgion. An arbitrary area—shown in green—is connected to the closest point in the river, marked by a red circle. The distance assigned to this arbitrary object will be the distance along the river from the connecting point (red circle) to the river mouth or outfall (red square).