Governing Environmental Markets: Evidence From Irrigation In Water Markets*

Maximiliano García [JMP]† José Belmar‡

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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. Using different identification strategies, we show that these efficiency gains are a result of both water redistribution and individual adaptation, as downstream farmers increase substantially their water consumption and agricultural yield, and also extend their growing season. Large farms adopt more efficient irrigation technologies, and overall gather more benefits from the analyzed property rights institution. Meanwhile, although upstream farmers reduce

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†Corresponding author. Brown University Center for Philosophy, Politics and Economics. Email: max_garcia@brown.edu. Mail Address: Box 2005, 25 George Street, Providence, RI 02912.

‡Inter-American Development Bank. Email: jbel@iadb.org.

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.*

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 legally 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 legally well defined across the territory. In a competitive market equilibrium, the marginal value of the resource should be equal across locations, with deviations from this benchmark indicating a Pareto inefficient allocation. 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 long run decisions such as 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 establish that Water Boards causally affect water allocation, we exploit the staggered adoption of Water Boards across basins in an event-study difference-in-differences design. Using remote sensing-based estimates of water consumption and agricultural yields at the farm-plot level, we measure the distributive impacts of Water Board establishment across locations within treated areas. We find that following the establishment of a Water Board, downstream farms increase their water consumption by 1 standard deviation of their individual historical distribution, growing up to 2 standard deviation after 7 years; upstream farms, instead, see reductions up to 0.8 standard deviations after 7 years. We also show how this addresses a source of misallocation directly: downstream farms increase their yields by 0.6 standard deviations after 7 years, while upstream farms do not see significant reductions in production.

We show that these redistributive farm-level impacts are explained by large-scale water redistribution by showing changes in river streamflows, the main physical channel through which Water Boards reallocate water for irrigation. Exploiting the staggered adoption of Water Boards in a difference-in-differences design at the river segment level, we find that Water Board establishment increases river streamflows by 25% during the dry season, when incentives to over-extract are strongest. This effect is concentrated in upstream monitoring stations and in areas with high agricultural intensity, consistent with Water Boards preventing upstream over-extraction and enabling water to reach downstream users. We do not find similar effects in the rest of the year, when the enforcement provided by the water boards is not relevant.

To identify long-run effects, we employ an instrumental variable strategy based on the cost of reaching the specific courts with jurisdiction to initiate Water Board establishment—costs that 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 68% among farms located in the most downstream tercile of each basin, while they reduce consumption among farms in the most upstream tercile by around 31%. We observe qualitatively similar effects in agricultural yield: an increase of 57% among downstream irrigated farmers, and no significant effects among upstream ones. Remarkably, these effects align with our DID estimates after 7 years, which rely on a different source of variation, serving as mutual robustness checks.

Our IV estimates further reveal that enforcement effects extend beyond the mechanical redistribution of water. The greater stability and predictability of water access enabled by Water Boards allows downstream farms to make complementary investments: they extend their growing season by approximately a month, allowing numerous farms to switch to summer crops, while large downstream farms adopt more efficient irrigation technologies. These induced private responses help explain the pattern observed in our event-study estimates, where increases in water consumption among downstream users exceed the reduction among upstream farmers, indicating that enforcement generates net gains through both direct reallocation and the productive investments it enables.

We conclude that Water Boards address misallocation by physically enforcing property rights, redistributing water 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). At a first glance, Chile's water rights system seems to satisfy 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 when formal property rights are already well established.

Related Literature. Our paper contributes to a range of literatures, including management of water and common pool resources in general, frictions in developing markets, and the economic impacts of agricultural infrastructure. We first contribute to the literature on common pool resource management.[2] Ostrom (1990) identifies local communities as

[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`

[2]Water exhibits the classic features of a common pool resource—difficulty enforcing exclusion and rivalry in consumption—creating incentives for over-extraction in the absence of effective governance (Hardin, 1968). Conventional approaches allocate decision rights to either the state or private agents through privatization, but implicitly assign monitoring and enforcement tasks to the state.

an alternative to state management or privatization for governing common pool resources, with subsequent work testing these ideas in small-scale settings through case studies and lab experiments (e.g. Ostrom and Gardner, 1993; Ostrom, 2009; Meinzen-Dick, 2007; Ostrom, 2010; Cardenas and Carpenter, 2008; Cárdenas and Ostrom, 2004; Henrich et al., 2006).[3] We extend this literature by showing how local enforcement organizations can address free-riding across multiple communities in large-scale river basins by wielding state-like authority to resolve disputes and sanction violations. More broadly, we contribute to work on water institutions and property rights enforcement (Libecap, 2011; Bauer, 2004; Jacoby et al., 2020; Chong and López-de Silanes, 2006; Edwards, 2015; Edwards et al., 2021; Edwards, 2016; Mesías and Torralba, 2023), providing the first design-based causal evidence on the impact of enforcement institutions in settings with well-defined, tradable property rights over common pool resources, and water in general.

We also contribute to the literature on the efficiency and operation of markets for natural resources and environmental goods.. In water markets, Rafey (2023) estimates substantial gains from trading in Australia under strong government enforcement, while other work on water compares markets to alternative allocation mechanisms, finding efficiency losses from rationing (Ryan and Sudarshan, 2022), mixed results relative to quota systems (Donna and Espín-Sánchez, 2023), and net gains relative to open access (Ayres et al., 2021). Research on misallocation in other natural resources shows how property rights reforms in land markets enable efficient reallocation and productivity gains (De Janvry et al., 2015; Chari et al., 2021; Gollin and Udry, 2021; Manysheva, 2022), while recent work on the operation of environmental markets has focused on pollution permits (Colmer et al., 2024; Greenstone et al., 2025). We contribute methodologically by developing a misallocation test for surface water that does not require measuring water consumption–critical since water use is not metered in many contexts. Our sufficient statistics approach recovers the marginal product of water from output responses to exogenous availability shocks. Substantively, we

[3] Among the conditions Ostrom (1990) identifies for successful community governance are monitoring capability, availability of sanctions among community members, and closed access to outsiders. However, in our context—distribution of water within basins encompassing multiple communities—these conditions do not directly apply: agents cannot observe actions outside their community, cannot exclude others from purchasing water rights, and asymmetric externalities (upstream actions harm downstream users, but not vice versa) prevent informal cooperation through repeated interactions.

provide the first causal evidence on how enforcement of property rights affects water allocation. Most related work identifies misallocation from legal limits on exercising property rights; we demonstrate how limits to government action— designed to prevent market interference—can undermine enforcement capacity and generate misallocation (Bauer, 2004).

We further contribute to research on the economic impacts of water infrastructure. Studies of large-scale irrigation infrastructure find increases in agricultural productivity alongside substantial distributional consequences (Duflo and Pande, 2007; Blakeslee et al., 2021; Asher et al., 2022; Burlig et al., 2024; Cisse et al., 2025). We document large differences in efficiency and benefits from infrastructure and markets within a country, and show how these productivity and distributional impacts depend critically on the interaction between local institutions and geography, documenting substantial heterogeneity by location (upstream vs. downstream) and farm characteristics.

Methodologically, we join the first wave of research using remote sensing to measure agricultural water consumption at the farm level (Boser et al., 2024), enabling causal analysis at scales previously infeasible.

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; Tamayo and Carmona, 2019). 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

[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).

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. The DGA guidelines establish that permanent water rights should have an exceedance probability of 85%, meaning that they can be created up to the point where the total volume claimed in a water source is available 85% of the time. This implies that water is insufficient to satisfy all rights–and so, that infrastructure should not bind–for almost two months per year on average.

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 20th 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 (Biblioteca del Congreso Nacional, 1981).[5] Their design combines features of private associations and local regulators: they maintain registries of water rights, mediate disputes, and enforce allocations during scarcity by physically controlling water flows to each user (Vergara Blanco, 2014; Donoso, 2016; Engler et al., 2021; Blanco and Donoso, 2024).

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 IV. This technology is not unique to the Chilean context (e.g., the case of Murcia, see Ostrom, 1990, pg. 77), nor costly: in 2005, membership fees represented less than 4% of the total average cost of production for farms growing the most common crops in the area of study (Jara et al., 2009).

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

[5] Figures A.II, A.III, and A.IV illustrate core functions typically performed by Water Boards, including (1) enforcement of water rights through proration during scarcity, (2) organization of general assemblies, and (3) maintenance of shared irrigation infrastructure such as canal cleaning and repairs. The images were retrieved on July 29, 2025, from LinkedIn posts and official websites of Water Boards in Chile.

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.[6] 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 V.

Administrative and Legal Jurisdiction. Water Boards' jurisdictions covers surface water bodies within their boundaries.[7]. 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.[8] 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. [9] 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

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

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

[8] 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.

[9] 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.

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 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 $0.05° \times 0.05°$ 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, DID and IV 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 and Canal Locations. 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. CIREN also has information on soil quality, measured as their suitability for irrigation. 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. We use EVI and Evapotranspiration estimates by the USGS based on LANDSAT 5 images. USGS estimates and maps Evapotranspiration using the SSEBop model (Senay, 2018; Senay et al, 2023). This method recovers Evapotranspiration from an Energy Balance condition that equates the measured sun radiation on the surface to the calculated surface reflectance, estimated soil heat absorption, and Evapotranspiration (which is recovered as a residual)(Allen et al., 2015). We use images captured since the year 1986 using as input Landsat-5 images, with a resolution of $30m \times 30m$, a resolution fine enough to allow us to perform plot-level analysis. We also use EVI estimates based on Landsat 5 images from the same source, also with 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.

Figure VII summarizes the correspondence between data sources, stage of analysis, and units of analysis employed throughout the paper.

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[10].

[10] 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

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

4.1 Model of Agricultural Production and Irrigation under Water Rights

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

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

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

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

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.

Time= 2 : Profits are realized

Finally, each production function F_c is increasing, continuous, strictly concave, and monotone[11].

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

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

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

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

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

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

The First Order Conditions of this problem are

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

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

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

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

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

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

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

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

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

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

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

Therefore, the optimal allocation satisfies $\frac{\partial \bar{\pi}_i}{\partial \bar{w}_i} = \frac{\partial \bar{\pi}_j}{\partial \bar{w}_j}, \forall i, j \in N$[12]. Note that:

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

where K represents the crop chosen by the farmer, and the second equality is a consequence of the Envelope Theorem.[13] In the socially optimal allocation, therefore, the expected shadow value of water is equal across farmers; any deviation from that implies the opportunity to increase expected welfare by redistributing water rights from users with a high shadow value of water to users with a low shadow value.

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

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

. So the total effect of an unexpected rainfall shock on production is equal to the shadow value of water of the affected farmer, times the marginal rate of technical substitution between irrigation water and rainfall. Note that Rafey (2023) estimate θ to be equal to 1.048 for annual irrigated crops, which is approximately equal to 1.[14]

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.

[12]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.

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

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

4.2 Test Implementation

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

We illustrate the construction of this variable in Figure VIII. We define useful rainfall as the total rainfall falling in a farmer's county during the months when their crop requires irrigation in the current agricultural year. In this example, Farms A and B are both located in County 1, with rainfall over the agricultural year represented by the blue bars. Farm A cultivates a crop that follows the yellow irrigation schedule, while Farm B cultivates one that follows the green schedule. Consequently, all rainfall received in December, January, and February is useful for Farm A but not for Farm B. Another source of variation comes from geography. Consider a farm with the same irrigation schedule as Farm A, but located in a nearby county where rainfall is represented by the red bars. This farm experiences a slightly different water input than Farm A, due to the distinct monthly rainfall pattern in its county. This variation, conditional on fine spatial fixed effects and agricultural choices, allows us to test for differences in the average shadow value of water between farms that rely on canal-based irrigation and those with water rights, even when located within 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.[15]

We estimate

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

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 $\text{rainfall}_{r,c}$ 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.[16] $\mathbb{X}_i^{2007}$ is the set of controls, which includes the logarithm of the total labor hired during the 2007 agricultural year, a vector of capital and technology choices and the irrigated surface. Board_c equals 1 if the farms belong to a county whose centroid falls inside the jurisdiction of a water board. Finally, μ_c is a county fixed effect, and μ_r is a crop fixed effect.

On estimating equation 5, we are exploiting within-county, within-crop variation in the timing of rainfall, which is arguably exogenous on most determinants of agricultural production. County fixed effects will capture common shocks to all farms and average expectations, and individual farm controls–including crop fixed effects– will capture long term and short term determinants of output. On estimating equation 5, we are exploiting within-county, within-crop variation in the timing of rainfall, which is arguably exogenous

[15] 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.

[16] 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.

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

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

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

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

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

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

Results. In Table II we present the results of estimating equation 5, considering an array of location-fixed effects. Our preferred specification is in column 4, which we also present graphically in Figure IX. The estimated coefficient associated with rainfall (β_6) implies that for farms in our sample - water right owners, affiliated to canal associations and with irrigation - an extra unit of water (Mega Liters/$ha/month$[17]) 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 IX 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[18].

In contrast, for counties within the jurisdiction of Water Boards, the average shadow value of water is similar, regardless of their distance to the river mouth. For counties located next to the coast, there is a non-significant reduction in value per hectare of around 5% per extra cubic meter of water per hectare per month), which is approximately the same for farms located $200km$ upstream. The average shadow value of water as a function of the distance to the coast is presented as the blue function in Figure IX, 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

[17] Considering only Summer months

[18] 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.

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 exclusively 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.[19].

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 farms. The results suggest that the yield per hectare increases by around 8% per extra unit of water at the coast. The increase in yield for farms located the farthest from the coast (at $219km$) is 11%, which is not statistically different from the effect on the coast. For counties with Water Boards, the corresponding estimates are 12% and 6%; they are not statistically different either. Importantly, all interaction terms involving the water board dummy are not significant and economically small. The last rows of Table III show that after including our finer spatial fixed effects –either 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 X presents the estimated functions of Average MPW for areas with and without water boards. The most important conclusion from the figure is that none of these funtions exhibit a significant slope, and despite the existence of some (statistically non-significant) differences in levels, both functions are contained in the confidence intervals of the other.

This placebo exercise suggests that the estimated effects of rainfall on irrigated parcels (our main exercise) recover a causal relationship between water and yield across different locations, and so our Misallocation Test identifies the underlying misallocation existing in the absence of water rights enforcement. More importantly, our test fails to find such misallocation in places with water boards exerting property rights enforcement, suggesting that we cannot reject the efficiency of water markets supported by Water Boards.

[19] 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

Other Robustness Checks. In Appendix A, Table A.I, we present additional robustness checks addressing different potential concerns. One is that crops with different requirements may exhibit different elasticities with respect to irrigation; in that case, the relationship found above could reflect crop choices rather than misallocation. In columns 1 and 2 of Table A.I, we re-estimate the models from columns 3 and 4 of Table II, but allow for interactions between crop fixed effects and useful rainfall. This effectively permits elasticities to useful rainfall to vary by crop. Reassuringly, the results are unchanged relative to the main estimates.

Another potential concern is that the relationship between revenue and useful rainfall may be confounded by other inputs or technology choices. In column 3 of Table A.I, we re-estimate our main equation, interacting useful rainfall with a dummy equal to one if a farm uses fertigation[20], a technology complementary to irrigation. The results remain unchanged.

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 employ two identification strategies—Event Study and Instrumental Variable—to investigate how Water Boards enhance agricultural productivity in both the short and long run. We will focus on mechanisms related to water redistribution to downstream users, and farmers' private responses, including crop and irrigation technology choices.

Our main 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 follow these farms between 1986 and 2012. We estimate plot-level water consumption using more than 15,000 images of a new LANDSAT 5-based product that provides estimates of Evapotranspiration at a 30m resolution every 16 days since 1986[21] ;boser2024field). In addition, we also estimate agricultural yield and crop choice using

[20]The application of fertilizer through the irrigation system

[21]Although LANDSAT 5 was launched in 1984, it actually started operating in 1985. Starting in 1986 there is stable supply of frequent images of our area of study (Senay, 2018; Senay et al., 2023).

Enhanced Vegetation Index (EVI) estimates from LANDSAT 5 from the same period. To illustrate the detailed nature of this data, Figures XIa and XIb 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 XIa we observe a decline in water consumption when comparing upstream (right) to downstream (left) locations. Similarly, Figure XIb presents a similar decline in yield. However, there is substantial intra-location variation, especially in upstream locations.

In Table IV we present summary statistics over our full sample. Farms within the jurisdiction of water boards have slightly lower EVI and evapotranspiration levels than farms outside them, but they also face substantially dryer conditions. In the next subsections, we will address the identification challenges by implementing first a Difference-in Differences and then an Instrumental Variable analysis.

5.1 Difference-in-Differences Analysis of Water Redistribution and Agricultural Productivity

In our first analysis, we exploit the staggered adoption of Water Boards across basins to estimate the causal impact of property rights enforcement and governance on the allocation of water. Table V presents the year of establishment of Water Boards, and the number of farm plots under their jurisdiction. Given the data available and the institutional design in place, we focus our analysis on the boards established after 1981 and before 2010. This window captures Water Board establishments under Chile's 1981 Water Code framework and before the severe hydrological changes experienced from 2010 onwards, ensuring our estimates reflect a consistent institutional and environmental context. We consider 5 years before and 7 years after the establishment of the board for our analysis.

Identification Strategy. The establishment of Water Boards is triggered by either an agreement among water users or a lawsuit by users who perceive their interests are being affected by the lack of governance in the basin. In both cases, there is latent conflict over the resource, driven by both water supply and demand factors.

We explore the potential role of water supply factors in Figure XII, where we show the standardized total precipitation over our sample of farms for each year around a Board Establishment event. This figure shows that, indeed, the years surrounding a Board Establishment event are drier: during the year of a Board Establishment, the farms under their jurisdiction experience almost 10% of a standard deviation lower precipitation. Therefore, although the timing of Board Establishment to environmental conditions, they seem to be most adverse for agricultural activity, making our estimates of benefits from Water Boards likely a lower bound of their true values.

Exploring demand side-drivers of Water Boards adoption is more complex, as they are mostly unobservable. The process, however, is long and irreversible, implying that the most likely driver of Water Boards adoption is long-term conflict[22]. Motivated by this, we will focus our analysis on a sample of ever-treated units, and therefore, for any Board Establishment event, we will consider as a control group only not-yet-treated plots.

Econometric Specification of the DID Analysis. Our main equation is:

$$\begin{aligned} \mathrm{Y}_{it} = &\sum_{k=-5}^{7} \delta_k \text{Board Establishment}_{it} \times 1\left[t - t^* = k\right] \\ &+ \beta \mathrm{X}_{it} + \alpha_i + \mu_{t,g(i),q(i)} + \varepsilon_{it} \end{aligned} \tag{8}$$

where Y_{it} is either Average Evapotranspiration in the Summer or the Peak Enhanced Vegetation Index (EVI) over the season at plot i in year t. These are satellite-derived variables averaged at the parcel level that proxy for water consumption and agricultural yield, respectively[23]. In our preferred implementation, we use standardized versions of these variables[24] to address the substantial heterogeneity across units in space and time. Board_{it} equals 1 if plot i is under any Water Board jurisdiction. t^* denotes the establishment year of the Water Board with jurisdiction over i. X_{it} is a vector of annual climatic characteristics, in-

[22]There is no systematic documentation of the length of the full constitution process, but one testimony about Water Board established through a lawsuit in 2015 describes a process of at least two years: the first year for lawsuit resolution and the second year for executing the resolution and establishing the board(CNR, 2018b).

[23]Evapotranspiration is measured in average millimeters per pixel during summer season (December-February). Peak EVI corresponds to the maximum value of Enhanced Vegetation Index over the growing season. Both variables are derived from LANDSAT 5 satellite imagery.

[24]Obtained by subtracting each plot's mean from its observed value and dividing by its standard deviation.

cluding total precipitation over the year and over the Summer, and the number of days with maximum temperatures in the following temperature ranges: $[25, 29], [29, 31], [31, 35]$, and $[35, \infty^+)$, in Celsius degrees. α_i is a plot-level fixed effect, while $\mu_{t,g(i),q(i)}$ denotes flexible time trends by geographical grid cell and quantile position within the basin, where $g(i)$ represents the $2° \times 2°$ latitude-longitude cell and $q(i)$ represents the quantile of distance to the river mouth for plot i. Quantiles correspond to terciles defining downstream, mid-section, and upstream farm locations.

Our main hypothesis is that Water Boards play a distributive role, which in our case translates into possible heterogeneous treatment effects across upstream and downstream locations within the basin. We therefore use the staggered difference-in-differences imputation estimator proposed by Borusyak et al. (2024). This approach handles within-cohort 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.[25]

Difference-in-Differences Results. Figure XIII presents our main set of results for the effect of Water Boards establishment on water consumption effects. Panel A (Figure XIIIa) shows heterogeneous effects estimates by location within basin. Downstream farms experience an immediate 1 standard deviation increase in water consumption, growing to 2 standard deviations after 7 years. Upstream plots show an increasing reduction in water consumption, that reaches 0.8 standard deviations after 7 years, while mid-section plots show no discernible pattern. There is some evidence of pre-trends, reflecting the increasing pressure on the resource in basins adopting these boards.

Panel B (Figure XIIIb) presents combined estimates across all locations to examine the net effect on basin-wide water consumption, testing whether downstream gains outweigh upstream losses. Although our average estimate is just over 0.5 standard deviations after 7 years, these estimates are statistically significant in only 2 out of 7 post-treatment years. Appendix Figure A.V shows similar patterns using non-standardized evapotranspiration: downstream farms increase water consumption by $0.7mm$ immediately, reaching $1.5mm$ af-

[25] Similar to our setting, Cisse et al. (2025) apply the same estimator to evaluate irrigation projects in the Senegal River Valley, where treatment timing is staggered and the panel is unbalanced due to missing satellite imagery, a challenge also present in our context.

ter 7 years, while upstream farms experience reductions of 0.3mm by year 7.

In Figure XIV we present our estimates of the effect of Water Boards establishment on agricultural yield. Panel A (Figure XIVa) shows heterogeneous effects estimates by location within basin. Downstream farms increase their yield by 0.4 standard deviations in the first year, and the gains increase to more than 0.6 standard deviations after 7 years. Upstream plots show lower average yields in the years after the event, with reductions smaller in magnitude (averaging 0.25 standard deviations), not significant for all years, and seeming to dissipate at 7 years. Mid-section plots do not show any discernible pattern.

Panel B (Figure XIVb) presents combined estimates for impacts on agricultural yield. These estimates are positive, but only significant for the year of the event. Appendix Figure A.VI presents estimates using non-standardized EVI, showing downstream farms increase peak EVI by 0.04 immediately and 0.06 after 7 years, while upstream farms experience smaller reductions. The downstream gains clearly outweigh upstream losses, though combined coefficients are significant only for a number of years.

Appendix Figure A.VII presents analogous heterogeneous estimates for both outcomes when including our full set of controls, confirming that downstream farms sustain sizable gains in yield and water consumption after 7 years, while upstream farms experience persistent reductions in water consumption and yield losses that dissipate by year 7

5.2 Instrumental Variable Analysis

In this section, we explore the long run impacts of Water Boards using an Instrumental Variables approach. A simple crossectional 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 V). 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 abundant may attract agricultural activity, but conflict may not escalate under abundance. As our sample only considers agricultural areas, we only observe them conditional on being able to support agriculture, leading to a potential downward bias.

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).

Instrument and Identification. We consider the costs of establishing a water board in the full geological basins. These are defined as the areas that drain to a river mouth on the sea coast and extend from the Andes Mountains in the East to the Pacific Ocean in the West. 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.

Our instrument consists of the square of the driving distance on the optimal route between a plot and the most eastward province capital city within each basin, in order to emphasize longer distances[26]. With this instrument, controlling for geographical characteristics, 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 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 XV, we illustrate the data and our instrument in a blue-to-red gradient. In the case of this instrument, we can see how downstream areas that are closer to the most upstream province capital city (in bluer colors) are eventually under the jurisdiction of a water board, while downstream farms too far from this city are not under the jurisdiction of any board.

Conceptually, we understand the process of establishing a water board as a collective action problem, where downstream users contribute to pay the cost of the Water Board

[26] In Appendix Tables A.III, A.IV, A.V and A.VI we show that other functional forms– linear and a piece-wise linear, designed to address potential externalities of cities over agricultural activity, including "agglomeration shadows" (e.g. Hornbeck, Michaels and Rauch, 2025)–provide similar results.

establishment lawsuit. They choose their contributions by comparing the net private benefits of establishing this institution to the outside option, which in this case corresponds to either relying only on the state-provided enforcement, or using rainfall as the main source of irrigation[27].Our instrument shifts the costs of this lawsuit by increasing the costs of attending hearings and proceedings in court. Violations of the Exclusion Restriction may show as correlations between the instrument and other determinants of either the outside option or costs. In Appendix Table A.II, we show that our instrument is not correlated to climatic variables, market access nor key farm characteristics, including farm size and potential yields..

Econometric Specification of the IV Analysis. 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[28] .

Our main specification for the long-run estimates is

$$\begin{aligned} \mathrm{Y}_{it} =& \alpha \mathrm{Board}_i + \gamma X_{it} + \mu_g(i) + \psi_t + \varepsilon_i \\ \mathrm{Board}_i =& \beta \mathrm{ucd}_i^2 + \delta X_{it} + \eta_g(i) + \zeta_t + u_{it} \end{aligned} \tag{9}$$

where Y_{it} is either Average Evapotranspiration in the Summer or the Peak Enhanced Vegetation Index (EVI) over the season at plot i in year t, observed annualy from 2005 to 2009. These variables proxy for water consumption and agricultural yield, respectively. Although the outcome Y_{it} and controls X_{it} vary across years, the treatment variable Board_i is time-invariant: it indicates whether farm i is under the jurisdiction of a Water Board by 2005, and remains constant thereafter. X_{it} is a vector of farm-level controls including market access measures (driving distance to Santiago and the main ports); dummies for soil qual-

[27]In the period under study, groundwater was not widely used as a source of irrigation (Taucare et al, 2024).

[28]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.

ity quartiles; annual, combined winter and spring, and summer precipitation; temperature, measured as the number of days with maximum temperatures in the following temperature ranges: $[25, 29], [29, 31], [31, 35]$, and $[35, \infty^+)$, in Celsius degrees (Hsiang, 2016); and a dummy for whether the plot has groundwater rights. $\mu_g(i)$ and $\eta_g(i)$ are $1° \times 1°$ latitude-longitude cell fixed effect. Our instrument is ucd_i^2, the square of the driving distance (in kilometers) along the optimal route from each plot to the most upstream provincial capital within its basin.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)[29].

IV Results. Table VI presents the Instrumental Variable estimates of equations 9 for our measure of water consumption (Evapotranspiration per pixel). Columns 1, 2 and 3 present OLS estimates. Columns 4, 5 and 6 present our main IV estimates by section of the river (Downstream, Mid-section and Upstream, respectively). For downstream farms (Column 4), Water Boards increase water consumption by downstream farms by $2.01mm$, equivalent to 68%. For upstream farms (Column 6), Water Boards reduce water consumption by $1.07mm$, equivalent to 31%. Overall, instrumenting for reveals an economically significant redistribution of water from upstream to downstream farms, with net gains concentrated downstream[30].

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 57% in yield for farms located downstream, but non-detectable effects for upstream farms

Comparison between DID and IV estimates and Interpretation. Our Difference-in-Differences and IV estimates yield consistent results across both water consumption and agricultural productivity measures. For water consumption, downstream farms increase

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

[30]Notably, we cannot reject equality between OLS and IV estimates for upstream locations, consistent with the idea that Water Board establishment is driven by decisions of downstream users and is therefore plausibly exogenous for upstream users.

usage by $1.5mm$ after 7 years (DID) and $2.01mm$ in the long run (IV), while upstream farms face smaller reductions of $-0.3mm$ (DID) to $-1.07mm$ (IV). For agricultural productivity, downstream farmers increase yields by 60% of a standard deviation after 7 years (DID) and 57% of the control group mean in the long run (IV), while upstream farmers face no significant costs.

These results indicate a substantial increase in water consumption for downstream farms, which translates into higher yields. Upstream locations experience smaller reductions in water access that do not lead to significant changes in yield. While these estimates seem large, they align with findings from other contexts, such as Cisse et al. (2025)'s analysis of irrigation infrastructure impacts in Senegal, which documented a sixfold increase in dry season cultivation rates. Our estimates show that institutions can generate substantial variation on the impacts of infrastructure investments.

The asymmetric pattern in our results—where downstream gains substantially exceed upstream losses—can be explained by different, non-mutually exclusive mechanisms; we discuss two here. First, downstream gains occur mainly along the extensive margin–shifting farms from no irrigation to irrigation –whereas upstream losses may occur along the intensive margin– farms with previously unrestricted access to water may face limitations after Water Board establishment. In Appendix Table A.VII, we provide supporting evidence for this mechanism. Using our IV approach we estimate equation 9 on a variable from the 2007 Agricultural Census indicating whether a farm has any irrigation from surface water sources. We find increases among downstream farms in this extensive margin measure of irrigation, especially among large ones. We do not find negative effects upstream along this extensive margin, although due to a very weak first stage, we do not consider this conclusive.

Second, the net increases in water consumption and yield may reflect complementarity between reliable water provision and individual or collective investments. We discuss these channels in Subsection 5.3.

Taken together, these results imply large-scale redistribution of water within the basin. In Section 6, we present further evidence of such redistribution focusing directly on river flow increases upon Water Board establishment.

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 Water Boards represents a public good that increases the reliability of the water supply from the perspective of the downstream irrigators. This enhanced reliability enables the cultivation of new crops requiring irrigation for extended seasons and complements technologies such as micro-irrigation, which depend on reliable water supply. However, the adoption of these complementary investments may be subject to credit or liquidity constraints, particularly affecting smaller farmers (e.g Karlan et al., 2014).

Crop choice and irrigation technology represent long-run outcomes that involve learning curves, as farmers require time to master new techniques and adapt to changing institutional and market conditions. In particular, they may be shaped in this context by international trade, specifically by the Free Trade Agreements signed by Chile with multiple trade partners in the early 2000s. Given this, and the timing of Water Board establishment events–mostly before these FTAs were discussed publicly–, we will follow the same Instrumental Variable strategy as in the previous section.

Crop Choice. We show that the presence of water Boards allows an expansion of the production possibility set. Table VIII presents estimates of equations 9 for two crop choice outcomes: the number of months between the beginning of the season and the month when the greenness peak is reached (Panel A) and 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 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.

Irrigation Technology. We present our estimates of impact on irrigation technology using 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[31].

The outcome variable in Columns 1 to 4 of Table IX 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[32]. Columns 1, 2, 5 and 6 (3, 4 ,7 and 8) present OLS (TSLS-IV) estimates. Finally, Panel A present estimates for the full sample of farms with irrigation, while Panel B only for large farms, and Panel C for small farms.

Our OLS results in for the full sample (Panel A) only show that plots in upstream areas with Water Boards are 3*pp* less likely to use furrow technology. Our IV estimates,

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

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

instead, show a reduction of 12*pp* in the use of traditional irrigation technologies. There is a statistically insignificant increase of 8*pp* in the use of micro-irrigation. Our IV estimates in Panel B, instead, show a significant reduction (20*pp*, statistically significant at 10%) in the use of traditional irrigation techniques among downstream large farms, accompanied by an equal increase (21*pp*, statistically significant at 5%) in the use of micro-irrigation techniques in the same group. Panel C shows that there are no changes in the irrigation technologies used by small farmers.

While our main IV results for water consumption and productivity (Tables VI and VII) and our baseline results for crop choice (Table VIII) do not distinguish by farm size, the disaggregated estimates in Annex Tables A.VIII, A.IX, and A.X show that the positive downstream effects are substantially larger for large farms. These farms experience greater increases in water consumption, agricultural productivity, and adjustments in crop choice—consistent with the shifts toward more efficient irrigation technologies documented here. In contrast, small farms exhibit smaller and mostly insignificant changes, in line with the limited water and yield gains observed in this group in our earlier results.

Overall, we conclude this section showing that the provision of property rights enforcement by water boards increases the reliability of the water supply, allowing farmers to grow crops that require irrigation during the summer, and also to switch to more efficient irrigation techniques that require a stable water input. These opportunities seem to be available just for the largest farms, implying that the distributive impacts discussed in the previous subsections 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 X 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 XVIa 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[33]. 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.XI. Figure XVIb 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

[33]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

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[34].

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 XVII. Figures XVIIa and XVIIb show that this is not the case for the dry season–if anything, precipitations are *lower* after a Board establishment, ruling out this situation.

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

$$\begin{aligned}\text{Stream}_{gmt} = &\sum_{i=-3}^{3} \delta_i \text{Board Establishment}_{gst} \times 1\left[t - t^* = i\right] \\ &+ \beta \text{X}_{gmt} + \gamma \text{WR}_{gmt} + \mu_t + \eta_{gm} + \varepsilon_{gmt}\end{aligned} \tag{10}$$

where Stream_{gmt} is the streamflow at monitoring station g in month m and year t, and 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. 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. WR_{gmt} corresponds to total Water Rights claimed in the area draining towards g. μ_t and η_{gm} are year

[34] 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.

and station-month fixed effects, accounting for seasonality at the station level[35].

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[36]. 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 XVIII presents our main estimates of the effect of Water Board establishment on summer streamflows. For our treated-only sample (Figure XVIIIb), 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% in streamflow. When averaging across all post-establishment years (0 to 3), we find an increase of 13%. The Full Sample estimates (Figure XVIIIa) 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.VIII), 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

[35] Equation 10 are derived from a water balance equation, where the inflows equalize outflows in a basin.

[36] In our sample, we do not find evidence of this effect.

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 XIX 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 XIXa) displays impacts for upstream monitoring stations, while the upper right panel (Figure XIXb) 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 XIX we compare our estimates of impacts for monitoring stations in areas with high cropland share (Figure XIXc) and low cropland share (Figure XIXd). 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 XX, 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 XXa), the strongest increases happened for upstream-high cropland share stations (Figure XXb). Monitoring stations in either downstream-high cropland share (Figure XXc) and upstream-low cropland share (Figure XXd) 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, causing substantial welfare losses: our results suggest that the impacts in water consumption after 1 year may duplicate the yields per hectare for the 20% of most downstream farms, without substantial upstream costs. This reflects a fundamental tension in environmental markets: empowering users over governing authorities may reduce some market frictions but weaken enforcement, as administrative actions under changing conditions remain necessary. We show that institutional arrangements that empower local communities can resolve this tension; however, the resulting efficiency gains are unevenly distributed. These findings have important implications for the design of environmental markets, suggesting that successful implementation requires careful attention to enforcement mechanisms and their distributional consequences.

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Tables

Table I: 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)	(2)	(3)	(4)
	m5	m6	m7	m8
Useful pp. (m3 per Ha per month)	-0.0606	0.00566	0.0146	0.0830
	(0.0502)	(0.0677)	(0.0493)	(0.0408)**
	[0.0473]	[0.0602]	[0.0466]	[0.0411]**
Distance to coast (100km)	-0.202	-0.168	0.194	
	(0.104)*	(0.114)	(0.0721)***	
	[0.0950]**	[0.105]	[0.0625]***	
Useful pp. (m3 per Ha per month) × Distance to coast (100km)	0.150	0.154	0.0407	0.0141
	(0.0439)***	(0.0447)***	(0.0282)	(0.0287)
	[0.0409]***	[0.0417]***	[0.0291]	[0.0263]
Water Board=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
Evapotranspiration (Summer)	3.28	1.2	1.7	4.7	0.0	7.8
Peak EVI over season	0.40	0.1	0.2	0.5	0.0	0.9
Area (m^2)	59659.00	132126.2	3920.7	150559.0	47.6	4199398.0
Latitude	-34.82	1.4	-36.8	-32.9	-37.7	-29.8
Longitude	-71.41	0.5	-72.2	-70.7	-73.0	-70.5
Mean annual prec.	1620.35	867.4	687.1	2873.4	0.0	5199.5
Mean summer prec.	184.81	145.9	40.5	406.2	0.0	1000.9
Distance to Santiago (main dom. market)	238.82	165.4	48.9	498.8	9.4	620.5
Distance to Valparaiso (main port)	305.83	187.7	89.4	592.2	15.8	707.2
Distance to San Antonio (second main port)	252.42	158.9	94.5	506.4	20.4	626.0
Distance to Coast (location in basin)	105.10	34.7	54.7	141.6	0.9	149.9
Distance to Upstream Capital	56.34	28.4	30.0	98.7	30.0	180.3
Observations	446177					

Panel B: Parcels Under Water Board Jurisdiction

	Mean	SD	p10	p90	Min	Max
Evapotranspiration (Summer)	2.95	1.4	1.1	4.7	0.0	7.8
Peak EVI over season	0.38	0.1	0.2	0.5	-0.1	0.9
Area (m^2)	58084.77	134182.9	3748.4	138617.7	24.9	3433859.8
Latitude	-33.62	2.0	-36.7	-30.7	-37.0	-29.8
Longitude	-71.20	0.4	-72.0	-70.7	-72.3	-70.5
Mean annual prec.	1108.56	643.9	427.4	1966.6	0.0	4285.9
Mean summer prec.	121.92	95.1	34.0	237.7	0.0	688.2
Distance to Santiago (main dom. market)	269.96	173.2	46.8	504.5	20.7	589.8
Distance to Valparaiso (main port)	299.32	165.2	102.1	548.4	35.5	609.3
Distance to San Antonio (second main port)	289.47	160.5	120.4	510.0	43.2	595.3
Distance to Coast (location in basin)	103.82	34.0	48.8	140.7	0.9	150.0
Distance Upstream Capital	58.31	24.7	30.0	97.1	30.0	126.3
Observations	193035					

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. Evapotranspiration and Enhanced Vegetation Index (EVI) are satellite-derived variables averaged at the parcel level. Evapotranspiration measured in average millimeters per pixel during summer season (December-February) between years 1986 and 2012. Peak EVI corresponds to the maximum value of Enhanced Vegetation Index. Area measured in square meters. All distance measures in kilometers. Santiago corresponds to the main domestic market. Valparaíso and San Antonio are the main ports. Distance to coast indicates location within basin. Upstream capital refers to the most eastward province capital city within each basin. Precipitation variables measured in millimeters.

Table V: Farm plots by Year of Board Establishment

	N plots	Percent	Cumulative perc.
1974	951	1.09	1.09
1989	1774	2.03	3.13
1993	920	1.06	4.18
1994	2338	2.68	6.86
1995	275	0.32	7.18
1996	2963	3.40	10.57
1997	1690	1.94	12.51
1998	755	0.87	13.38
1999	10055	11.53	24.91
2000	515	0.59	25.50
2001	689	0.79	26.29
2003	262	0.30	26.59
2004	1769	2.03	28.62
2005	2090	2.40	31.02
2010	28	0.03	31.05
2011	182	0.21	31.26
2012	1464	1.68	32.94
2013	2652	3.04	35.98
2018	694	0.80	36.77
2019	620	0.71	37.48
No Board	54512	62.52	100.00
Total	87198		

Notes: This table shows the total number of farm plots in our area of study, and the establishment date of a water board.

Table VI: Water Consumption: Instrumental Variables Estimation at the Parcel Level

Panel A: Main Result

	OLS			IV		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	-0.0210	-0.0993	0.0487	2.010	-9.785	-1.071
	(0.101)	(0.0677)	(0.0851)	(0.759)***	(42.88)	(0.601)*
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes
Plot controls	Yes	Yes	Yes	Yes	Yes	Yes
Spatial cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	139,693	144,580	143,795	139,693	144,580	143,795
R-squared	0.298	0.357	0.371	0.028	-11.566	0.249
Mean Dependent Var.				2.953	3.476	3.407
AR test CI				[.7185, ∞)	(-∞, ∞)	(-∞, -.2224]

Panel B: First Stage

	(1) Downstream	(2) Mid section	(3) Upstream
ucd^2	-0.0000290	0.00000260	0.0000308
	(0.00000815)***	(0.0000116)	(0.0000122)**
Observations	141,675	144,580	143,795
R-squared	0.534	0.320	0.368
Effective F-stat	12.266	0.051	6.430

Notes: This table presents estimates of equation 9 for parcels located at elevations below 1,000 meters and within 150 km of the river mouth in the study area. The outcome variable is the average Evapotranspiration for each plot in the Summer months (January and February) for the period 2005-2009. 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 market access measures (driving distance to Santiago and the main ports of Valparaíso and San Antonio); dummies for soil quality quartiles; annual, combined winter and spring, and summer precipitation; temperature, measured as the number of days with maximum temperatures in the following ranges: $[25, 29]$, $[29, 31]$, $[31, 35]$, and $[35, \infty^{+})$ in Celsius degrees; and a dummy for whether the plot has groundwater rights. All regressions include $1^{\circ} \times 1^{\circ}$ cell fixed effects and year fixed effects. Standard errors are clustered by county.

Table VII: Agricultural Productivity: Instrumental Variables Estimation at the Parcel Level

Panel A: Main Result

	OLS			IV		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	0.000500	-0.000508	0.0120	0.205	-0.590	0.00281
	(0.00740)	(0.00656)	(0.00647)*	(0.0695)***	(2.573)	(0.0352)
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes
Plot controls	Yes	Yes	Yes	Yes	Yes	Yes
Spatial cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	141,675	144,580	143,795	141,675	144,580	143,795
R-squared	0.278	0.178	0.247	-0.001	-4.119	0.246
Mean Dependent Var.				0.370	0.413	0.410
AR test CI				[.09944, ∞)	(-∞, ∞)	[-.1132, .1028]

Panel B: First Stage

	(1) Downstream	(2) Mid section	(3) Upstream
ucd^2	-0.0000290	0.00000260	0.0000308
	(0.00000815)***	(0.0000116)	(0.0000122)**
Observations	141,675	144,580	143,795
R-squared	0.534	0.320	0.368
Effective F-stat	12.622	0.051	6.430

Notes: This table presents estimates of equation 9 for parcels located at elevations below 1,000 meters and within 150 km of the river mouth in the study area. The outcome variable is the maximum value of the Enhanced Vegetation Index (EVI) reached within the year for the period 2005-2009. Distance to the coast wasmeasured through the river network. Plot-level controls include market access measures (driving distance to Santiago and the main ports of Valparaíso and San Antonio); dummies for soil quality quartiles; annual, combined winter and spring, and summer precipitation; temperature, measured as the number of days with maximum temperatures in the following ranges: $[25, 29]$, $[29, 31]$, $[31, 35]$, and $[35, \infty^{+})$ in Celsius degrees; and a dummy for whether the plot has groundwater rights. All regressions include $1^{\circ} \times 1^{\circ}$ cell fixed effects and year fixed effects. Standard errors are clustered by county.

Table VIII: Crop Choice: Instrumental Variables Estimation at the Parcel Level

Panel A: Peak after December (dummy)

	OLS			IV		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	0.0353	0.0114	0.00136	0.416	2.319	0.106
	(0.0213)	(0.0142)	(0.0234)	(0.138)***	(9.875)	(0.168)
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes
Plot controls	Yes	Yes	Yes	Yes	Yes	Yes
Spatial cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	141,675	144,580	143,795	141,675	144,580	143,795
R-squared	0.076	0.113	0.129	0.007	-3.406	0.123
Mean Dependent Var.				0.280	0.369	0.353
Effective F-stat				12.622	0.051	6.430
AR test CI				[.1742, .8482]	(-∞, ∞)	[-.2311, ∞)

Panel B: Season Length (months)

	OLS			IV		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	0.105	0.00839	-0.00977	1.148	6.179	-0.0296
	(0.0620)*	(0.0402)	(0.0463)	(0.374)***	(26.50)	(0.310)
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes
Plot controls	Yes	Yes	Yes	Yes	Yes	Yes
Spatial cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	141,675	144,580	143,795	141,675	144,580	143,795
R-squared	0.078	0.118	0.131	-0.002	-4.534	0.131
Mean Dependent Var.				6.924	7.121	7.060
Effective F-stat				12.622	0.051	6.430
AR test CI				[.5155, ∞)	(-∞, ∞)	[-.9328, .9642]

Notes: This table presents estimates of equation 9 for parcels located at elevations below 1,000 meters and within 150 km of the river mouth in the study area. The outcome variable in Panel A is 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, for the period 2005-2009. The outcome variable in Panel B is the the number of months between May (first month of the agricultural year) and peak of EVI within the corresponding year, for the period 2005-2009. Distance to the coast was measured through the river network. Plot-level controls include market access measures (driving distance to Santiago and the main ports of Valparaíso and San Antonio); dummies for soil quality quartiles; annual, combined winter and spring, and summer precipitation; temperature, measured as the number of days with maximum temperatures in the following ranges: $[25, 29]$, $[29, 31]$, $[31, 35]$, and $[35, \infty^{+})$ in Celsius degrees; and a dummy for whether the plot has groundwater rights. All regressions include $1^\circ \times 1^\circ$ cell fixed effects and year fixed effects. Standard errors are clustered by county.

Table IX: Irrigation Technology: Instrumental Variables Estimation at the Farm Level

Panel A: Full Sample

	Traditional Irrigation (Furrow)				Micro Irrigation			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
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]	$(-\infty, \infty)$			[-.0281, .4113]	$(-\infty, \infty)$

Panel B: Large Farms

	Traditional Irrigation (Furrow)				Micro Irrigation			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
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	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream
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]	$(-\infty, \infty)$			[.09749, .8081]	$(-\infty, \infty)$

Panel C: Small Farms

	Traditional Irrigation (Furrow)				Micro Irrigation			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
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	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream
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]	$(-\infty, \infty)$			[-.3621, .2486]	$(-\infty, \infty)$

Notes: This table presents estimates of equation 9 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.

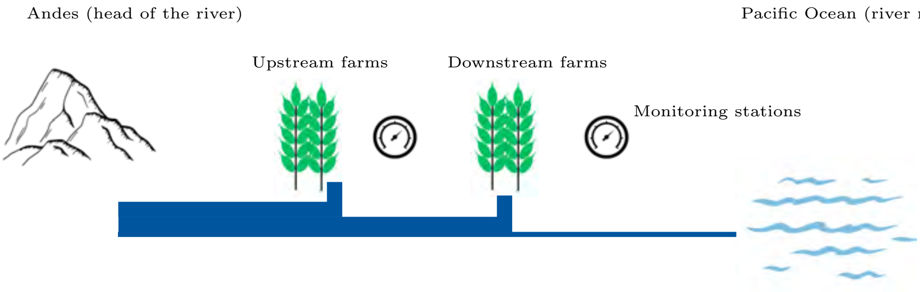
Table X: Monitoring Stations by Year of Board Establishment

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		

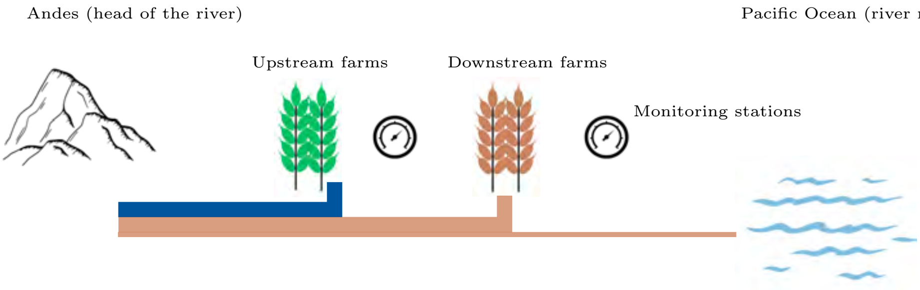
Notes: This table shows the total number of monitoring stations in our area of study, and the establishment date of a water board (in case the monitoring station is in a subsubbasin within the jurisdiction of a water board).

Figures

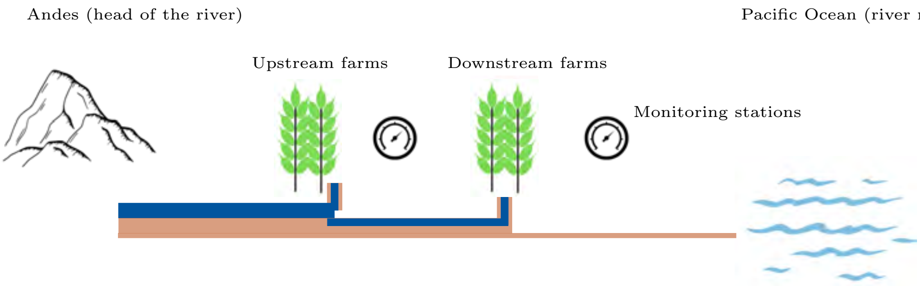
Figure I: How Property Rights Enforcement Affects Water Allocation and Agricultural Outcomes



(a) No drought

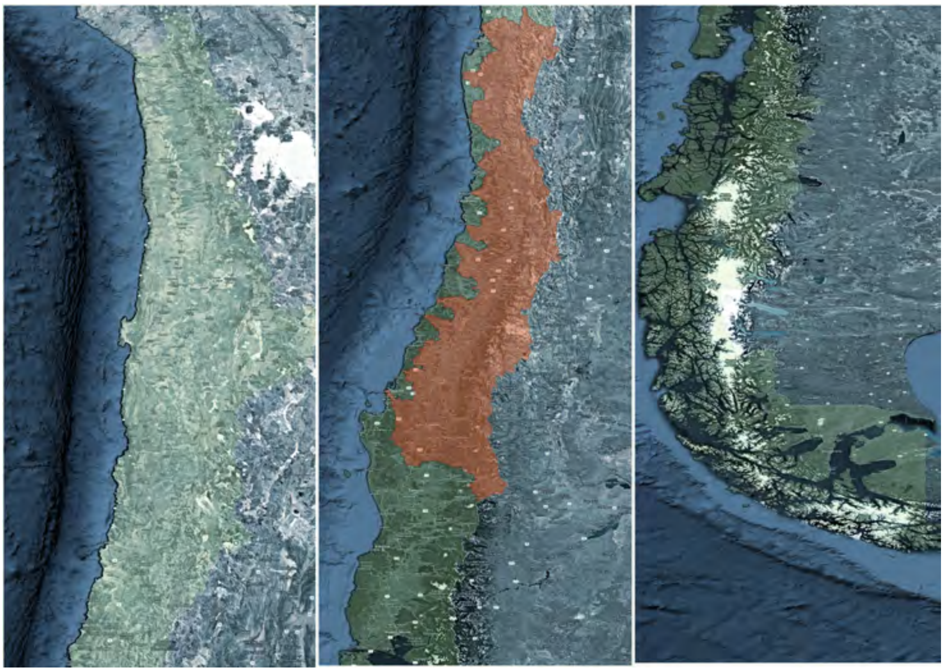


(b) Drought, and no enforcement of water rights



(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.

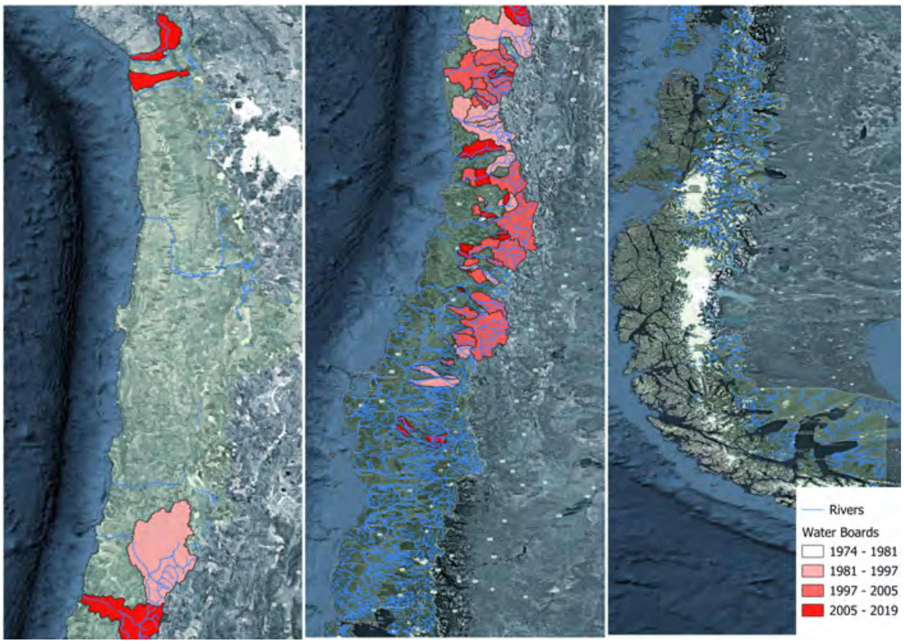
Figure III: Basins and Rivers in Area of Study

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: 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.

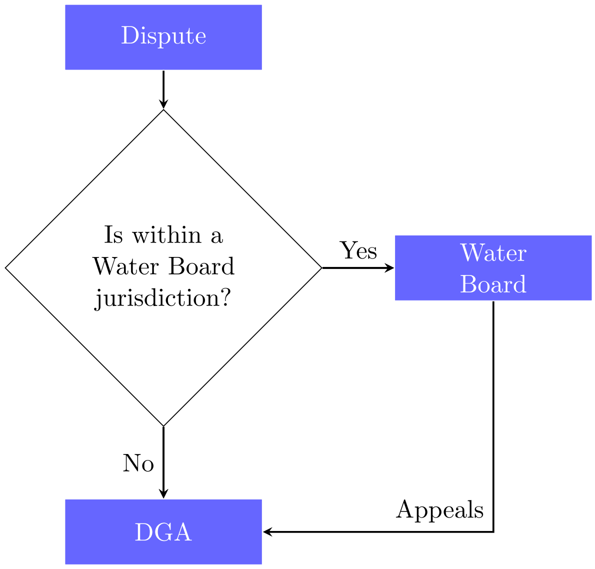
Figure V: Water Boards Jurisdictions



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 VI: Administrative and Legal Hierarchy of Institutions over Water Rights Issues

(a) Administrative



(b) Legal

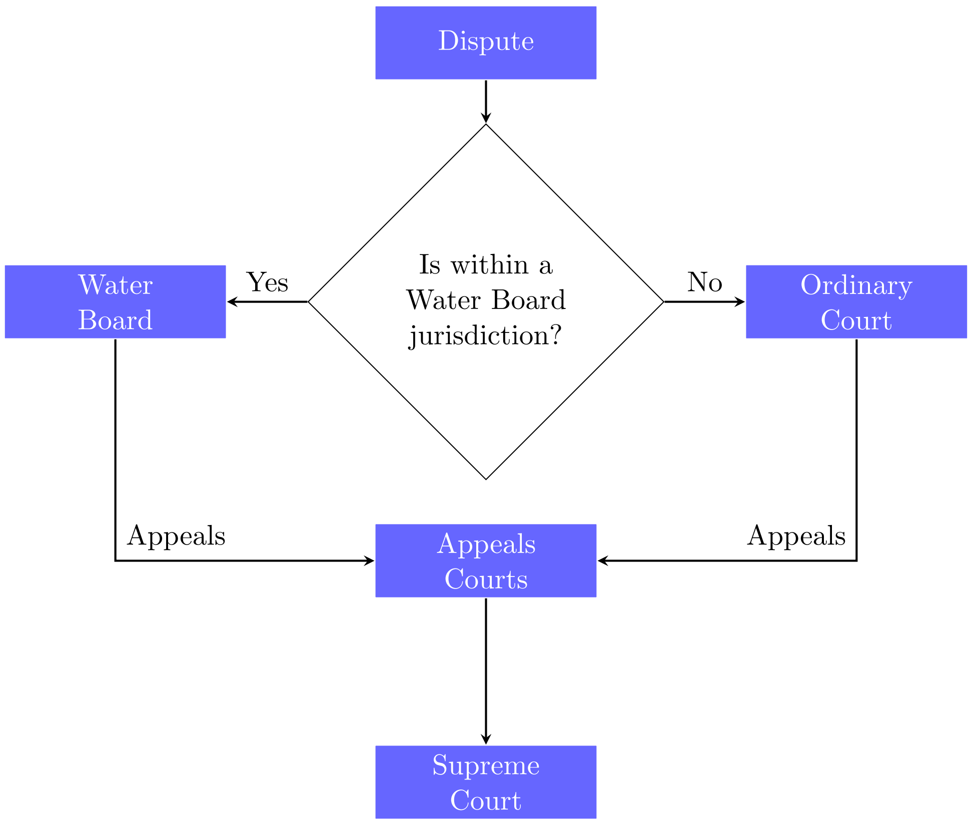
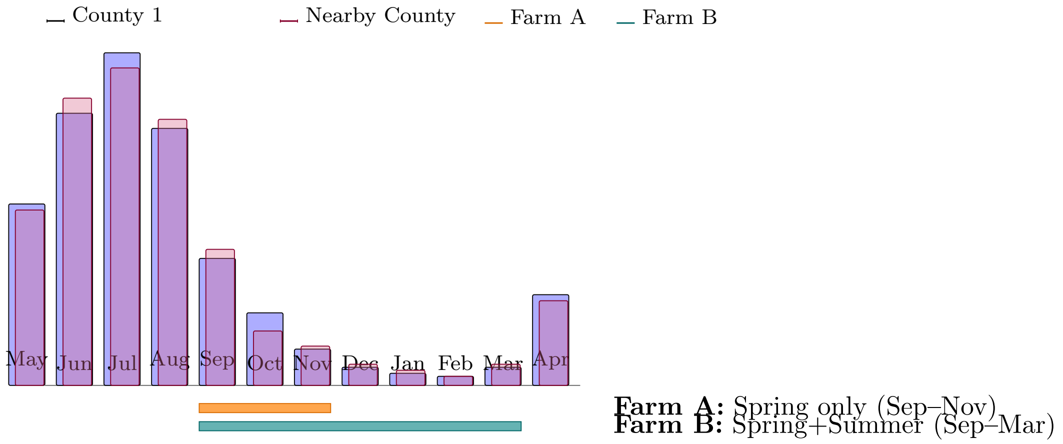


Figure VII: Data Sources and Corresponding Analyses

Data Sources	Analysis (Section)	Unit
2007 Agricultural Census	Misallocation Test (Section 4)	Farm Level
Land Plots (SII/CIREN) Satellite Data (LANDSAT 5)	DID & IV Analysis (Section 5)	Plot Level
Streamflow Data (DGA)	Basin Analysis (Section 6)	Basin Level

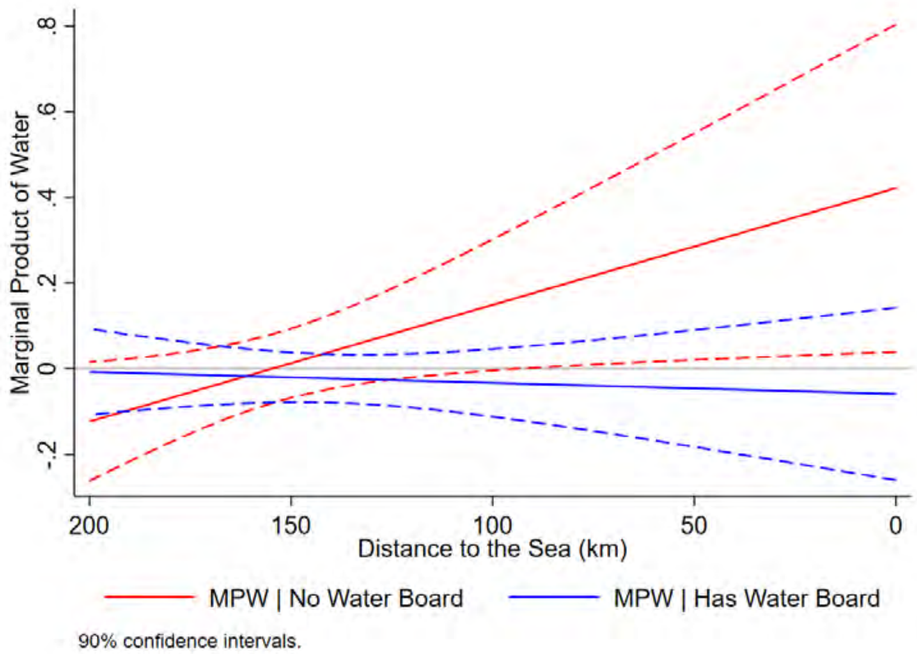
Notes: All analyses use water organization data (DGA), as well as climate data and basin boundaries from CR^2, as common inputs. The table presents additional data sources, along with their corresponding analyses and units of observation.

Figure VIII: Construction of Useful Rainfall



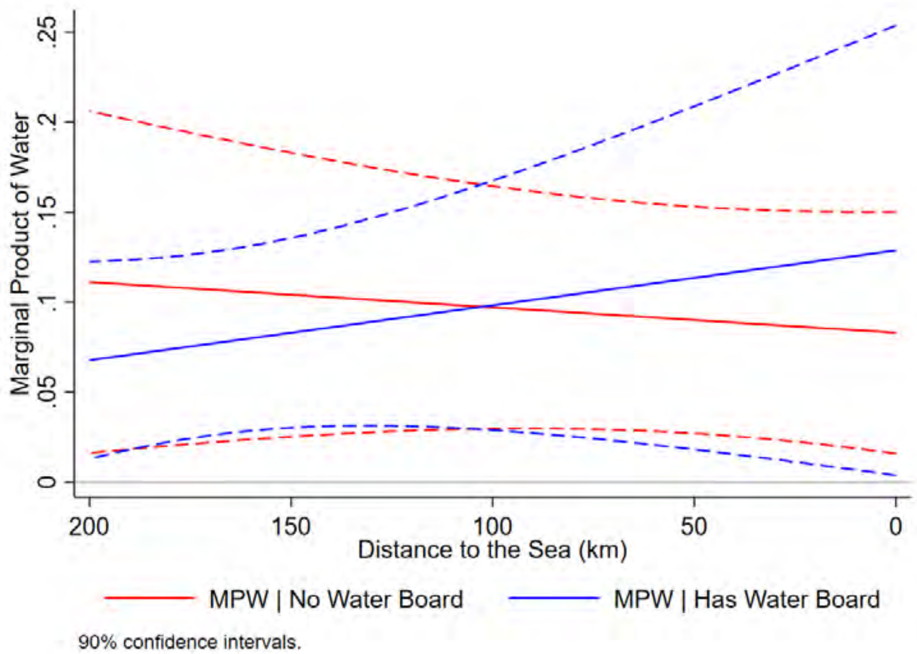
Notes: This figure illustrates the construction of our measure of useful rainfall, and the sources of variation. We define useful rainfall as the rainfall falling in a farmer's county when their crop needs irrigation. In this example, Farm A and Farm B are located in County 1, with rainfall over the agricultural year depicted with the blue bars. While Farm A chose a crop that follows the yellow irrigation schedule, Farm B chose one that follows the green schedule. Therefore, all the rainfall received by both farms in the months of December, January and February is useful for farm A but not farm B. Another source of variation is provided by the space: consider another farm following the same irrigation schedules as farm A, but located in a nearby county, facing rainfall illustrated in red bars. That farm will have a marginally different water input than A, given the different rainfall received on each month in their county.

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

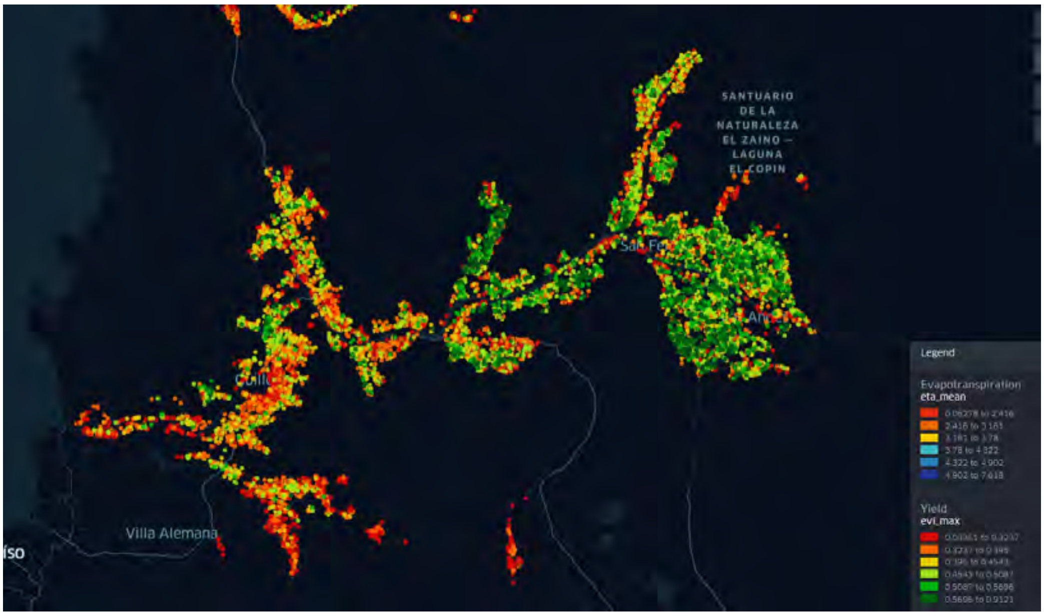


Notes: Graphical representation of results in Table III.

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

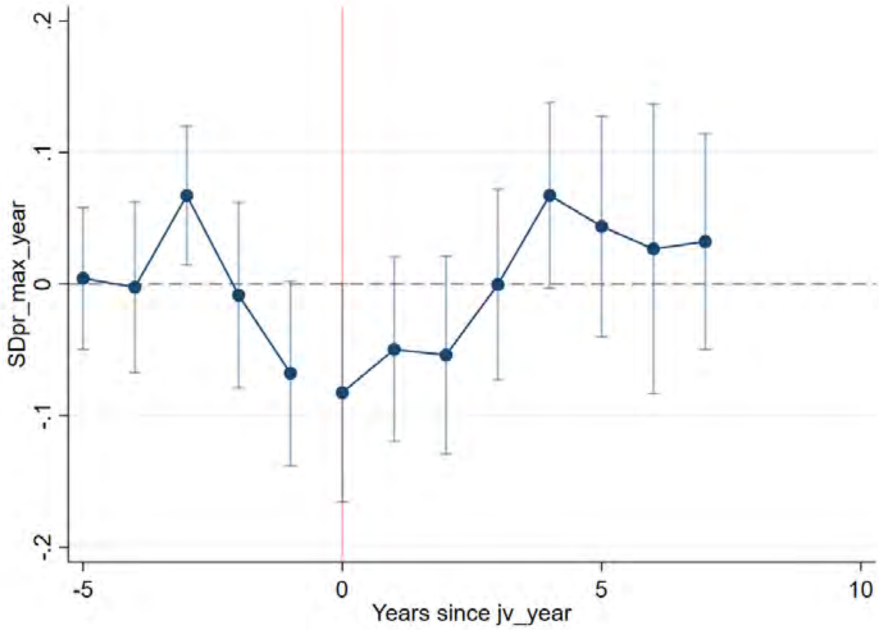
(a) Water Consumption

(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.

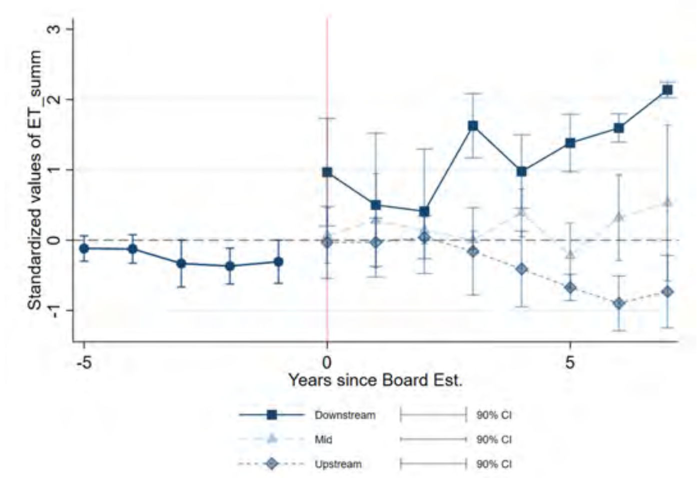
Figure XII: Precipitation dynamics around Water Board events



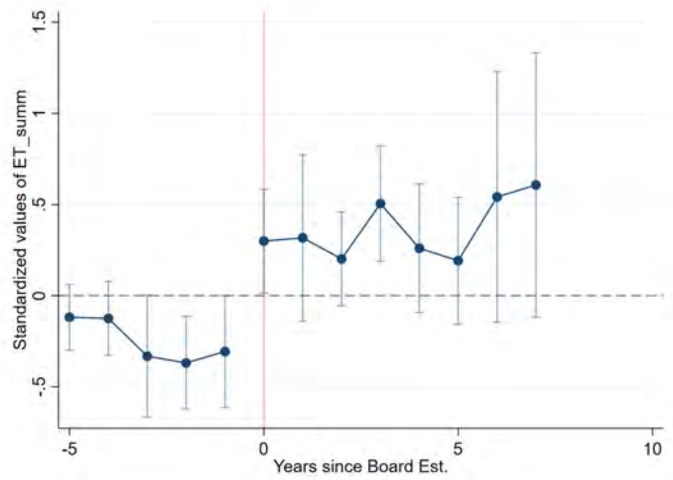
Notes: This figure presents the dynamics of standardized precipitation around Water Board establishment events, using the staggered difference-in-differences imputation estimator by Borusyak et al. (2024). The x-axis shows years relative to the establishment year, with year 0 indicating the establishment year. The sample includes farms located in basins with Water Boards established between 1981-2010, covering 5 years pre- and 7 years post-establishment. Controlling for plot-level fixed effects, and flexible time trends by latitude-longitude cells (2°×2°) and quantile of location in the basin. Standard errors estimated using Borusyak et al. (2024) leave-one-out procedure, clustering at the 3rd level basin.

Figure XIII: Differences-in-Differences estimates of Impacts of Water Boards on Standardized Water Consumption

(a) Heterogeneous Impacts, by tercile of distance to the coast.



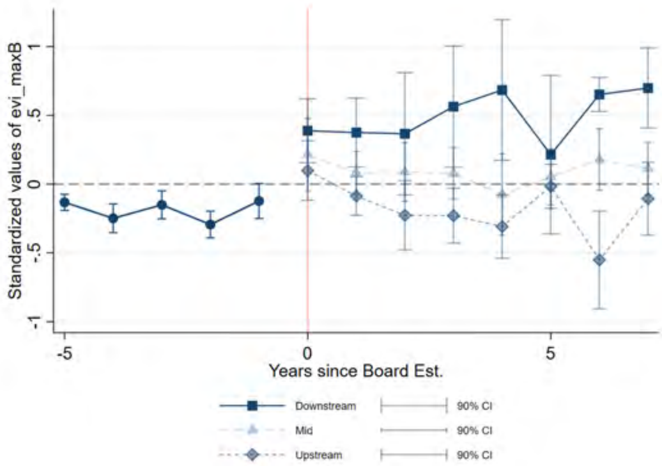
(b) Combined estimates.



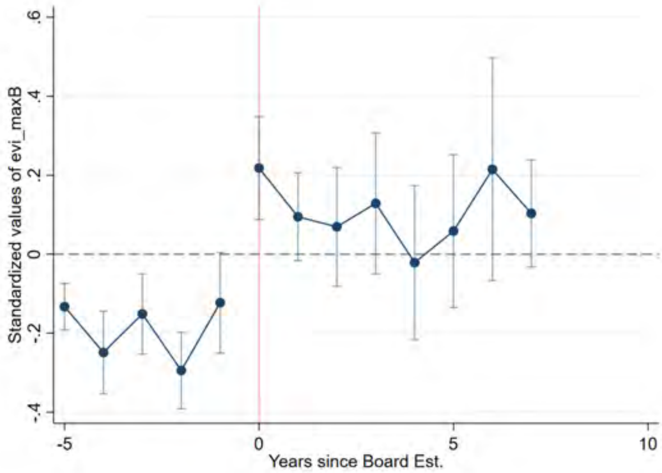
Notes: This figure presents difference-in-differences estimates of the impact of Water Board establishment on standardized summer evapotranspiration, using the staggered difference-in-differences imputation estimator by Borusyak et al. (2024).Panel A presents heterogeneous effects by location within the river basin, where the solid blue line with squares represents downstream farms, the dashed gray line with triangles shows mid-basin farms, and the dotted line with diamonds represents upstream farms. Panel B presents combined estimates aggregating across all farm locations within basins. The x-axis shows years relative to Water Board establishment, with year 0 marking the establishment year. The sample includes farms located in basins with Water Boards established between 1981-2010, covering 5 years pre- and 7 years post-establishment. Controlling for plot-level fixed effects and flexible time trends by latitude-longitude cells ($2^{\circ}\times2^{\circ}$) and quantile of location in the basin. Standard errors estimated using Borusyak et al. (2024) leave-one-out procedure, clustering at the clustering at the 3rd level basin.

Figure XIV: Differences-in-Differences estimates of Impacts of Water Boards on Standardized Agricultural Yield

(a) Heterogeneous Impacts, by tercile of distance to the coast.

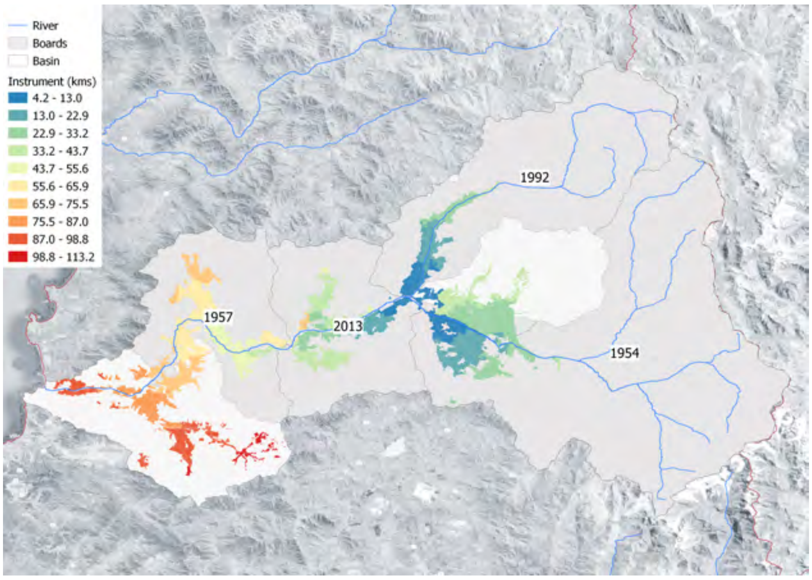


(b) Combined estimates.



Notes: This figure presents difference-in-differences estimates of the impact of Water Board establishment on standardized agricultural productivity (EVI), using the staggered difference-in-differences imputation estimator by Borusyak et al. (2024). Panel A presents heterogeneous effects by location within the river basin, where the solid blue line with squares represents downstream farms, the dashed gray line with triangles shows mid-basin farms, and the dotted line with diamonds represents upstream farms. Panel B presents combined estimates aggregating across all farm locations within basins. The x-axis shows years relative to Water Board establishment, with year 0 marking the establishment year. The sample includes farms located in basins with Water Boards established between 1981-2010, covering 5 years pre- and 7 years post-establishment. Controlling for plot-level fixed effects and flexible time trends by latitude-longitude cells ($2^{\circ}\times 2^{\circ}$) and quantile of location in the basin. Standard errors estimated using Borusyak et al. (2024) leave-one-out procedure, clustering at the clustering at the 3rd level basin.

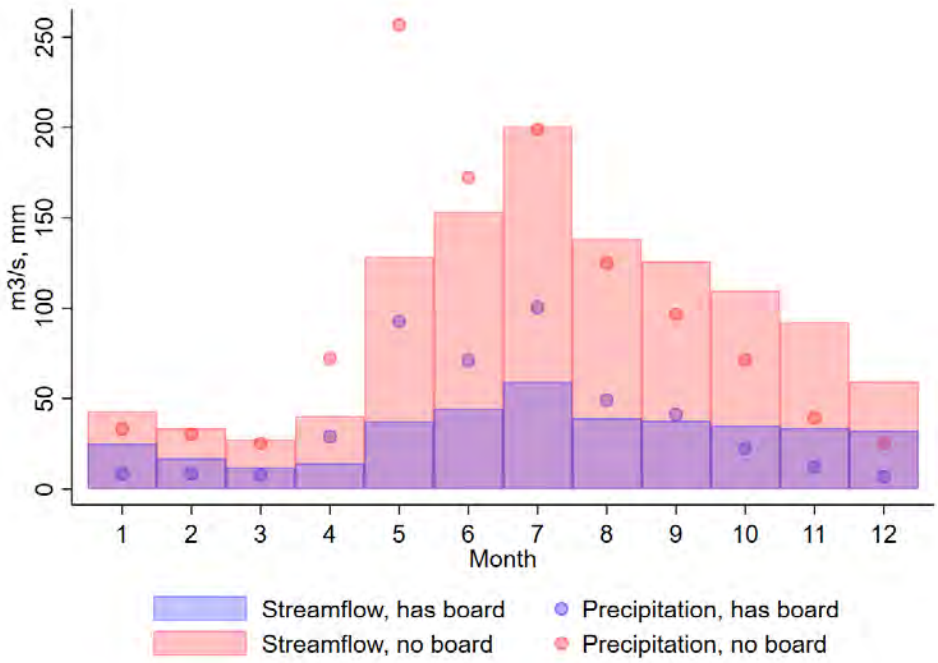
Figure XV: Example: Farm Level Data and Distance to Most Upstream in Aconcagua Basin Capital



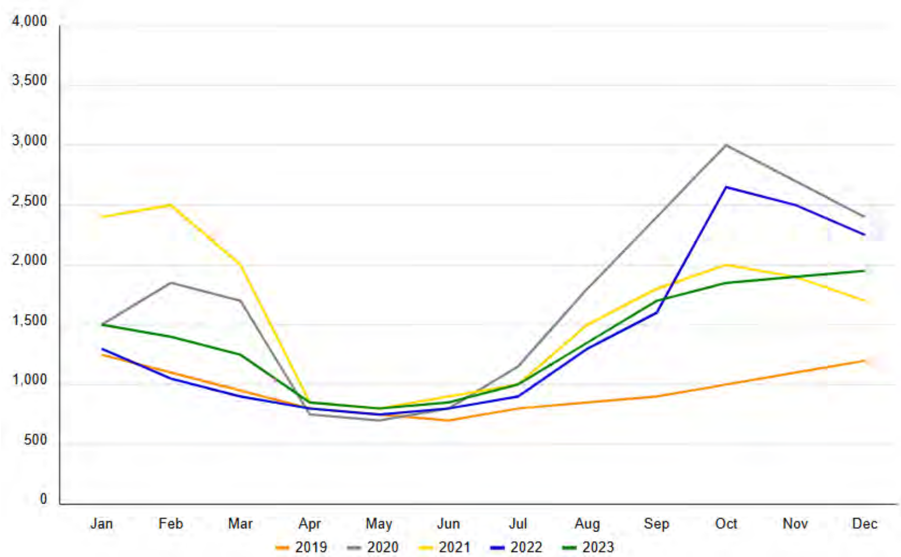
Notes: The map presents the Aconcagua Basin, illustrating the jurisdiction and year of Establishment of its four Water Boards, and our sample of irrigated farms. The color of each farm plot represents distance through the road network to the most upstream province capital.

Figure XVI: Comparing rivers with and without Water Boards

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

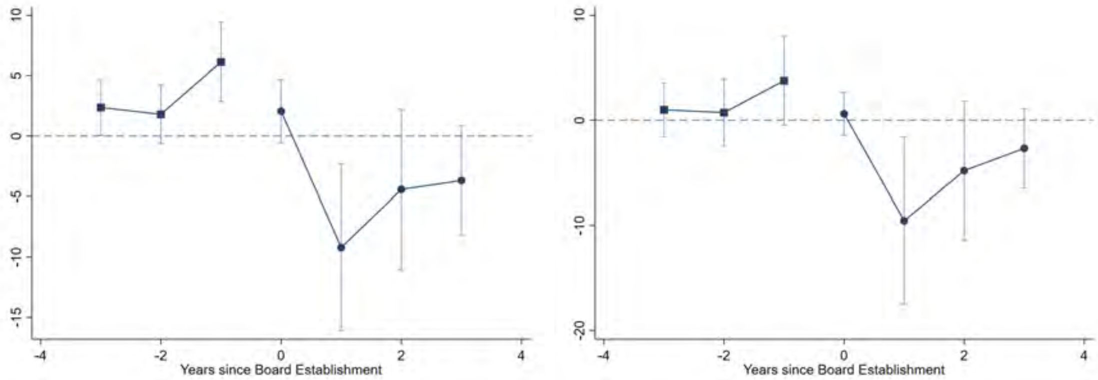


(b) Water Distribution by El Arrayan Water Board to Governed Canals, 2019-2023



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.

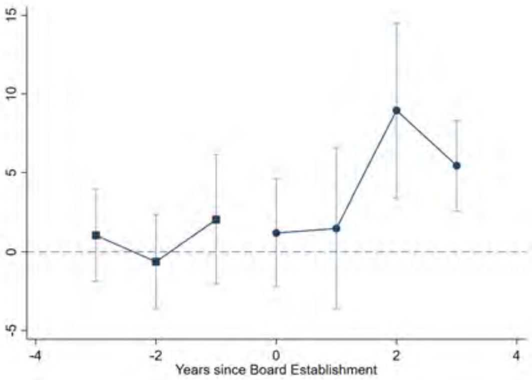
Figure XVII: Precipitations and Board Establishment Events (Placebo) Event



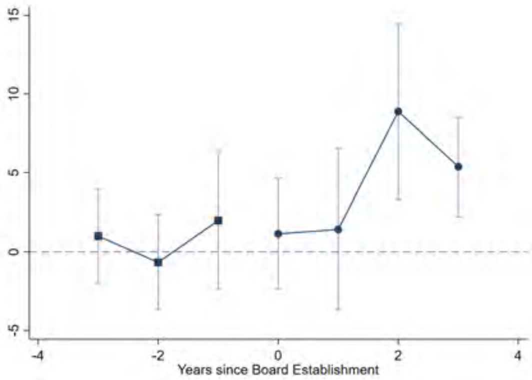
(a) Full sample (b) Event Study sample

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.

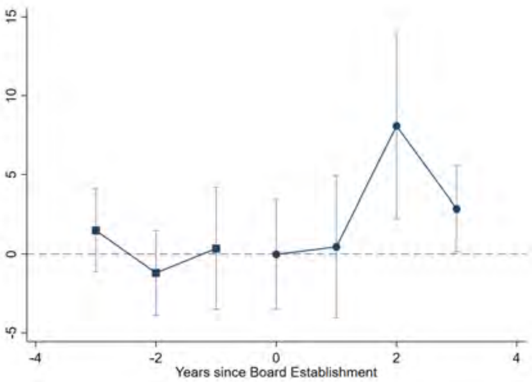
Figure XVIII: Dynamic Effects of Board Establishment Events on Dry Season Streamflow



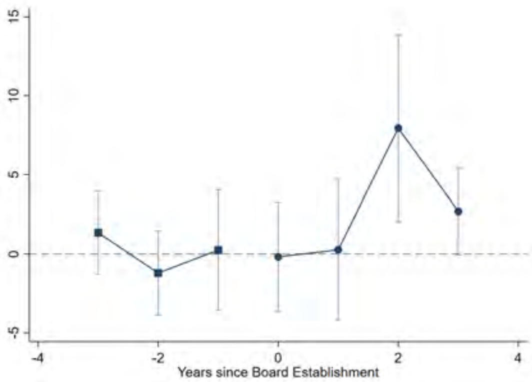
(a) Full sample



(b) Full sample - water reclamations control



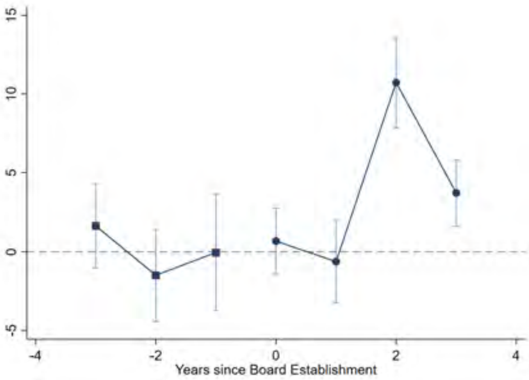
(c) Event Study sample



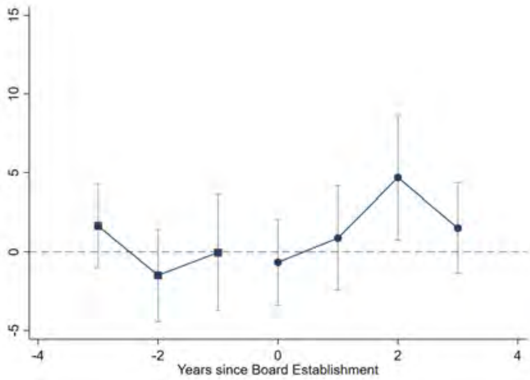
(d) Event Study sample - water reclamations control

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.

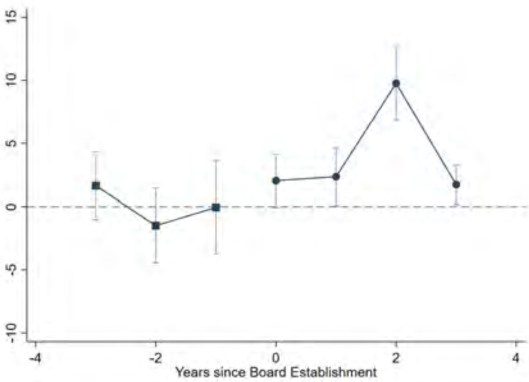
Figure XIX: Heterogeneous Effects on Dry Season Streamflow by Location and Cropland Share



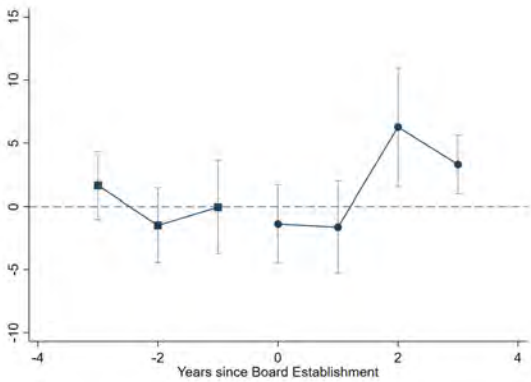
(a) Upstream monitoring stations



(b) Downstream monitoring stations



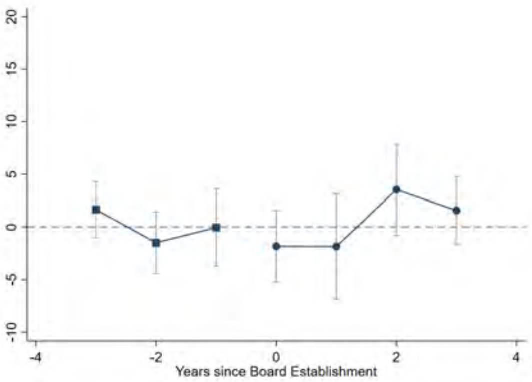
(c) Above median cropland share



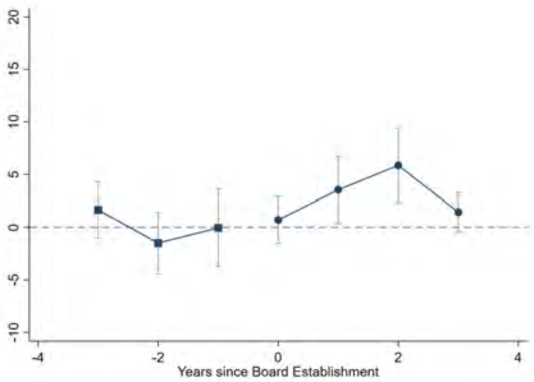
(d) Below median cropland share

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.

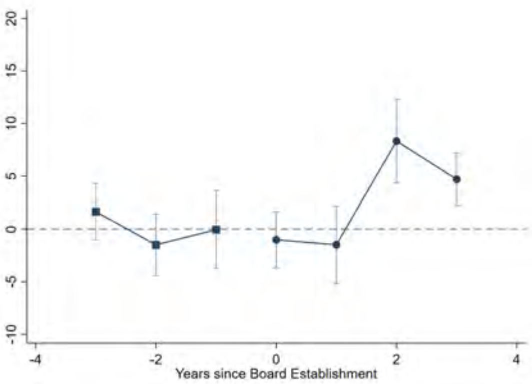
Figure XX: Heterogeneous Effects on Dry Season Streamflow by Location-Cropland Combinations



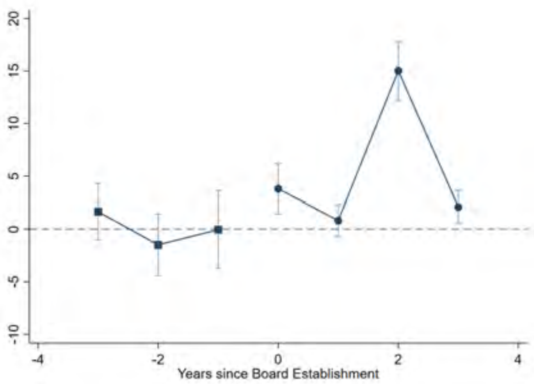
(a) Downstream farms with low cropland share



(b) Upstream farms with low cropland share



(c) Downstream farms with high cropland share

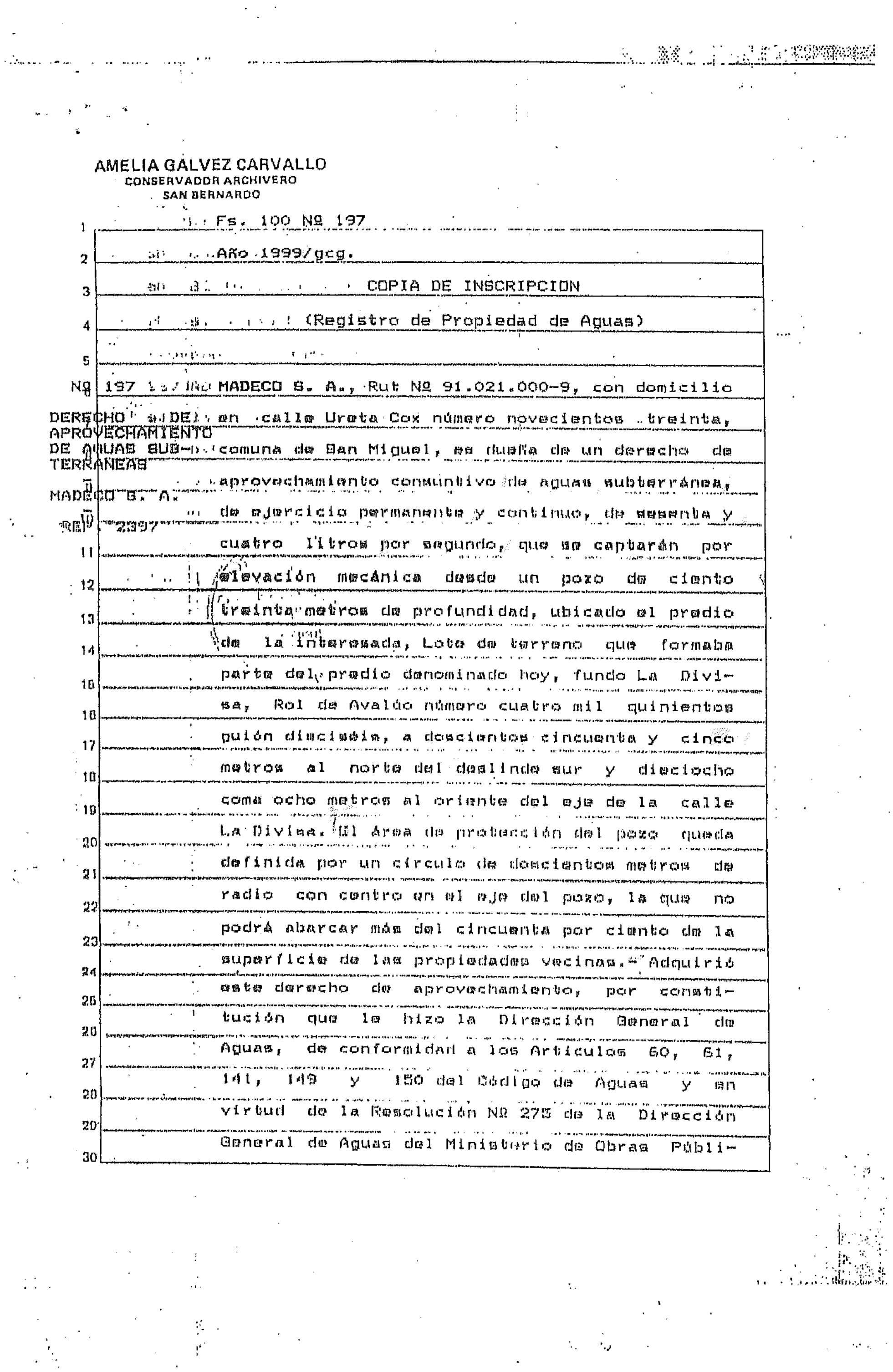


(d) Upstream farms with high cropland share

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.

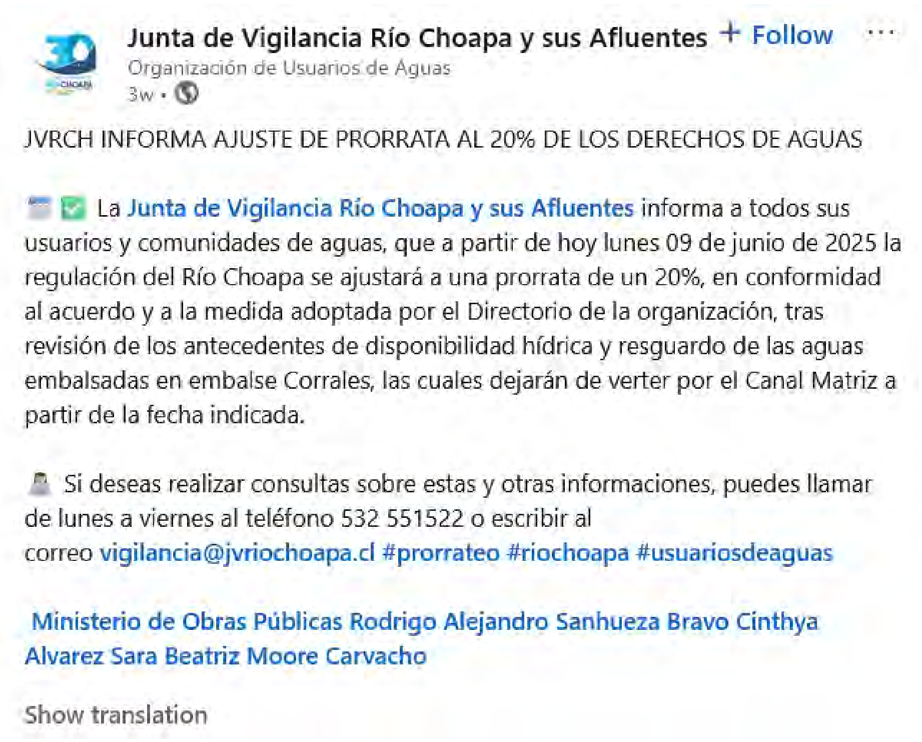
COPIA DE INSCRIPCION

(Registro de Propiedad de Aguas)

Nº 197 — DERECHO DE APROVECHAMIENTO DE AGUAS SUBTERRANEAS — MADECO S. A. — REP 2397

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 área de protección del pozo queda definida por un círculo de doscientos metros de radio con centro en el eje del pozo, la que no podrá abarcar más del cincuenta por ciento de la superficie de las propiedades vecinas.- Adquirió este derecho de aprovechamiento, por constitución que le hizo la Dirección General de Aguas, de conformidad a los Artículos 60, 61, 141, 149 y 150 del Código de Aguas y en virtud de la Resolución Nº 275 de la Dirección General de Aguas del Ministerio de Obras Públi-

Figure A.II: Water Rights Proration Adjustment



Junta de Vigilancia Río Choapa y sus Afluentes + Follow ···

Organización de Usuarios de Aguas

3w •

JVRCH INFORMA AJUSTE DE PRORRATA AL 20% DE LOS DERECHOS DE AGUAS

La Junta de Vigilancia Río Choapa y sus Afluentes informa a todos sus usuarios y comunidades de aguas, que a partir de hoy lunes 09 de junio de 2025 la regulación del Río Choapa se ajustará a una prorrata de un 20%, en conformidad al acuerdo y a la medida adoptada por el Directorio de la organización, tras revisión de los antecedentes de disponibilidad hídrica y resguardo de las aguas embalsadas en embalse Corrales, las cuales dejarán de verter por el Canal Matriz a partir de la fecha indicada.

Si deseas realizar consultas sobre estas y otras informaciones, puedes llamar de lunes a viernes al teléfono 532 551522 o escribir al correo vigilancia@jvriochoapa.cl #prorrateo #riochoapa #usuariosdeaguas

Ministerio de Obras Públicas Rodrigo Alejandro Sanhueza Bravo Cinthya Alvarez Sara Beatriz Moore Carvacho

Show translation

Notes: Screenshot taken on July 29, 2025, from a LinkedIn post by Junta de Vigilancia Río Choapa y sus Afluentes.

Figure A.III: General Assembly of Water Users

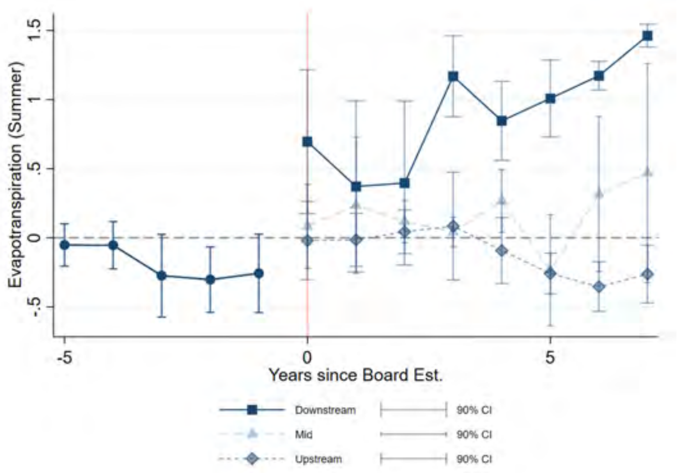
Notes: Screenshot taken on July 29, 2025, from a LinkedIn post by Junta de Vigilancia Río Choapa y sus Afluentes.

Figure A.IV: Irrigation Infrastructure Maintenance

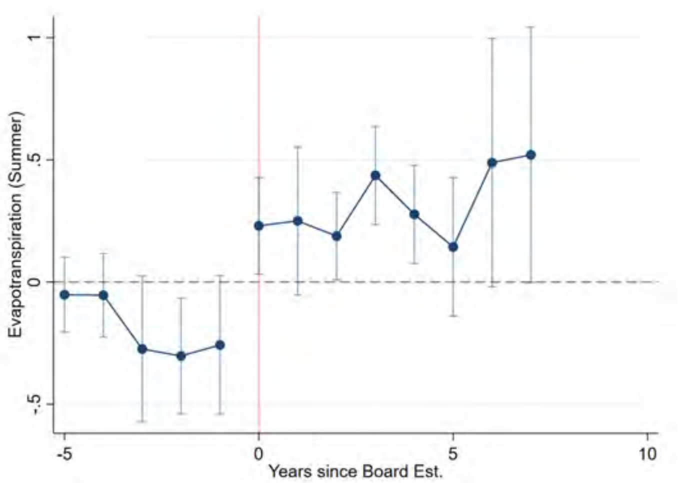
Notes: Photograph of a cleaning campaign, as featured on the official website of the Junta de Vigilancia del Río Maipo, depicting canal maintenance activities. Image retrieved on July 29, 2025, from their website: https://jvriomaipo.cl/limpieza-basura-canales-regadio/.

Figure A.V: Difference-in-Differences estimates of Impacts of Water Boards on Water Consumption (non-standardized)

(a) Heterogeneous Impacts, by tercile of distance to the coast.



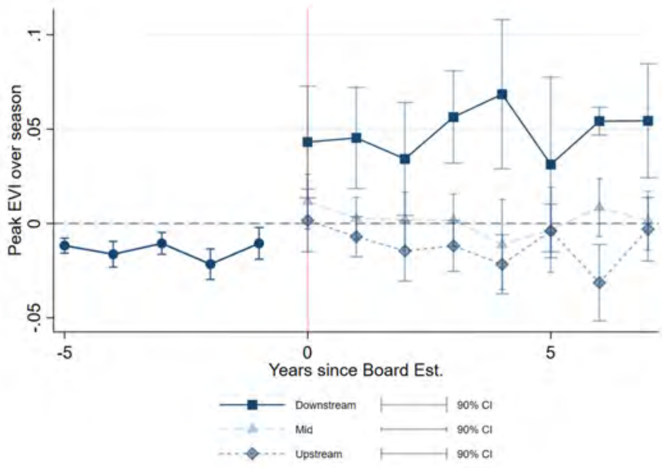
(b) Combined estimates



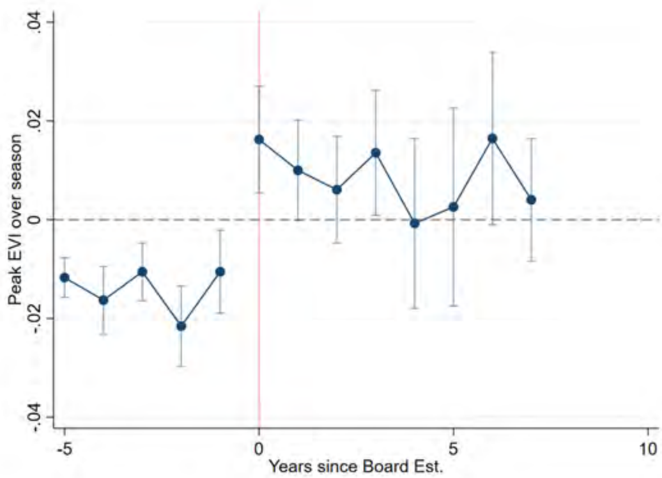
Notes: This figure presents difference-in-differences estimates of the impact of Water Board establishment on non-standardized standardized summer evapotranspiration, using the staggered difference-in-differences imputation estimator by Borusyak et al. (2024). Panel A presents heterogeneous effects by location within the river basin, where the solid blue line with squares represents downstream farms, the dashed gray line with triangles shows mid-basin farms, and the dotted line with diamonds represents upstream farms. Panel B presents combined estimates aggregating across all farm locations within basins. The x-axis shows years relative to Water Board establishment, with year 0 marking the establishment year. The sample includes farms located in basins with Water Boards established between 1981-2010, covering 5 years pre- and 7 years post-establishment. Controlling for plot-level fixed effects and flexible time trends by latitude-longitude cells (2°×2°) and quantile of location in the basin. Standard errors estimated using Borusyak et al. (2024) leave-one-out procedure, clustering at the clustering at the 3rd level basin.

Figure A.VI: Difference-in-Differences estimates of Impacts of Water Boards on Agricultural Yield (non-standardized)

(a) Heterogeneous Impacts, by tercile of distance to the coast.



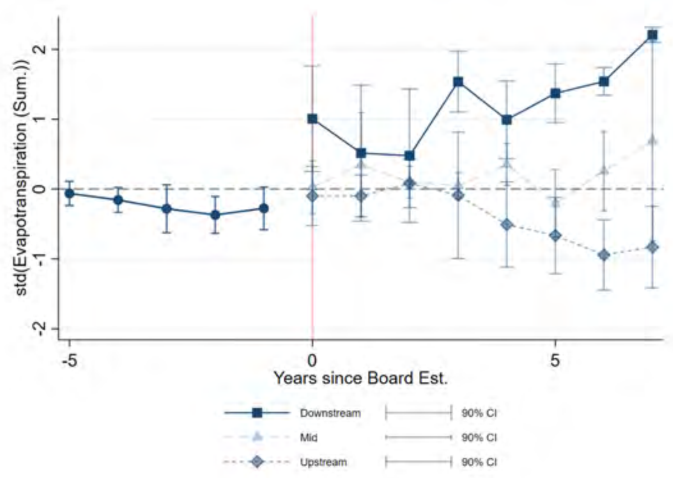
(b) Combined estimates



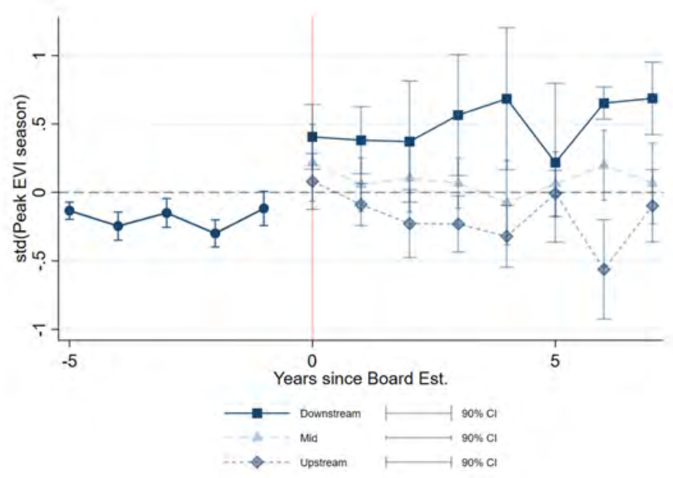
Notes: This figure presents difference-in-differences estimates of the impact of Water Board establishment on non-standardized agricultural productivity (EVI), using the staggered difference-in-differences imputation estimator by Borusyak et al. (2024). Panel A presents heterogeneous effects by location within the river basin, where the solid blue line with squares represents downstream farms, the dashed gray line with triangles shows mid-basin farms, and the dotted line with diamonds represents upstream farms. Panel B presents combined estimates aggregating across all farm locations within basins. The x-axis shows years relative to Water Board establishment, with year 0 marking the establishment year. The sample includes farms located in basins with Water Boards established between 1981-2010, covering 5 years pre- and 7 years post-establishment. Controlling for plot-level fixed effects and flexible time trends by latitude-longitude cells (2°×2°) and quantile of location in the basin. Standard errors estimated using Borusyak et al. (2024) leave-one-out procedure, clustering at the clustering at the 3rd level basin.

Figure A.VII: Differences-in-Differences estimates of Impacts of Water Boards with Controls

(a) Water Consumption: Heterogeneous Impacts, by tercile of distance to the coast.

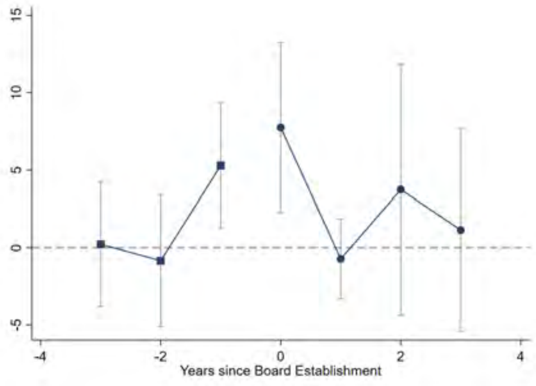


(b) Agricultural Yield: Heterogeneous Impacts, by tercile of distance to the coast.

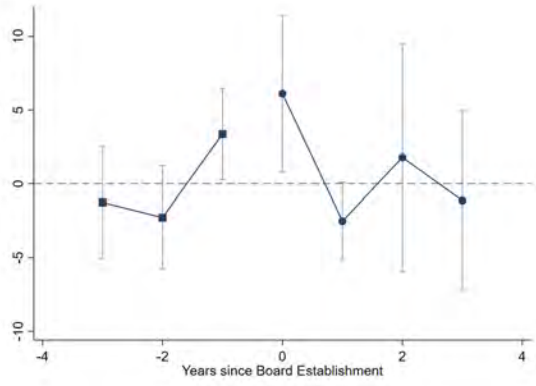


Notes: Notes: This figure presents heterogeneous effects by location within the river basin for standardized Water Consumption (Panel A) and standardized agricultural yield (Panel B), using the staggered difference-in-differences imputation estimator by Borusyak et al. (2024). In both panels, the solid blue line with squares represents downstream farms, the dashed gray line with triangles shows mid-basin farms, and the dotted line with diamonds represents upstream farms. The x-axis shows years relative to Water Board establishment, with year 0 marking the establishment year. The sample includes farms located in basins with Water Boards established between 1981–2010, covering 5 years pre- and 7 years post-establishment. Estimates control for plot-level fixed effects, annual climatic characteristics (total precipitation, summer precipitation, and temperature ranges), and flexible time trends by latitude-longitude cells (2°×2°) and quantile of location in the basin. Standard errors are estimated using the Borusyak et al. (2024) leave-one-out procedure, clustering at the 3rd level basin.

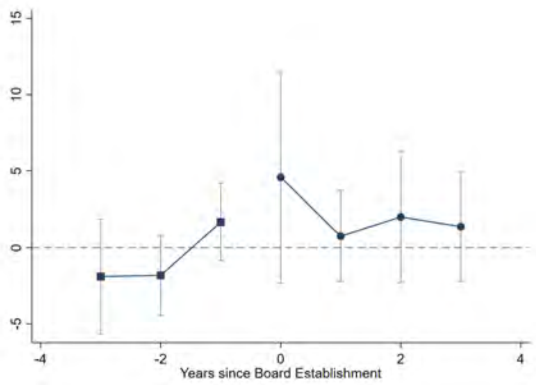
Figure A.VIII: Dynamic Effects of Board Establishment Events on Streamflow - Full Year



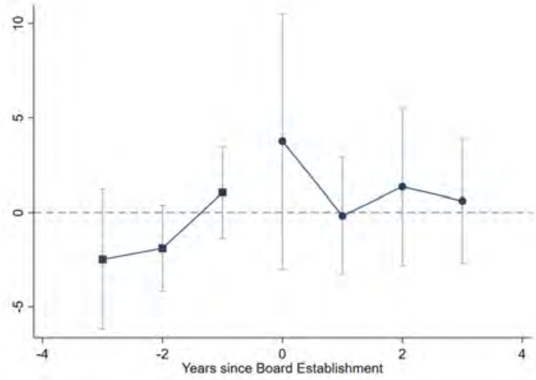
(a) Full sample



(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: Misallocation Test: Additional robustness checks

	Outcome is log(Value Yield p/Hectare)		
	(1)	(2)	(3)
	m5	m6	m7
Useful pp. (m3 per Ha per month) × Distance to coast (100km)	-0.221	-0.203	-0.270
	(0.118)*	(0.110)*	(0.147)*
	[0.116]*	[0.108]*	[0.143]*
Water Board=1 × Useful pp. (m3 per Ha per month)	-0.362	-0.410	-0.480
	(0.242)	(0.223)*	(0.256)*
	[0.234]	[0.218]*	[0.249]*
Water Board=1 × Useful pp. (m3 per Ha per month) × Distance to coast (100km)	0.208	0.262	0.297
	(0.160)	(0.147)*	(0.168)*
	[0.152]	[0.141]*	[0.162]*
Parcel Controls	Yes	Yes	Yes
County Controls	Yes	No	No
Bin (Lat, Lon) FE	Yes	No	No
County FE	No	Yes	Yes
Useful Rain. × Crop FE	Yes	Yes	No
Useful Rain. × Fertirigation	No	No	Yes
Observations	14,714	14,712	14,712
R-squared	0.662	0.674	0.642
Misallocation Test: Water Board=0	0.06	0.07	0.07
Misallocation Test: Water Board=1	0.89	0.52	0.74

Notes: this table present different robustness check, including new control variables and interactions of useful rainfall with some relevant controls. We regress $\log(Y)$ of rainfall during the irrigation season by longitude and treatment status for irrigated parcels registered in canal associations.

Table A.II: Correlation between the Instrumental Variable and Other Covariates

	(1) Downstream	(2) Mid Section	(3) Upstream
Climatic covariates			
Mean summer prec.	.0055 (.0039)	.0038 (.0033)	.00034 (.0021)
Mean annual prec.	.01 (.024)	.022 (.023)	.0044 (.016)
Days between 25 and 29 $°C$	-.00024 (.0003)	-.00041 (.00036)	-.00013 (.00039)
Days between 29 and 31 $°C$	-.00004 (.00013)	-.000038 (.00016)	-.00012 (.0002)
Days between 31 and 35 $°C$	.000012 (.00013)	.000027 (.0001)	-.00022 (.00017)
Days above 35 $°C$	-.000011 (.000015)	-3.6e-06 (.000024)	-.000044 (.000026)
Market Access			
Distance to Santiago (main dom. market)	.0011 (.00077)	.0024 * (.0014)	.0017 (.0014)
Distance to Valparaiso (main port)	-.0016 (.0011)	.001 (.0015)	.000045 (.0015)
Distance to San Antonio (second main port)	.0004 (.00092)	.00077 (.0015)	.000031 (.0015)
Farm Characteristics			
log(area)	-.000039 (.000023)	.000051 *** (.000013)	.000014 (.000017)
Potential Yield under irrigation, high input (FAO/GAEZ)	-.016 (.01)	.022 (.017)	.011 (.011)

Notes: Each row reports the coefficient from a separate regression of the listed covariate on the instrument. All regressions include fixed effects for year and for 1°×1° grid cells. No additional controls are included. Standard errors clustered by county.

Table A.III: Water Consumption: IV Estimation using Linear Distance Instrument

Panel A: Main Result

	OLS			IV		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	-0.0210	-0.0993	0.0487	2.148	-2.733	-0.555
	(0.101)	(0.0677)	(0.0851)	(0.981)**	(3.453)	(0.480)
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes
Plot controls	Yes	Yes	Yes	Yes	Yes	Yes
Spatial cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	139,693	144,580	143,795	139,693	144,580	143,795
R-squared	0.298	0.357	0.371	-0.010	-0.524	0.336
Mean Dependent Var.				2.953	3.476	3.407
AR test CI				[.6008, 5.955]	$(-\infty, \infty)$	[-2.331, .3081]

Panel B: First Stage

	(1) Downstream	(2) Mid section	(3) Upstream
ucd	-0.00435	0.00121	0.00429
	(0.00133)***	(0.00151)	(0.00143)***
Observations	141,675	144,580	143,795
R-squared	0.532	0.322	0.379
Effective F-stat	10.164	0.637	8.963

Notes: This table presents estimates of equation 9 for parcels located at elevations below 1,000 meters and within 150 km of the river mouth in the study area. The outcome variable is the average Evapotranspiration for each plot in the Summer months (January and February), for the period 2005-2009. The instrument corresponds to the optimal-route distance between the land plot and the most upstream province capital city in the basin. 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 market access measures (driving distance to Santiago and the main ports of Valparaíso and San Antonio); dummies for soil quality quartiles; annual, combined winter and spring, and summer precipitation; temperature, measured as the number of days with maximum temperatures in the following ranges: $[25, 29]$, $[29, 31]$, $[31, 35]$, and $[35, \infty^{+})$ in Celsius degrees; and a dummy for whether the plot has groundwater rights. All regressions include $1^{\circ} \times 1^{\circ}$ cell fixed effects and year fixed effects. Standard errors are clustered by county.

Table A.IV: Agricultural Productivity: IV Estimation using Linear Distance Instrument

Panel A: Main Result

	OLS			IV		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	0.000500	-0.000508	0.0120	0.212	-0.105	0.0289
	(0.00740)	(0.00656)	(0.00647)*	(0.0884)**	(0.175)	(0.0330)
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes
Plot controls	Yes	Yes	Yes	Yes	Yes	Yes
Spatial cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	141,675	144,580	143,795	141,675	144,580	143,795
R-squared	0.278	0.178	0.247	-0.018	0.041	0.244
Mean Dependent Var.				0.370	0.413	0.410
AR test CI				[.08338, .574]	($-\infty$, ∞)	[-.0425, .1301]

Panel B: First Stage

	(1) Downstream	(2) Mid section	(3) Upstream
ucd	-0.00435	0.00121	0.00429
	(0.00133)***	(0.00151)	(0.00143)***
Observations	141,675	144,580	143,795
R-squared	0.532	0.322	0.379
Effective F-stat	10.703	0.637	8.963

Notes: This table presents estimates of equation 9 for parcels located at elevations below 1,000 meters and within 150 km of the river mouth in the study area. The outcome variable is the maximum value of the Enhanced Vegetation Index (EVI) reached within the year, for the period 2005-2009. The instrument corresponds to the optimal-route distance between the land plot and the most upstream province capital city in the basin. Distance to the coast was measured through the river network. Plot-level controls include market access measures (driving distance to Santiago and the main ports of Valparaíso and San Antonio); dummies for soil quality quartiles; annual, combined winter and spring, and summer precipitation; temperature, measured as the number of days with maximum temperatures in the following ranges: $[25, 29]$, $[29, 31]$, $[31, 35]$, and $[35, \infty^{+})$ in Celsius degrees; and a dummy for whether the plot has groundwater rights. All regressions include $1^{\circ} \times 1^{\circ}$ cell fixed effects and year fixed effects. Standard errors are clustered by county.

Table A.V: Water Consumption: IV Estimation using Piece-wise Linear Distance Instrument

Panel A: Main Result

	OLS			IV		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	-0.0210	-0.0993	0.0487	1.976	-3.299	-0.844
	(0.101)	(0.0677)	(0.0851)	(0.871)**	(4.507)	(0.527)
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes
Plot controls	Yes	Yes	Yes	Yes	Yes	Yes
Spatial cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	139,693	144,580	143,795	139,693	144,580	143,795
R-squared	0.298	0.357	0.371	0.036	-0.944	0.293
Mean Dependent Var.				2.953	3.476	3.407
AR test CI				[.5774, 5.146]	($-\infty$, ∞)	[-3.439, -.03336]

Panel B: First Stage

	(1) Downstream	(2) Mid section	(3) Upstream
$\min\{pcd, 30\}$	-0.00489	0.00120	0.00492
	(0.00144)***	(0.00159)	(0.00178)***
Observations	141,675	144,580	143,795
R-squared	0.536	0.321	0.376
Effective F-stat	11.046	0.565	7.672

Notes: This table presents estimates of equation 9 for parcels located at elevations below 1,000 meters and within 150 km of the river mouth in the study area. The outcome variable is the average Evapotranspiration for each plot in the Summer months (January and February), for the period 2005-2009. The instrument corresponds to the maximum between the optimal-route distance between the land plot and the most upstream province capital city in the basin, and $30km$. 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 market access measures (driving distance to Santiago and the main ports of Valparaíso and San Antonio); dummies for soil quality quartiles; annual, combined winter and spring, and summer precipitation; temperature, measured as the number of days with maximum temperatures in the following ranges: $[25, 29]$, $[29, 31]$, $[31, 35]$, and $[35, \infty^{+})$ in Celsius degrees; and a dummy for whether the plot has groundwater rights. All regressions include $1^\circ \times 1^\circ$ cell fixed effects and year fixed effects. Standard errors are clustered by county.

Table A.VI: Agricultural Productivity: IV Estimation using Piece-wise Linear Distance Instrument

Panel A: Main Result

	OLS			IV		
	(1) Downstream	(2) Mid section	(3) Upstream	(4) Downstream	(5) Mid section	(6) Upstream
Board	0.000500	-0.000508	0.0120	0.200	-0.198	0.0125
	(0.00740)	(0.00656)	(0.00647)*	(0.0805)**	(0.287)	(0.0328)
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes
Plot controls	Yes	Yes	Yes	Yes	Yes	Yes
Spatial cell FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	141,675	144,580	143,795	141,675	144,580	143,795
R-squared	0.278	0.178	0.247	0.014	-0.302	0.247
Mean Dependent Var.				0.370	0.413	0.410
AR test CI				[.08163, .5131]	($-\infty$, ∞)	[-.07429, .1067]

Panel B: First Stage

	(1) Downstream	(2) Mid section	(3) Upstream
$\min\{pcd, 30\}$	-0.00489	0.00120	0.00492
	(0.00144)***	(0.00159)	(0.00178)***
Observations	141,675	144,580	143,795
R-squared	0.536	0.321	0.376
Effective F-stat	11.579	0.565	7.672

Notes: This table presents estimates of equation 9 for parcels located at elevations below 1,000 meters and within 150 km of the river mouth in the study area. The outcome variable is the maximum value of the Enhanced Vegetation Index (EVI) reached within the year, for the period 2005-2009. The instrument corresponds to the maximum between the optimal-route distance between the land plot and the most upstream province capital city in the basin, and $30km$. Distance to the coast was measured through the river network. Plot-level controls include market access measures (driving distance to Santiago and the main ports of Valparaíso and San Antonio); dummies for soil quality quartiles; annual, combined winter and spring, and summer precipitation; temperature, measured as the number of days with maximum temperatures in the following ranges: $[25, 29]$, $[29, 31]$, $[31, 35]$, and $[35, \infty^{+})$ in Celsius degrees; and a dummy for whether the plot has groundwater rights. All regressions include $1^{\circ} \times 1^{\circ}$ cell fixed effects and year fixed effects. Standard errors are clustered by county.

Table A.VII: Extensive Margin Irrigation: Instrumental Variables estimation at the parcel level.

Panel A: Full Sample

	OLS		IV	
	(1)	(2)	(3)	(4)
Board	0.05	0.04	0.16	0.10
	(0.04)	(0.04)	(0.09)*	(0.22)
Farm level controls	Yes	Yes	Yes	Yes
County level controls	Yes	Yes	Yes	Yes
1x1 degree cell FE	Yes	Yes	Yes	Yes
Observations	67,713	42,236	67,713	42,236
R-squared	0.703	0.696	0.700	0.695
Sample	Downstream	Upstream	Downstream	Upstream
Mean Dependent Var.	0.322	0.342	0.185	0.342
Effective F-stat			5.989	0.521
AR test CI			[-.07419, .435]	$(-\infty, \infty)$

Panel B: Large Farms

	OLS		IV	
	(1)	(2)	(3)	(4)
Water Board	0.13	0.04	0.48	0.46
	(0.05)**	(0.04)	(0.16)***	(0.54)
Farm level controls	Yes	Yes	Yes	Yes
County level controls	Yes	Yes	Yes	Yes
1x1 degree cell FE	Yes	Yes	Yes	Yes
Observations	14,236	11,730	14,236	11,730
R-squared	0.533	0.582	0.473	0.520
Sample	Downstream	Upstream	Downstream	Upstream
Mean Dependent Var.	0.462	0.491	0.462	0.491
Effective F-stat			3.653	0.427
AR test CI			[.186, 1.148]	$(-\infty, \infty)$

Panel C: Small Farms

	OLS		IV	
	(1)	(2)	(3)	(4)
Board	-0.00	0.00	0.07	0.11
	(0.01)	(0.01)	(0.04)*	(0.19)
Farm level controls	Yes	Yes	Yes	Yes
County level controls	Yes	Yes	Yes	Yes
1x1 degree cell FE	Yes	Yes	Yes	Yes
Observations	40,807	23,536	40,807	23,536
R-squared	0.681	0.868	0.070	0.073
Sample	Downstream	Upstream	Downstream	Upstream
Mean Dependent Var.	0.059	0.045	0.059	0.045
Effective F-stat			6.422	0.204
AR test CI			[-.107, .1569]	$(-\infty, \infty)$

Notes: This table presents estimates of equation 9. The outcome is a dummy variable that equals 1 if the farm reports any type of irrigation technology. 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. The instrument corresponds to the optimal-route distance between the land plot and the most upstream province capital city in the basin, entered in the specification as both a linear and a squared term. 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 A.VIII: Water Consumption and Heterogeneous Effects by Farm Size

Panel A: Main Result

	OLS, small		OLS, large		IV, small		IV, large	
	(1) Downstream	(2) Upstream	(3) Downstream	(4) Upstream	(5) Downstream	(6) Upstream	(7) Downstream	(8) Upstream
Board	-0.00700	0.130	-0.0691	-0.00476	1.465	-0.722	4.534	-1.758
	(0.115)	(0.0923)	(0.0990)	(0.0979)	(0.618)**	(0.644)	(1.891)**	(0.855)**
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Plot controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Spatial cell FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	74,563	69,650	25,092	29,905	74,563	69,650	25,092	29,905
R-squared	0.285	0.397	0.337	0.334	0.138	0.325	-0.836	0.032
Mean Dependent Var.					2.758	3.282	3.346	3.649
AR test CI					[.3216, 3.146]	(-∞, .2615]	[2.173, ∞)	(-∞, -.6504]

Panel B: First Stage

	First stage, small		First stage, large	
	(1) Downstream	(2) Upstream	(3) Downstream	(4) Upstream
ucd^2	-0.0000333	0.0000309	-0.0000192	0.0000284
	(0.00000824)**	(0.0000142)**	(0.00000861)**	(0.0000114)**
Observations	75,915	69,650	25,235	29,905
R-squared	0.541	0.364	0.577	0.345
Effective F-stat	15.928	4.732	4.945	6.203

Notes: This table presents estimates of equation 9 for parcels located at elevations below 1,000 meters and within 150 km of the river mouth in the study area. The outcome variable is the average Evapotranspiration for each plot in the Summer months (January and February), for the period 2005-2009. Distance to the coast was measured through the river network. Plot-level controls include market access measures (driving distance to Santiago and the main ports of Valparaíso and San Antonio); dummies for soil quality quartiles; annual, combined winter and spring, and summer precipitation; temperature, measured as the number of days with maximum temperatures in the following ranges: $[25, 29]$, $[29, 31]$, $[31, 35]$, and $[35, \infty^{+})$ in Celsius degrees; and a dummy for whether the plot has groundwater rights. All regressions include $1^{\circ} \times 1^{\circ}$ cell fixed effects and year fixed effects. Standard errors are clustered by county.

Table A.IX: Agricultural Productivity and Heterogeneous Effects by Farm Size

Panel A: Main Result

	OLS, small		OLS, large		IV, small		IV, large	
	(1) Downstream	(2) Upstream	(3) Downstream	(4) Upstream	(5) Downstream	(6) Upstream	(7) Downstream	(8) Upstream
Board	-0.00626	0.0176	-0.00613	0.00650	0.142	0.0115	0.459	-0.0464
	(0.00753)	(0.00798)**	(0.00733)	(0.00724)	(0.0559)**	(0.0405)	(0.202)**	(0.0487)
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Plot controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Spatial cell FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	75,915	69,650	25,235	29,905	75,915	69,650	25,235	29,905
R-squared	0.282	0.242	0.320	0.262	0.126	0.242	-0.857	0.233
Mean Dependent Var.					0.349	0.398	0.412	0.424
AR test CI					[.04895, .3097]	[-.154, .2007] $\cup$ [.4289, ∞)	[.2218, ∞)	(-∞, .03637]

Panel B: First Stage

	First stage, small		First stage, large	
	(1) Downstream	(2) Upstream	(3) Downstream	(4) Upstream
ucd^2	-0.0000333	0.0000309	-0.0000192	0.0000284
	(0.00000824)**	(0.0000142)**	(0.00000861)**	(0.0000114)**
Observations	75,915	69,650	25,235	29,905
R-squared	0.541	0.364	0.577	0.345
Effective F-stat	16.301	4.732	4.963	6.203

Notes: This table presents estimates of equation 9 for parcels located at elevations below 1,000 meters and within 150 km of the river mouth in the study area. The outcome variable is the maximum value of the Enhanced Vegetation Index (EVI) reached within the year, for the period 2005-2009. Distance to the coast was measured through the river network. Plot-level controls include market access measures (driving distance to Santiago and the main ports of Valparaíso and San Antonio); dummies for soil quality quartiles; annual, combined winter and spring, and summer precipitation; temperature, measured as the number of days with maximum temperatures in the following ranges: $[25, 29]$, $[29, 31]$, $[31, 35]$, and $[35, \infty^+)$ in Celsius degrees; and a dummy for whether the plot has groundwater rights. All regressions include $1^\circ \times 1^\circ$ cell fixed effects and year fixed effects. Standard errors are clustered by county.

Table A.X: Crop Choice: Heterogeneous Effects by Farm Size

Panel A: Peak after December (dummy)

	OLS, small		OLS, large		IV, small		IV, large	
	(1) Downstream	(2) Upstream	(3) Downstream	(4) Upstream	(5) Downstream	(6) Upstream	(7) Downstream	(8) Upstream
Board	0.0472	0.0133	-0.00188	-0.00106	0.352	0.217	0.887	-0.00339
	(0.0219)**	(0.0289)	(0.0242)	(0.0294)	(0.111)***	(0.225)	(0.382)**	(0.198)
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Plot controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Spatial cell FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	75,915	69,650	25,235	29,905	75,915	69,650	25,235	29,905
R-squared	0.064	0.123	0.098	0.136	0.017	0.099	-0.205	0.136
Mean Dependent Var.					0.231	0.324	0.375	0.414
Effective F-stat					16.301	4.732	4.963	6.203
AR test CI					[.1355, .635]	[-.1648, ∞)	[.4261, ∞)	[-.6148, .6272]

Panel B: Season Length (months)

	OLS, small		OLS, large		IV, small		IV, large	
	(1) Downstream	(2) Upstream	(3) Downstream	(4) Upstream	(5) Downstream	(6) Upstream	(7) Downstream	(8) Upstream
Board	0.134	0.0150	-0.0233	-0.0202	1.012	0.179	2.293	-0.302
	(0.0650)**	(0.0587)	(0.0566)	(0.0618)	(0.292)***	(0.401)	(1.022)**	(0.406)
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Plot controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Spatial cell FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	75,915	69,650	25,235	29,905	75,915	69,650	25,235	29,905
R-squared	0.068	0.113	0.096	0.145	0.011	0.110	-0.245	0.136
Mean Dependent Var.					6.810	6.994	7.124	7.197
Effective F-stat					16.301	4.732	4.963	6.203
AR test CI					[.4693, 1.796]	[-.8499, ∞)	[1.086, ∞)	(-∞, .565]

Notes: This table presents estimates of equation 9 for parcels located at elevations below 1,000 meters and within 150 km of the river mouth in the study area. The outcome variable in Panel A is 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, for the period 2005-2009. The outcome variable in Panel B is the the number of months between May (first month of the agricultural year) and peak of EVI within the corresponding year, for the period 2005-2009. Distance to the coast was measured through the river network. Plot-level controls include market access measures (driving distance to Santiago and the main ports of Valparaíso and San Antonio); dummies for soil quality quartiles; annual, combined winter and spring, and summer precipitation; temperature, measured as the number of days with maximum temperatures in the following ranges: $[25, 29]$, $[29, 31]$, $[31, 35]$, and $[35, \infty^+)$ in Celsius degrees; and a dummy for whether the plot has groundwater rights. All regressions include $1^\circ \times 1^\circ$ cell fixed effects and year fixed effects. Standard errors are clustered by county.

Table A.XI: 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.

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.

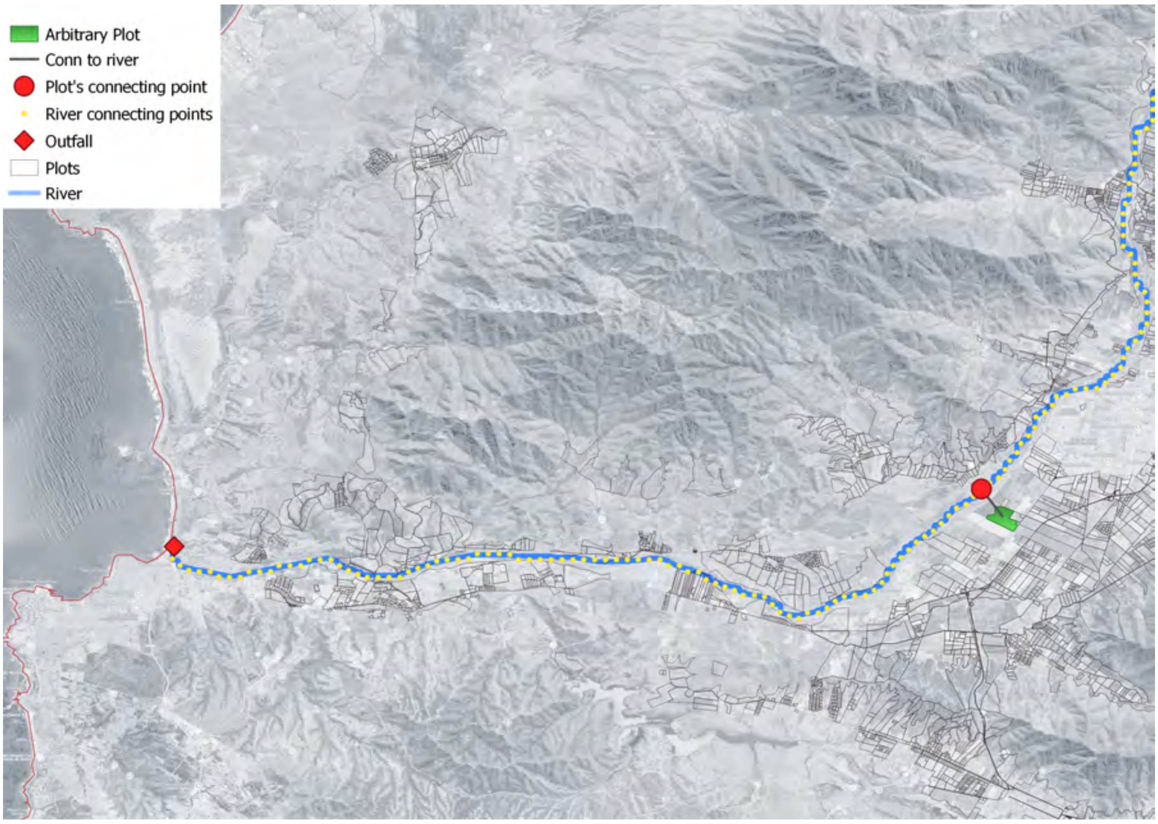


Figure B.I: Altorithm Illustratgion. An arbitrary area—shown in green—is connected to the closest point in the river, marked by a red circle. The distance assigned to this arbitrary object will be the distance along the river from the connecting point (red circle) to the river mouth or outfall (red square).