Governing the Privatized Commons: Evidence from the introduction of Water Boards
VERY PRELIMINARY, DO NOT CIRCULATE

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August 17, 2023

Abstract

Water resources present a classic tragedy of the commons that is of increasing relevance as a result of climate change. This paper uses the staggered introduction of a local governance institution to estimate the causal effect of governance and property rights enforcement on the allocation of water in Chile. We find that the establishment of legally empowered boards representing water right holders leads to increased water access in downstream locations, reallocating water from upstream to downstream users: we observe an increase of more than 20% in streamflows during the irrigation season, which would reflect a reduction in illegal extractions. The presence of a board also slows down the creation of titles over river waters, which we attribute to improved monitoring of the state of the river by the boards. These results are stronger in basins with higher land concentration. We attribute 89% of the increase in streamflow to enforcement, and only 11% to improved monitoring of water sources. We further present evidence of greater misallocation of water in basins without boards, where the shadow value of water is higher in downstream locations than in upstream locations. We conclude that legally empowered community enforcement improves the performance of markets in absence of state capacity.

1 Introduction

The potential to exclude others from the control and use of a resource is at the core of property rights: property rights enforcement involves, in essence, the ability to create such exclusion. For most physical goods and natural resources, exclusion is a matter of infrastructure investments (e.g. the fencing of land, as discussed by Coase (1960) and Hornbeck (2010)); but for others, it may require a more complicated set of tasks under complex institutional arrangements that allocate the power to exclude and the responsibility of the final allocation of the good. The responsibility of performing such tasks may rely either on the state or on smaller, local communities, depending on the formal and informal institutions in place.

States and communities face different challenges in enforcing property rights. Lack of state capacity and backfiring protections against expropriation may limit the scope of effective enforcement by the government (Besley and Persson, 2009; Bauer, 2004). Community-based governance, on the other hand, requires a system of monitoring and lawful enforcement, combined with clear limits to the access of new users to succeed in a local setting (Ostrom, 1990, 2009). In this paper, we study an intermediate case in the context of private property rights: community governance empowered by the law, with the ability to define their own taxes, effectively building up locally-governed state capacity, while the good is allocated by the market.

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We study the economic consequences of the establishment of legally empowered boards, elected and funded by the users themselves, on enforcing formal private property rights over river waters. The regulation of water matters and courts have restrained government action in order to protect users against expropriation, leaving downstream users unprotected from over-extraction by upstream users. These boards, called Water Boards[1], have the power to enforce water allocation and to adjudicate conflicts among users. The basins governed by such boards -adopted independently over time- are otherwise legally identical to neighboring areas, providing a setting that is well-suited to studying the economic implications of enforcement of property rights and governance over economic resources.

We show that property rights enforcement changes the economic geography: water boards increase river streamflows in the dry season -when incentives to over-extract are strongest- by more than 20%, and at upstream locations -where people have more opportunities to over-extract. These results suggest that the lack of enforcement allows over-extraction from upstream users.

In addition, we provide evidence that these boards slow down the rate of reclamation of rivers, by reducing the amount of new water rights created after their establishment. Given the legal attributions of these boards, this reduction in the creation of water rights can be attributed to better monitoring of the water source. We decompose the increase in streamflows into the direct effect of water boards -which arguably reflects the effect of introducing enforcement of property rights- and their indirect effect through water rights -i.e. the increase in streamflows caused by the lower rate of water rights creation. We do so by implementing a statistical mediation exercise and show that 89% of the increase in streamflows is caused by enforcement and just 11% can be attributed to monitoring.

These changes in the allocation of the resource, in turn, have economic impacts: the introduction of enforcement reduces misallocation. A market equilibrium should equalize the marginal value of the resource within a market, and deviations from this benchmark would imply a Pareto inefficient allocation in place or unexploited arbitrage opportunities. We design a misallocation test, that compares the shadow value of water at different locations in a basin. We test for the existence of differences in the productivity of irrigation water within a basin. Our results imply that the average marginal productivity of water is constant within basins governed by water boards. Areas without boards, instead, display increasing marginal productivity of water as we move downstream, suggesting over-extraction by upstream users. This allows us to estimate the economic losses due to the lack of property rights enforcement.

This paper, therefore, provides novel insights into how markets allocate resources under private property, and how the success of natural resources privatization relies heavily on the institutions in place. The same decision-making power and infrastructure that allows the government to enforce contracts could be used to expropriate, explicitly or implicitly (e.g. Espín-Sánchez and Truffa, 2020). The protections against expropriation in the Chilean context, instead, effectively left the state powerless to enforce private property rights in water matters. The institution of Water Boards partially fills the institutional void left by the state, so we interpret the economic effects we find as evidence of the economic effects of governance over privatized natural resources. This paper, therefore, provides evidence on the tension in market design between effective governance and protections against expropriation.

Finally, Water Boards are controlled by the local elites by design: voting power within a board is proportional to water ownership. Our results suggests that most of the observed effects are driven by basins with a higher land concentration, suggesting that the presence of big actors is necessary to effectively enforce property rights.

[1]The actual name is "Juntas de Vigilancia" (Spanish for "vigilance boards") and it comes from the legal tradition of cooperatives; this explains why it is not self-explanatory.

Related Literature

Our paper contributes to different strands of the literature. The first is the literature on the economic consequences of natural resources property and allocation mechanisms. While this literature is extensive, to our knowledge, this is the first paper to causally estimate the economic value of enforcement of private property rights, and also over water specifically. Most of the related work identifies misallocation caused by limits on the exercise of property rights, which translate into market frictions. We provide evidence of the opposite: how limits to government action -in place to avoid interference on markets- can also be a source of misallocation (Bauer, 2004).

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

We also contribute to the literature in environmental economics on the management of common resources. Water is considered a common pool resource, given the difficulties in enforcing exclusion, and the rivalry on its consumption (Ostrom and Gardner, 1993), implying the emergence of a "Tragedy of the Commons", where free-riding behavior leads to the over-exploitation of the resource (Hardin, 1968). Traditional approaches to managing common pool resources allocate the decision rights over the resource to either the state or private agents through privatization, but implicitly assigning the tasks of monitoring and enforcing the decisions to the state[2]. In a classic work, Ostrom (1990) identifies local communities as a third possible managing agent and discusses conditions under which communities can succeed in environments where neither state management nor privatization can, by introducing locally managed monitoring and enforcement. Among these conditions, she identifies monitoring capability, availability of sanctions among community members and closed access to outsiders. In the environment we are studying -distribution of water within basins encompassing several local communities-, these conditions do not apply[3]. Our results, therefore, extend Ostrom's by showing how local communities can address free-riding problems in wider environments by relying on tools usually reserved for the state, like the authority to resolve legal disputes or establish punishments.

Finally, reforms in several countries established private property rights over water, opening questions about how water markets work. The prior work closest to our own includes Rafey (2023), who estimates the gains from trading water rights in the context of Australia, where the government exerts stronger monitoring, control and enforcement of property rights over water across the full country. Studies that compare markets versus others allocation mechanisms include Ryan and Sudarshan (2022), who estimate the efficiency losses from rationing groundwater relative to a counterfactual Pigouvian allocation, and Donna and Espín-Sánchez (2023), who study how liquidity constraints may imply that markets are less efficient than a quota system on allocating water in Spain. This work studies the efficiency gains associated with different institutional arrangements; our work shows a preexisting condition for the proper operation of markets, namely, governance over the resource and enforcement of property rights.

[2] The literature on the different institutional arrangements over water is extensive. Meinzen-Dick (2007) and Ostrom (2010) provide good reviews and discussions on this topic.

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

This paper is organized as follows: in Section 2 we present the Chilean system of property rights over water, the institution of Water Boards and how both operate and in Section 3 we present the different datasets we use on our analysis. In Section 4 we present our identification strategy and discuss our implementation, while in Section 5 we show our results. Finally, in Section 6 we present our misallocation test and our results.

2 Context

We study the introduction of Water Boards, a local governance institution that mainly serves two basic purposes: to manage rivers in periods of relative water scarcity and to solve legal conflicts among resource users. In contrast to centralized control, Water Boards, because of their local presence, have direct knowledge of and interaction with water users. In this section, we provide background information on the study area and the system of property rights over water, which is essential to understanding how the Water Boards affect water allocation.

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 2. This area covers 87% of Chile's population and 85% of the agricultural GDP. The geography is marked by both the Andes -which defines the eastern border of the country- and Coastal Mountain Ranges that extend in a North-South axis. Most agricultural activity takes place in the Central Valley that separates both ranges, and most rivers run from the Andes (East) to the Coast (West)(Fernández and Gironás, 2021). This rugged geography makes very costly the construction of infrastructure connecting basins.

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

Background on the Chilean System of Private Property Rights

Since 1981, Chile is 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; Bank, 2011, 2021). These rights are fully transferable, separated from land, and they are legally considered real estate; so a legal transaction of water rights is equivalent to a purchase of land (CNR, 2018a)[4]. These rights are defined in terms of a stream of water (measured in liters per second) to be extracted from a specific location and source and following a monthly schedule; all these attributes are defined during the creation of each water right. Figure 12 in Appendix B presents an example of a water right.

These rights can be claimed for free through public requests to the Directorate of Water (DGA, an institution equivalent to the US Bureau of Reclamation), the technical government institution in charge of assessing water resources. These rights can be created until the DGA declares the river exhausted. The process comprehends the following steps (the process is summarized in figure 1):

1. The person or firm interested in claiming the water starts a claim at the DGA.

[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).

2. The DGA sends a field officer, who will check the physical and legal availability of water in the source.

3. After this, the agent interested in the water right has to publish the claim. There is a 30 business days period open for complaints, and for other potential users to express interest in the newly established right (if it is not possible to create rights for the two users).

   (a) Any complaints will be reviewed by a judge; if the judge rules them as valid, the new water right is not created.

   (b) If any other user is interested in the water right, there is an auction

4. The title is created, legalized and registered in a local property registrar.

After a source is declared exhausted, any user needing water rights in the area must purchase them from other users. They can be freely traded among both individuals and firms, without any interference by the government.

The legal body that regulates water matters is the Water Code of 1981. Before 1981, there were two legal bodies regulating water(Peña, 2021):

1. Water Code of 1951: here it was presented the process of creation of water rights as it exists now, but only for agricultural users. The titles were created in a process similar to the current one, but they were tied to a specific land parcel and were not subject to trade. The administration of canals was left to Canal Associations, while the administration of rivers and other legal bodies was left to the Water Boards wherever there was one in place, or to the state otherwise.

2. Water code of 1967: this water code was enacted to harmonize the legal administration of water to the successive Land Reforms implemented between 1962 and 1973. In essence, this code reallocated the management of all water bodies to the state, and all water titles in place were replaced by new titles that allocated water proportionally to the plot size. This code was never fully implemented, but it created an administrative disorder and future confusion regarding what titles were valid after the 1981 code was enacted.

Enforcement in principle relies on the actions of the DGA, which is supposed to address water stealing and over-extraction. However, this institution has been overruled and their actions limited systematically by courts (Bauer, 2004). A second enforcement layer is that the infrastructure in place should be built consistent with the water rights owned: the diameter of the pipe -checked by DGA agents at the moment of the 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 (del Congreso Nacional, 1981), the infrastructure does not adapt accordingly.

Background on Water Boards

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

In response to droughts, early in the XX century agricultural users created the legal figure of the Water Boards, which legally control rivers and other water bodies when there is increased scarcity

(Peña, 2021)[5]. According to the Water Code of 1981, the legal body that currently regulates all water matters (del Congreso Nacional, 1981), Water Boards have the legal authority

1. to determine and enforce water allocations across legal users under extraordinary circumstances, such as drought,[6]
2. to adjudicate disputes among users within their jurisdiction,
3. to keep track of Water Rights claims, and
4. to provide common goods such as legal assistance and common infrastructure, and define its own funding sources.

They report only to their constituents -who elect them with votes weighted by their Water Rights streamflow property- during their 2 or 3-year tenure. They are subject to regulation by the DGA, but different courts have overruled them, limiting the scope of administrative intervention. Therefore, Water Boards are effectively the highest legal authority in water-related issues in the basins under their jurisdiction, except for emergency situations[7].

The creation of Water Boards is triggered by either an agreement by at least half of the water rights owners within the area under consideration, or a lawsuit by at least one water user. 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 is presented in figure 2.

Administrative and legal jurisdiction

We present in figure 3 flowcharts of how water boards relate to the administrative (figure 3a) and legal institutions (figure 3b) in Chile on water matters. Administrative decisions, such as cutting allotments in the context of drought, will be decided by the Water Board, for water rights within their jurisdiction[8]. If any user wants to dispute this decision, they can appeal to the DGA; however, in practice, DGA's decisions had been overruled by courts in several lawsuits (Bauer (2004)).

In the case of legal actions, any people and firms owning water rights should ask for a ruling from the Water Board that has jurisdiction over the source[9]. Part of the duties of a Water Board is to appoint a "Judge of Waters", who most of the time is part of the board or an employee of the board. This judge has full authority to solve legal disputes and to enforce their ruling, with the authority of the Water Board. In the absence of a Water Board, instead, the only option users face is to initiate legal action on ordinary courts (civil or penal courts, depending on the nature of the conflict). Water Boards substitute ordinary courts on water matters, with additional field expertise.

[5]The Civil Procedure Code of 1902 introduced the legal figure of the Water Boards as a representative of the water users (Peña, 2021)

[6]This was reformed in 2018, allowing the DGA to overrule Water Boards decisions under said circumstances(Riestra, Silva, and Valenzuela, 2021).

[7]"The President of the Republic, with the DGA report, can declare a zone to be in "extraordinary drought". In those cases, the DGA can authorize emergency measures regarding water usage, and, eventually, intervene in distribution, replacing the role of the surveillance board" (Peña, 2021). In practice, this scenario has never materialized.

[8]For water rights registered in canals, Water Boards take 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.

Appeals to Water Board rulings -or lawsuits against the boards themselves- must be made to the Appeals Courts -which almost in all cases have jurisdiction over Regions, the first level administrative unit in Chile-, and eventually can be escalated to the Supreme Court. Bauer (2004) discusses how higher courts lacked water-specific knowledge and have ignored in their rulings substantive water issues, focusing exclusively on the legal issues at hand and emphasizing the "letter of the law".

Lastly, the Water Code of 1981 limited Water Boards' jurisdictions to surface water bodies, leaving groundwater outside their ruling. Governance over aquifers was exerted by a different type of institution called "Comunidades de Agua", with similar powers and regulations but limited adoption. A reform in 2005 expanded the scope of Water Boards to groundwater, leaving the existing Comunidades de Agua under the Water Boards authority (CNR, 2018a).

3 Data

We gathered a richness of information that reflect the *de jure* and *de facto* allocation of water across space and time, together with detailed agricultural information to measure outcomes and climatic controls.

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.

Basins, Streamflows and Climate

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

In parallel, CR^2 has also created daily climatic estimates for the entire Chilean territory at a $70km \times 70km$ resolution, by calibrating satellite measures with local input from climatic monitoring stations (Alvarez-Garreton, Mendoza, Boisier, Addor, Galleguillos, Zambrano-Bigiarini, Lara, Puelma, Cortes, Garreaud, McPhee, and Ayala, 2018). These estimates include precipitation, potential evapotranspiration and minimum and maximum temperatures. We aggregate these climatic estimates at the drainage basin or the county level, according to the analysis on which the data is being used.

Water Rights

The DGA has been collecting information on water rights in the last decade across the different local agencies and registrars where the titles have been created. With this input, the DGA publishes a Water Rights Cadaster, that includes detailed information about each water right, including the monthly schedule of extractions, the source (including if the source is a surface water body or groundwater), the name of the original owner of the right and the geographic coordinates of the water intake. From the name of the original owner, we infer if they are people or firms (and in the latter case, their economic sector when it is reflected by the name).

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 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 (specifically to Canal Associations).

4 Empirical Strategy

To study the effect of governance, we explore the full causal chain that links board establishment and agricultural outcomes. The first stage is to show that boards cause changes in both the *de jure* allocation of water (i.e. that they modify the rate of creation of water rights) and the *de facto* allocation of water (i.e. streamflows, which reflect where water is being extracted), to therefore show the economic consequences of the reallocation of water caused by the establishment of the boards. Here we explain the identification strategy of the first stage.

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 11 in Appendix B presents the year of establishment of Water Boards, and the number of river segments under their jurisdiction -defined by the locations of streamflow monitoring stations in the river network. Given the data available and the institutional design in place, we focus our analysis on the boards established after 1982[10].

Sample

The establishment of Water Boards is triggered by either an agreement among water users or a lawsuit by one user that perceives their interest to be affected by the lack of governance in the basin. In both cases, there is conflict latent over the resource, driven by both water supply and demand factors. The process is long and irreversible, though, implying that (perceived as) long-term conflict is more likely to drive their adoption[11].

The first challenge in building the counterfactual water availability and reclamation for treated areas 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. Rivers with a nivo-glacial regime (i.e. the streamflow is high in the seasons when snow and glacier are melting) will have relatively more water available in the Summer. This season is when water is more needed for irrigation, especially for high-value crops and fruits that need year-round water input.

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

[11]There is no systematic documentation of the time length of the full constitution process, but one testimony about the establishment of a water board through a lawsuit in 2015 describes a process of at least two years, with the lawsuit resolution taking the first year and the second year devoted to the execution of the resolution; the organization of the board was actually started during this year (CNR, 2018b).

In figure 4a, we present the monthly pre-1985 streamflow and precipitation medians for all river segments without boards before 1980, separating between those which eventually were under a Water Board (treated segments onwards) and those which are not (control segments). Relative to control river segments, treated segments have lower streamflow and total precipitation, with hydrological regimes less dependent on rainfall and more on snow-melting, which is reflected by having peak streamflows in the Austral Spring (October and November) instead of the Winter.

To ensure a comparable control group, we identify non-treated units that satisfy three sets of conditions:

1. Common Support: we identify a Common Support condition based on two observable measures in the baseline: average streamflows and total water rights in 1980[12]. For each measure, we identify the support of the distribution for the treated and exclude control segments whose values fall out of it. Since both quantities are non-negative and the minimum values for the treated and control groups are similar and close to zero, this implies excluding segments with streamflows and water rights higher than the maximum observed for the treated group.

2. Only non-yet-treated units: to address non-observable trends, we only consider river segments where water boards were eventually established.

3. No externalities: we exclude all river segments subject to externalities from previously established boards, or water boards established before the 1981 Water Code.

Figure 4b presents the streamflows over the year and precipitation for the final sample, and now treated and control units have comparable streamflows across the whole year, and overall a similar hydrological regime.

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

Difference-in-Difference Design for Water Rights creation

We implement Cengiz, Dube, Lindner, and Zipperer (2019) Stacked DID design to estimate the following baseline equation:

$$\text{Water Rights}_{gst} = \beta \text{Board}_{gst} + \gamma X_{gst} + \mu_t + \eta_g + \varepsilon_{gst} \tag{1}$$

where WR_{gst} denote the total water rights issued in river segment g in basin s and year t and Board_{gt} is an indicator function that equals 1 if segment g is within a Water Board jurisdiction. X_{gst} is a vector of covariates that include rainfall, potential evapotranspiration and temperatures, η_g correspond to segment fixed effects and μ_{st} are year fixed effects[13]. We use detailed georeferenced Water Rights records from the National Water Rights Cadaster, combined with climatic estimates by Alvarez-Garreton, Mendoza, Boisier, Addor, Galleguillos, Zambrano-Bigiarini, Lara, Puelma, Cortes, Garreaud, McPhee, and Ayala (2018) and the geological basin borders identified by CR2.

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

$$\text{Water Rights}_{gst} = \sum_{i=-4}^{4} \beta_i \text{Board}_{gst} \times 1\left[t - t^* = i\right] + \gamma X_{gst} + \mu_t + \eta_g + \varepsilon_{gst} \tag{2}$$

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

[13]Following Cengiz, Dube, Lindner, and Zipperer (2019), the time fixed effects are actually separated by treatment adoption event. This applies to all DID estimates throughout the paper.

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

The identification assumption in both cases corresponds to parallel counterfactual trends: water rights created in treated basins would have grown the same as control basins' water rights grew around the establishment of a board.

Difference-in-Difference Design for Streamflow

Streamflow effects estimations present the additional challenge of seasonality: rivers and precipitation display seasonal patterns that introduce noise in the estimation, and could potentially bias the estimation of board effects when focusing on the dry season. To address this, we estimate:

$$\text{Stream}_{gmt} = \delta \text{Board}_{gt} + \sum_{k=m}^{m-L} \alpha_2^k \text{Rain}_{gskt} + \alpha_3 \text{PET}_{gmt} + \alpha_4 \text{Water Rights}_{gmt} + \mu_t + \eta_{gm} + \varepsilon_{gmt} \tag{3}$$

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

We can also estimate dynamic effects, by estimating:

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

This specification will allow us to identify pre-trends.

Equations 3 and 4 are derived from a water balance equation, where the inflows equalize outflows in a basin. The equation does not exactly hold, given the use of proxy variables[14] and measurement error[15]. However, the most important concern regards the potential endogeneity of upstream streamflow and water rights: while the first can be affected by the establishment of water boards through some formal [16] or informal channels[17], the second is literally among the outcomes we are estimating the effect. Our results will not depend on the inclusion or exclusion of these variables.

5 Results

In this section, we present estimates of the impact of Water Boards on the creation of water rights and streamflows. Using OLS and Poisson regressions, in subsection 5.1 we show that the establishment of

[14] For example, potential evapotranspiration instead of effective evapotranspiration, or rainfall instead of runoff.

[15] Especially among climatic variables, which are based on a combination of in-ground measures and estimates.

[16] e.g. if the water board includes the above station, then it is lawful and expected that the board will adjust the amount of water passing from one segment to the other.

[17] e.g. a board may try to affect the amount of water they received from upstream users through lawsuits or other threats.

boards decreases the rate of water rights creation by 40% in the 4 years after its establishment. We find limited evidence of displacement of the demand for new water rights from surface to groundwater sources, which are outside the Water Boards' jurisdiction. Using a similar strategy, in subsection 5.2 we find that streamflows increase by between 5% to 8%, and more than 20% during the dry season. Additional results show these effects are concentrated in upstream locations.

5.1 Water Boards impact on water rights creation

In this section, we present the impacts of Water Boards' establishment on water rights creation. While water boards are not entitled to prevent the creation of water rights, they can affect their growth indirectly by identifying potential conflicts between new applications for water rights creation with already existing rights. We expect Water Boards to do this faster than the government because they keep detailed updated records of water rights in their jurisdiction[18].

We present our results on the estimation of equation 1 in table 2 and 3. Table 2 present our estimates of equation 1 using Poisson regression[19]. Column 1 shows the results for the total streamflow allocated through new water rights within 4 years after the establishment of a water board, while column 2 shows the result for total surface water rights per km^2 of the surface of the basin: the coefficient implies a reduction of 36% in the reclamation of the river.

We test for the displacement of the demand towards less regulated sources of water in columns 3 and 4, where we present the results for total groundwater rights (column 3) and for groundwater rights per km^2 (column 4). Aquifers were outside the Water Boards' jurisdiction until 2005. Before 2005, groundwater governance relied on a different type of institution ("Comunidades de Agua") with very limited adoption, leaving groundwater extraction in most of the country with poor to null regulation (Peña, 2021). There is an increase in groundwater rights of a similar magnitude to the reduction in surface water rights found in column 2. The coefficients are similar, but they imply an increase of around 55%.

Table 3 presents the results using OLS. The results are qualitatively similar: column one implies a reduction of $0.031 m^3/s$, which is a 18% reduction in reclamation. Column 2 considers the Inverse Hyperbolic Sine instead of levels of Water Rights, and it gives similar qualitative results. Column 3 presents the results divided by area, and the coefficient is not significant anymore. Columns 4 to 6 estimate similar models for groundwater rights, and while the coefficients are not significant, they remain of similar magnitude (but with opposite sign) as the ones for surface water.

Figure 5 presents estimates of dynamic effects (i.e. equation 2) over total water rights created in the segment, for surface sources and for groundwater sources. There is no evidence of pre-trends for surface rights, and for groundwater rights, anticipation seems limited to the last year before the establishment of the board. Also, the figure shows the reduction in surface water rights and an increase of similar magnitude for groundwater rights but with more noisy estimates.

In figure 6 we present our estimates of dynamic effects for surface (left) and underground (right) water rights created by km^2. The reduction in surface water rights is robust to the change of dependent variable, while for groundwater rights the estimates are noisier and in the last period they reverse their sign. In this case, there is no evidence of pre-trends.

Tables 12 and 13 in Appendix B present the full set of estimates of dynamic effects over surface and groundwater water rights, both totals and per unit of surface, using OLS and Poisson regression.

[18] Bauer (2004) points out how the lack of centralized records allowed the reclamation of duplicated water rights by some users: by claiming the same title through more than one channel, they were allowed to duplicate their ownership and to sell them.

[19] We use this method as it allows to deal with heavy right-tails while properly dealing with zeroes; our data on water rights satisfies both characteristics.

Overall, we conclude that water boards reduce the creation of water rights on surface water -where they have jurisdiction-, while there is some non-robust evidence of displacement.

5.2 Water Boards impact on streamflows

In this subsection, we present the impacts of the establishment of water boards on river streamflows. This is our most important outcome, given that this reflects the effects of water boards on the *de facto* allocation of water. We expect that enforcement will cause increases in the streamflow, as this would reflect the existence of previous extraction by agents located upstream to a given monitoring station, an action that is stopped by the water board once it starts its operation.

We do not expect this effect to be uniform across the agricultural production cycle, though. Irrigation does not have the same intensity across months, as in wet months it is possible to rely only on precipitation (and so irrigation may even be damaging), and so the incentives to over-extract will be strongest in the dry season. At the same time, the mandate of Water Boards to guarantee access to water to their lawful users may not require any actions under normal circumstances, and would only require their intervention in the dryest seasons and years.

Table 4 presents the results of estimating equation 3 for 4 years after the establishment of the board, for the full year. Panel A presents the results for the Common Support sample: the boarding establishment increases the average streamflow between 4% to 10%, but the increase is not significant.

The former results ignore the fact that most irrigation takes place in the dry season. Table 5, therefore, estimates the same models but only for the months of January and February, when water is more scarce and there is more irrigation, and so, incentives to over-extract are stronger. The estimated effect is stable across specifications: water boards increase the streamflow between 0.96 and 1.46 m^3/s, which represents an increase between 23% to and 34% of the average seasonal streamflow.

To understand better the results in tables 4 and 5, we estimate equation 3 but interacting the Board establishment dummy with dummies per month. These coefficients will reflect the impact of Water Boards on streamflow for each month. We present the results of this exercise in figure 7.

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

5.2.1 Dynamic effects

In this subsection, we present estimates of dynamic effects using equation 4 using OLS. The intra-segment-inter-year variance in streamflows is high for Central Chile, due to short-term cycles with droughts of varying intensity every 2 to 7 years -mostly associated with the ENSO (El Niño-Southern Oscillation cycle)(Fernández and Gironás, 2021). Given this challenge, we estimate dynamic effects binning relative years to gain power. The results are presented in figures 8a for the full year and 8b for the dry season. We fixed as the baseline period the bin containing the two years prior to the board establishment event.

In both figures, there is no evidence of pre-trends in years prior to the establishment of the board, and the specifications that control only for the set of fixed effects and contemporaneous climatic variables display persistent effects across all years post-board establishment. While for the full year (figure 8a) there is weak evidence of increases in the first 2 bins(years 0 to 3), for the dry season (figure 8b) the evidence is clear, with all specifications giving statistically and economically significant increases in streamflows. In the third bin (years 4 and 5 after board establishment), instead, the results are mixed, so effects continue to be significant in the model that do not control for lags of precipitation or water rights.

Overall, we conclude that the boards have a short-term positive effect on streamflows. We expect to improve our long-term analysis of streamflow effects in the future (see section 7).

Tables 14 in Appendix B present the full set of estimates of dynamic effects over streamflows during the full year and in the dry season.

5.2.2 Redistribution within the basin

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

Figures 9a, 9b and 9c illustrate why we expect higher streamflow increases in upstream locations: in normal times (figure 9a), the infrastructure itself restricts users from over-extracting water. In a drought, the total streamflow available for distribution is reduced, and so the law established proportional reductions for all users. Figure 9b presents this case when no board is in charge of enforcing water rights: as the infrastructure is not binding anymore, the users upstream are able to over-extract, leaving not enough water for downstream users. Figure 9c shows how this situation changes in the presence of water boards: enforcement by the water boards implies increased streamflows between upstream and downstream locations. The increase in streamflow will be captured by the monitoring stations located between the users that would over-extract in the absence of a board, and those who receive water thanks to the board.

Table 6 presents estimates of heterogeneous effects, by interacting the treatment variable with dummy variables for river segments closer to the coast (below the median of the distribution of distances to the coast, in degrees) or farther away from the coast. Columns 1 and 2 consider the full year, while columns 2 and 4 only include the dry season.

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

5.2.3 Land Concentration and Water Boards

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

In table 7 we compare the impacts of the establishment of Water Boards in basins with higher versus lower land concentration. Using 2013 data on farm size, we measure land concentration for all the river segments under analysis[20].

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

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

One interpretation for the former results is that the presence of local elites -associated with higher land concentration- enhances the performance of water boards: local elites may be able to discipline more effectively the team managing the river[21]. It is possible, too, that these aggregate results hide heterogeneous distributional impacts, and so these improvements in property rights enforcement are beneficial only for local elites[22][23]. We are exploring further data sources to obtain more conclusive results on the interactions between property rights enforcement and concentration of property.

5.3 Monitoring and Enforcement

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

1. Monitoring: water boards, by keeping track of the creation of water rights, are in a better position than both the state and the water users to identify interference by new water rights, and so introduce more complaints to stop the creation of rights.

2. Enforcement: water boards reallocate water according to the legal mandate to enforce the existing water rights.

Our results in sections 5.1 and 5.2 suggest that both mechanisms are working, opening the question of their relative roles in shaping the allocation of water in the space.

In order to disentangle the relative roles of both mechanisms, we apply a statistical mediation argument (Baron and Kenny, 1986; Valeri and VanderWeele, 2013) to estimate the direct causal effect of water boards on streamflows, and their indirect effect, mediated by their effect on water rights. Statistical mediation exercises rely on several assumptions, but the Difference-in-difference design already assumes part of them[24].

To formalize the argument, let's consider a simplified version of equation 2 i.e. our models for water rights:

$$\mathrm{WR}_{gst} = \beta_1 \mathrm{Board}_{gst} + \beta_2 X_{gst} + \mu_t + \eta_g + \varepsilon_{gst} \tag{5}$$

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

[22] We are addressing this in parallel work.

[23] Another possibility is that baseline levels of over-extraction are higher in basins with higher land concentration, i.e. there is no issue to be addressed by a Water Board in places with lower land concentration. Given the scale of the basins under study -longer than $100km$, serving thousands of users-, this possibility seems less plausible, though.

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

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

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

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

$$\begin{aligned} \text{Stream}_{gmt} = &\alpha_1 \text{Board}_{gt} + \alpha_2 \text{WR}_{gmt} + \alpha_3 \text{Board}_{gt} \times \text{WR}_{gmt} \\ &+ \alpha_4 \text{X}_{gsmt} + \mu_t + \eta_{gm} + \varepsilon_{gmt} \end{aligned} \tag{6}$$

Then, from estimates of equations 5 and 6, we can recover the effect of water boards on streamflows, mediated by water rights. Following Baron and Kenny (1986) and Valeri and VanderWeele (2013), we define

1. Natural Direct Effect of Water Boards on Streamflows:

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

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

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

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

In table 8 we present the results of the mediation exercise. The Natural Indirect Effect of water boards mediated by water rights is an increase of just $0.097m^3/s$; the Natural Direct effect is $0.842m^3/s$. Taken together, these results imply that just 10.3% of the total effect of water boards on streamflows is mediated by water rights. This suggests a limited role of Monitoring in increasing streamflows, compared to the effects of Enforcement.

6 Testing for Misallocation

In this section, we provide evidence of water misallocation in areas without water boards, which is absent in areas with water boards. We propose a test of misallocation based on the idea that if irrigation water can be reallocated within a basin through a frictionless market, the marginal productivity of water (MPW) should be equalized within the basin.

The full argument is as follows[25]:

1. Consider the problem of a farmer choosing the amount of water rights to acquire at the beginning of the season, knowing that they define the maximum amount of irrigation the farmer could use during the irrigation season. Also, rainfall is a perfect substitute for irrigation water, but it falls according to a known random distribution. The First Order Condition of this problem is that the farmer acquires water rights such that the expected marginal productivity of water is equal to the shadow value of water in the irrigation season.

2. The effect of an unexpected rainfall shock during the irrigation season is equal to the marginal productivity of water (up to the 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).

[25] The details of the theoretical model are included in Appendix A

3. A benevolent Social Planner maximizing the total value of the production by society will equate the shadow values of water across users.

To test this hypothesis, we estimate the relationship between the value of yield per hectare and water input, conditional on the position within the basin, for treated and control areas.

One challenge in implementing the former test is the fact that we do not observe the effective water input for each parcel. But as rainfall is a perfect substitute for irrigation water, up to an absorption rate (equal to the marginal rate of technical substitution between rainfall and irrigation water) (Rafey, 2023), we exploit the timing of rainfall to get within county variation in water input received during the irrigation season -which we call "useful rainfall"- at the parcel level across the production cycle. This will allow us to test for differences in the average shadow value of water among farms with canal-based irrigation and with water rights, in different locations in the same basin.

We implement this 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[26].

We estimate

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

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, Distance to Coast_c is the distance to the coast of the centroid of county c (in longitude degrees). $\mathbb{X}_i^{2007}$ 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. Finally, μ_c is a county fixed effect, and μ_r is a crop fixed effect.

On estimating equation 7, we are exploiting within county-across-crop, within crop-climatic zone across counties variation in the timing of rainfall, which is arguably exogenous on most determinants of agricultural production[27]. More importantly, the former equation allows us to estimate directly the functions needed for our Misallocation Test:

- Average Shadow Value of Water as a function for the distance to the coast, in the absence of water boards:

$$\frac{\partial\mathbb{E}\left\{\pi_i | I_0, \text{Distance to Sea, No Board}\right\}}{\partial w_i} = \beta_2 + \beta_6 \times \text{Distance to Sea} \tag{7}$$

[26] This is to eliminate outliers; the results do not change qualitatively including operations above this threshold, but the standard errors are higher.

[27] Table 15 in Appendix B presents a balance table for Useful Rainfall across specifications; there are no significant differences in Useful Rainfall, and more importantly, there are no differences between treated and control areas across positions within basins.

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

$$\frac{\partial \mathbb{E}\left\{\left.\pi_i\right| I_0, \text{Distance to Sea, Board}\right\}}{\partial w_i} = (\beta_2 + \beta_4) + (\beta_6 + \beta_7) \times \text{Distance to Sea} \tag{8}$$

We test for Misallocation over the water flow direction dimension: we test if the shadow value of water is equal at the top of the basin (head of the river) and where the river drains to the sea (mouth of the river). Our null hypothesis is that there is no misallocation: the marginal productivity of water is equal across locations in the river. Rejecting the null may happen due to higher shadow values of water upstream or downstream.

In table 9 we present the results of estimating equation 7, considering an array of location fixed effects. Our preferred specification is in column 4, which we also present graphically in figure 10. For counties outside any water board jurisdiction located on the coast, for farms with water rights, affiliation to a canal association and irrigation, an extra cubic meter of water per hectare per month would increases yield by more than $100pp$, while for farms located approximately $200km$ upstream, the increase is a nonsignificant reduction of $30pp$. The estimated average MPW is presented as the red function in figure 10 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 the creation and enforcement of contracts that would imply such reallocation of water. In fact, at the bottom of table 9 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[28].

In contrast, for counties located within the jurisdiction of water boards, the average shadow value of water is similar: for counties located next to the coast, there is a non-significant reduction in value per hectare of around $10pp$ 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 10, is flat compared to the function for places with boards, and never significantly different from zero. These results do now allow us to reject that the shadow value of water differs within basins governed by Water Boards, as it is reflected in the last row of table 9. The results are similar controlling for basin, 0.5-degree cells and county fixed effects.

Placebo exercise: rainfed parcels

To address concerns regarding potential confounders that may cause the former cross-sectional results, we present a placebo exercise, where we estimate equation 7 including the same set of controls, but for rainfed parcels. These parcels display different technology choices but are located in the same counties as the former sample, so they are exposed to similar geographies and climates. While there may exist spatial sorting within these counties, with parcels deciding to focus on rainfed strategies instead of irrigation; given the Chilean geography, the within-county differences may not be comparable (and be smaller than) across-county differences. For these parcels, there is no control over the water input, and so our estimates will correspond to the Marginal Productivity of Water[29]. More importantly, we do not expect any effect of water boards on these parcels, as the boards cannot affect their water input (i.e. rainfall).

Table 10 presents the results of this exercise. Our preferred specification is in column 4, where we again exploit within-county variation in useful rainfall across crops. The results suggest that the

[28] 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.

[29] Manysheva (2022) and Rafey (2023) use this strategy to estimate the production functions of rainfed farms

yield per hectare increases by around 20*pp* per extra cubic meter of water per hectare per month at the coast. The increase in yield for farms 160 from the coast is 25*pp*, which is not statistically different from the effect on the coast. This may be due to the fact that precipitation is higher in areas closer to the coast (see table 15), implying a higher marginal productivity of water in areas farther away. Importantly, all interaction terms with the water board dummy are not significant and economically small. The last rows of table 10 show that after including 0.5-degree cells or county fixed effects, we cannot reject that the MPW is equal for all locations, either with or without water boards, as expected.

Figure 11 present the estimated functions of Average MPW for areas with and without water boards. The most important conclusion from the figure is that both functions are parallel, and despite existing 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 geographies, 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.

7 Conclusions

In this paper, we estimated the causal effects of property rights enforcement on the allocation of water, provide and evidence of how it reduces misallocation. To this end, we study Water Boards, legally empowered boards, elected and funded by the users themselves, in charge of enforcing formal private property rights over river waters. We first show that property rights enforcement allows to limit the *de jure* allocation of the good -i.e. slowing down the creation of titles created over water- by centralizing records and responsibility over the resource. Second, we show how the introduction of enforcement affects the *de facto* allocation of water by displacing water from upstream users to downstream users. We also show that the institutions in place are able to accommodate increased demand for water when the resource is relatively abundant, but constrain the actions of the users when the resource is scarce and so the incentives for over-extraction are strongest.

In our analysis, we provide evidence of the existence of misallocation of irrigation water in areas that do not have a Water Board, suggesting over-extraction by upstream users -i.e. those who have the opportunity to over-extract, given their relative position in the basin. We cannot find similar evidence of misallocation in areas governed by Water Boards. The fact that water rights are perpetual, fully transferable, separated from land, and legally equivalent to any real estate and that the market for trading water rights does not have any special regulations in all areas -either governed by water boards or not-, suggest that the enforcement of property rights is essential for the operation of markets, and so to realize the efficiency gains from trade, it is necessary the existence of authorities with the power to take and implement decisions to adapt to special circumstances -such as droughts- and to enforce those decisions. These attributes, in turn, may allow said authority to expropriate under some legal and political circumstances.

This tension between the threat of expropriation and property rights enforcement arises from the lack of perfect information and "automatic" enforcement (i.e. we need agents that enforce in order to allocate physical resources), which leads us to a second-best world where market designers need to choose between giving more space to one threat or another. While most of the literature has focused on the economic consequences of insecure property rights due to the threat of expropriation, we are to the best of our knowledge the first ones providing causal evidence of the economic costs of insecure property rights due to a deliberate institutional design that, in order to minimize the threat of expropriation, weakened the state capacity and so the enforcement of property rights.

Our next steps will focus first on estimating the economic losses from lack of enforcement, building up on our misallocation test. A second area for future work is on the long-term consequences of property rights enforcement, estimating the impacts on agricultural choices such as land use, crop choice and technology adoption. A stable water supply for irrigation may be a substitute or complement with improved irrigation techniques and other investments (Rafey, 2023). Most of the previous literature addresses uncertainty due to climate and geography, conditional on the institutional design in place; we focus on uncertainty directly linked to the institutional arrangements in place, providing evidence on how institutions shape economic geography.

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8 Tables and Figures

8.1 Tables

Table 1: Number of river segments and Board establishment year

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

Table 2: Effect of Water Boards on creation of new water rights within their jurisdictions (Poisson)

	Surface WR		Groundwater WR	
	(1) Water Rights (m3/s)	(2) Surface WR/Area	(3) Groundwater Rights (m3/s)	(4) Groundwater WR/Area
Board established	-0.450	-0.461	0.449	0.452
	(0.172)***	(0.144)***	(0.0625)***	(0.164)***
Climatic controls	Yes	Yes	Yes	Yes
Segment FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	736	736	608	608
Outcome mean	0.325	0.025	0.137	0.006
Outcome SD	0.900	0.084	0.232	0.011

Notes: this table present estimates of equation 1 using Poisson regression. Implemented using Stacked DID design by Cengiz, Dube, Lindner, and Zipperer (2019) design, considering $segment \times event$ and $year \times event$ fixed effects, climatic controls for January and February and also including 8 lags of precipitation and precipitation squared. Standard errors clustered at the river-segment level.

Table 3: Effect of Water Boards on creation of new water rights within their jurisdictions (OLS)

	Surface Water Rights			Groundwater WR		
	(1) Water Rights (m3/s)	(2) asinh^{-1}(Surface WR)	(3) Surface WR/Area	(4) Groundwater Rights (m3/s)	(5) asinh^{-1}(Groundwater WR)	(6) Groundwater WR/Area
Board established	-0.0314	-0.0270	-0.00318	0.0362	0.0283	-0.000314
	(0.0181)*	(0.0127)**	(0.00272)	(0.0335)	(0.0293)	(0.00124)
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes
Segment FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,248	1,248	1,248	1,248	1,248	1,248
R-squared	0.938	0.932	0.951	0.773	0.789	0.683
Outcome mean	0.192	0.128	0.015	0.067	0.063	0.003
Outcome SD	0.709	0.384	0.066	0.176	0.160	0.008

Notes: this table present estimates of equation 1 using OLS. Implemented using Stacked DID design by Cengiz, Dube, Lindner, and Zipperer (2019) design, considering $segment \times event$ and $year \times event$ fixed effects, climatic controls for January and February and also including 8 lags of precipitation and precipitation squared. Standard errors clustered at the river-segment level.

Table 4: Effect of Water Boards on streamflows

	Streamflow					
	(1)	(2)	(3)	(4)	(5)	(6)
Board established	0.838	0.413	1.051	0.656	0.750	0.539
	(0.543)	(0.464)	(0.580)*	(0.478)	(0.581)	(0.483)
Water Rights (m3/s)					-1.070	-0.439
					(0.359)***	(0.307)
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes
Precipitation lags	No	Yes	No	Yes	No	Yes
Segment FE	Yes	Yes	No	No	No	No
Segment x Month FE	No	No	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	13,856	12,841	13,792	12,759	13,792	12,759
R-squared	0.507	0.585	0.702	0.776	0.702	0.776
Outcome mean	10.086	10.210	10.105	10.237	10.105	10.237
Outcome SD	20.366	20.475	20.402	20.527	20.402	20.527

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

Table 5: Effect of Water Boards on streamflows during the Dry Season (January and February)

	Streamflow in Dry Season (Jan-Feb)							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Board established	1.457	1.014	1.443	0.961	1.046	1.013	1.019	0.959
	(0.586)**	(0.312)***	(0.573)**	(0.307)***	(0.439)**	(0.338)***	(0.424)**	(0.329)***
Water Rights (m3/s)					-1.398	-0.00359	-1.439	-0.0103
					(0.972)	(0.287)	(1.015)	(0.297)
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Precipitation lags	No	Yes	No	Yes	No	Yes	No	Yes
Segment FE	Yes	Yes	No	No	Yes	Yes	No	No
Segment x Month FE	No	No	Yes	Yes	No	No	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2,285	2,037	2,277	2,025	2,285	2,037	2,277	2,025
R-squared	0.450	0.681	0.478	0.699	0.454	0.681	0.481	0.699
Outcome mean	4.150	4.021	4.160	4.019	4.150	4.021	4.160	4.019
Outcome SD	8.345	8.222	8.358	8.222	8.345	8.222	8.358	8.222

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

Table 6: Heterogeneous effects, by distance to the coast.

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

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

Table 7: Water Board effects and Land Concentration

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

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

Table 8: Monitoring vs Enforcement

	Mediation exercise: indirect effect of water boards	
	(1) Water Rights (m3/s)	(2) River level (m3/s)
Board established	-0.154	
	(0.0940)	
Board established=1		1.115
		(0.392)***
Water Rights (m3/s)		-0.00632
		(0.293)
Board established=1 × Water Rights (m3/s)		-0.621
		(0.784)
Climatic controls	Yes	Yes
Precipitation lags	Yes	Yes
Segment FE	Yes	No
Segment x Month FE	No	Yes
Year FE	Yes	Yes
Observations	1,704	2,025
R-squared	0.868	0.699
Natural Direct Effect		0.842
Natural Indirect Effect		0.097

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

Table 9: Shadow Value of Water: Impact of rainfall on Production Value during the irrigation season for irrigated parcels, by longitude and treatment status

	Main Equation: effect on irrigated farms			
	(1) log(value production/Ha.)	(2) log(value production/Ha.)	(3) log(value production/Ha.)	(4) log(value production/Ha.)
Useful pp. (m3 per Ha per month)	1.284	0.816	1.111	1.181
	(0.557)**	(0.564)	(0.604)*	(0.667)*
	[0.558]**	[0.569]	[0.603]*	[0.661]*
Useful pp. (m3 per Ha per month) × Distance to coast (100km)	-0.833	-0.699	-0.833	-0.767
	(0.374)**	(0.366)*	(0.387)**	(0.424)*
	[0.369]**	[0.367]*	[0.378]**	[0.411]*
Water Board=1 × Useful pp. (m3 per Ha per month)	-0.764	-0.958	-1.538	-1.297
	(0.697)	(0.677)	(0.662)**	(0.733)*
	[0.693]	[0.667]	[0.663]**	[0.709]*
Water Board=1 × Useful pp. (m3 per Ha per month) × Distance to coast (100km)	0.332	0.555	0.967	0.793
	(0.489)	(0.476)	(0.447)**	(0.480)
	[0.480]	[0.461]	[0.441]**	[0.458]*
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	0.537	0.571	0.583	0.639
Misallocation Test: No Board	0.03	0.06	0.03	0.07
Misallocation Test: with Board	0.05	0.59	0.56	0.91

Notes: This table present estimates of equation 7 for irrigated parcels, with water rights, registered in canal associations. Distance to the coast measured through the river network. Controlling for capital and technology choices, logarithm of labor input and irrigated surface, and County and Crop fixed effects. Standard errors clustered at the county level (round parenthesis) and at the county× irrigation season level (squared parentheses.

Table 10: Placebo exercise: Impact of rainfall on Production Value during the irrigation season by longitude and treatment status for rainfed parcels.

	Placebo: effect on rainfed farms			
	(1) log(value production/Ha.)	(2) log(value production/Ha.)	(3) log(value production/Ha.)	(4) log(value production/Ha.)
Useful pp. (m3 per Ha per month)	-0.191	0.135	-0.0117	0.216
	(0.175)	(0.195)	(0.178)	(0.125)*
	[0.158]	[0.171]	[0.176]	[0.133]
Distance to coast (100km)	-0.171	-0.174	0.150	
	(0.107)	(0.114)	(0.0892)*	
	[0.0976]*	[0.106]	[0.0843]*	
Useful pp. (m3 per Ha per month) × Distance to coast (100km)	0.285	0.411	0.0780	0.0158
	(0.160)*	(0.137)***	(0.0826)	(0.0766)
	[0.147]*	[0.128]***	[0.0913]	[0.0741]
Water Board=1	-0.841	-0.997	0.128	
	(0.436)*	(0.507)*	(0.526)	
	[0.443]*	[0.477]**	[0.502]	
Water Board=1 × Useful pp. (m3 per Ha per month)	0.339	0.420	-0.230	0.0271
	(0.404)	(0.323)	(0.255)	(0.183)
	[0.458]	[0.381]	[0.422]	[0.186]
Water Board=1 × Distance to coast (100km)	0.887	1.059	-0.0490	
	(0.316)***	(0.365)***	(0.384)	
	[0.318]***	[0.340]***	[0.379]	
Water Board=1 × Useful pp. (m3 per Ha per month) × Distance to coast (100km)	-0.356	-0.500	0.182	-0.0387
	(0.314)	(0.251)**	(0.199)	(0.138)
	[0.339]	[0.280]*	[0.333]	[0.137]
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	56,717	56,716	56,716	56,715
R-squared	0.564	0.575	0.606	0.626
Misallocation Test: No Board	0.08	0.00	0.35	0.84
Misallocation Test: with Board	0.79	0.69	0.15	0.83

Notes: This table present estimates of equation 7 for non-irrigated parcels, as a placebo exercise. Distance to the coast measured through the river network. Controlling for capital and technology choices, logarithm of labor input and irrigated surface, and County and Crop fixed effects. Standard errors clustered at the county level (round parenthesis) and at the county× irrigation season level (squared parentheses).

8.2 Figures

Figure 1: Water Right creation process.

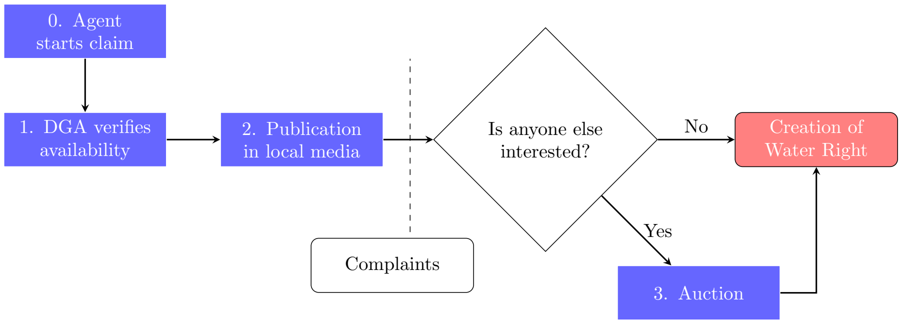
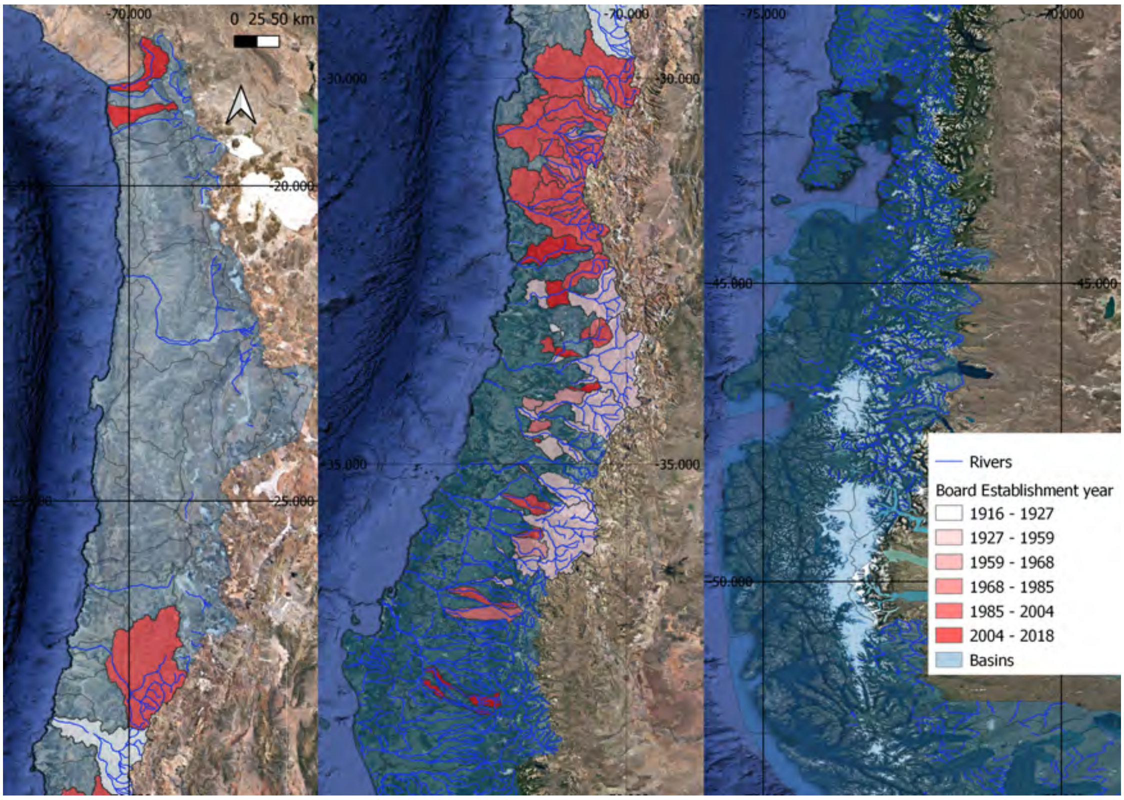


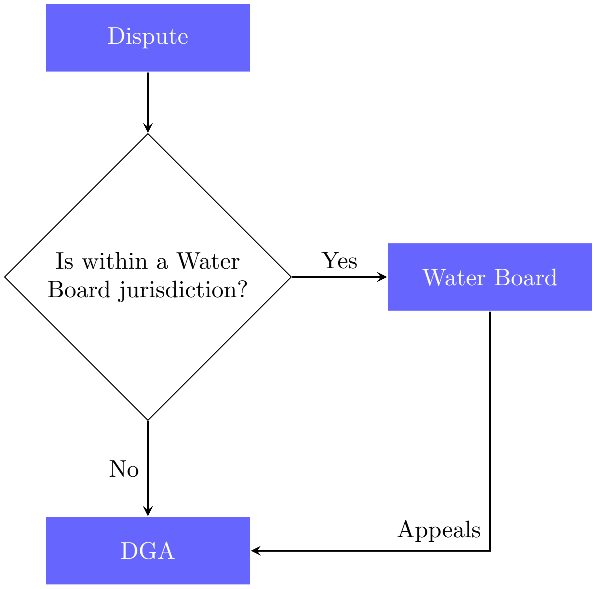
Figure 2: Area of study and Water Boards jurisdictions



Notes: Left, center and right panels corresponds to the northern, central and southern areas of Chile. The colored areas represent each of the existing Water Boards jurisdictions, with their color reflecting the establishment year.

Figure 3: Administrative and legal hierarchy of institutions over water rights issues.

(a) Administrative



(b) Legal

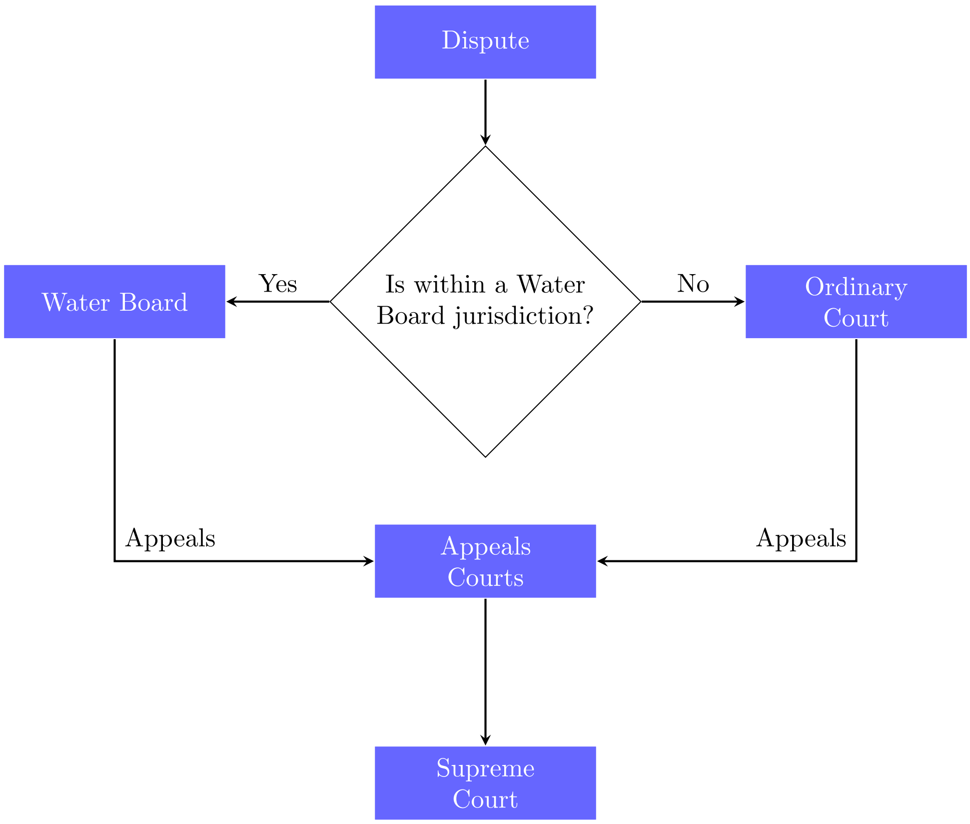
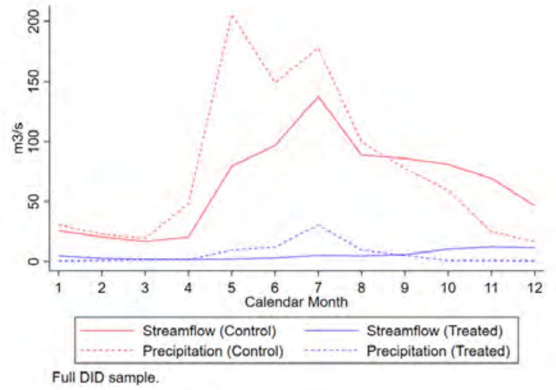
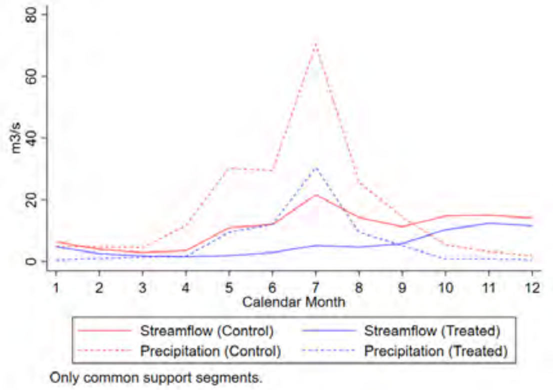


Figure 4: Hydrological regime before 1985, by treatment assignment

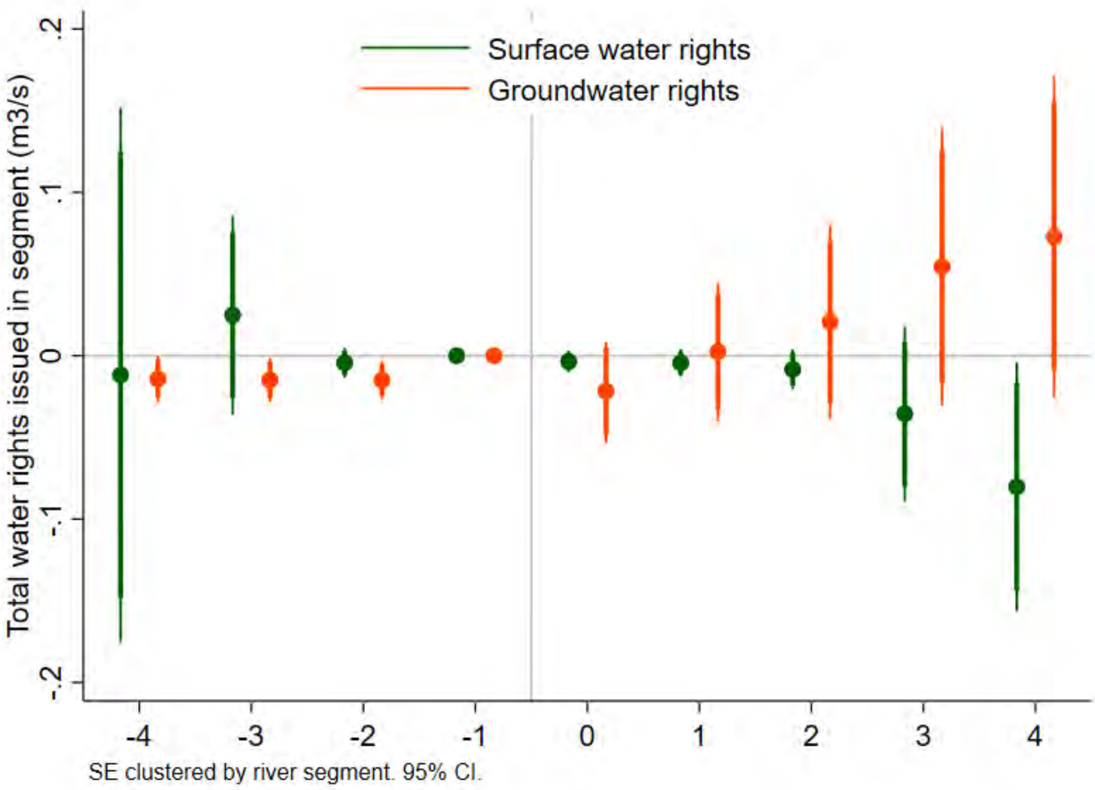


(a) Hydrological regime before 1985, by treatment assignment. Full sample.



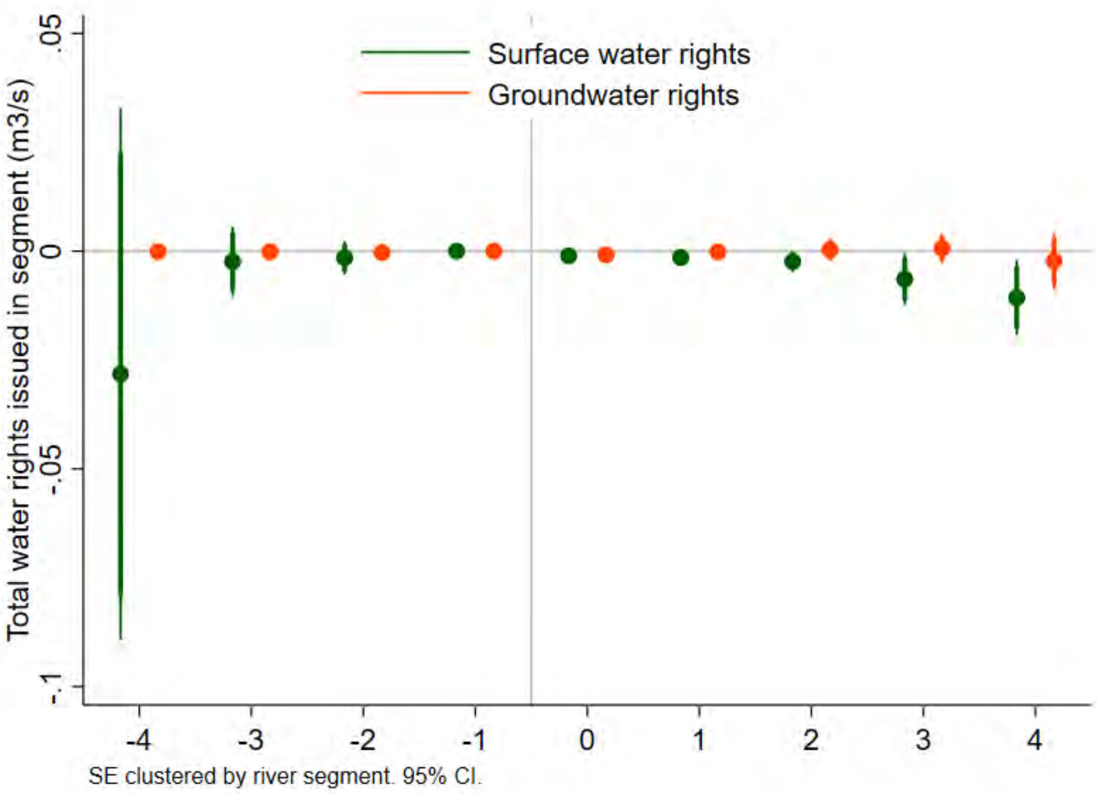
(b) Hydrological regime before 1985, by treatment assignment. Study sample: only segments within the common support in average streamflow and pre-existing water rights in 1980, that eventually have Water Boards.

Figure 5: Effect of boards establishments on Water Rights issued in their jurisdictions, by source of the water.



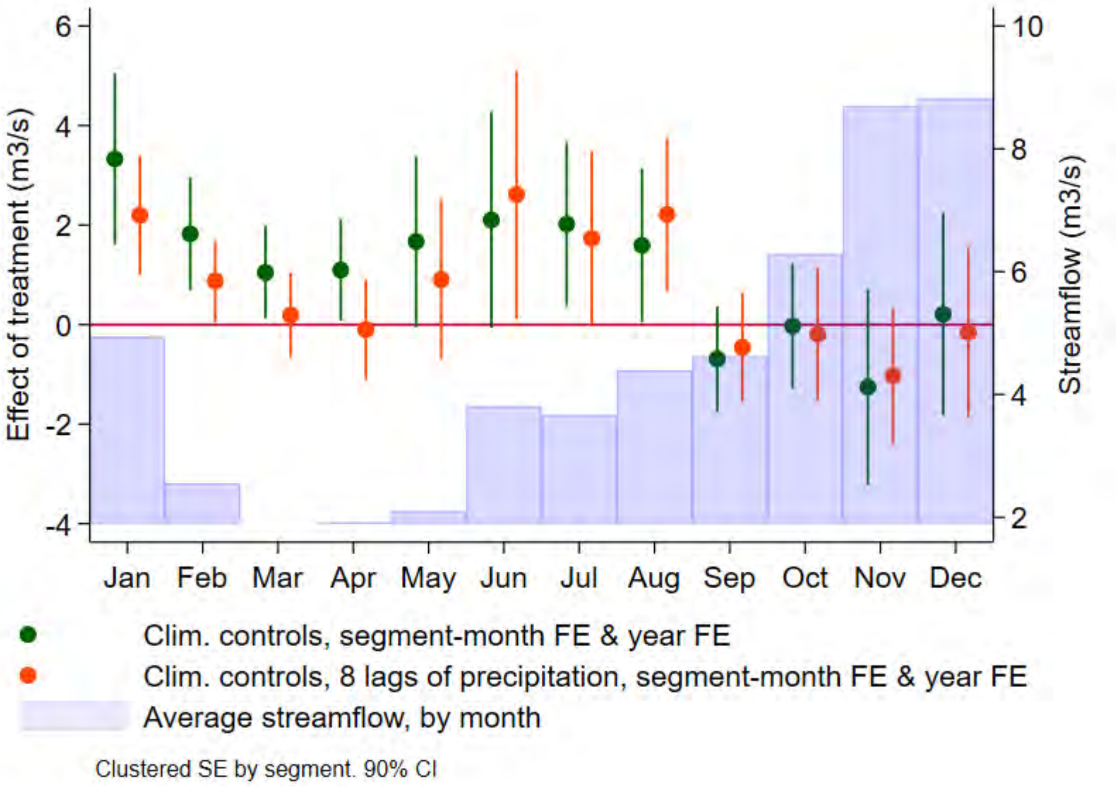
Notes: this figure present estimates of dynamic effects of water boards on water rights issued (measured in m^3/s) separately by source: in green, the effect of water boards on surface water rights; in orange, the effect of water boards on groundwater rights. Using OLS, implemented using Stacked DID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

Figure 6: Effect of boards establishments on Water Rights issued per km^2 in their jurisdictions, by source of the water.



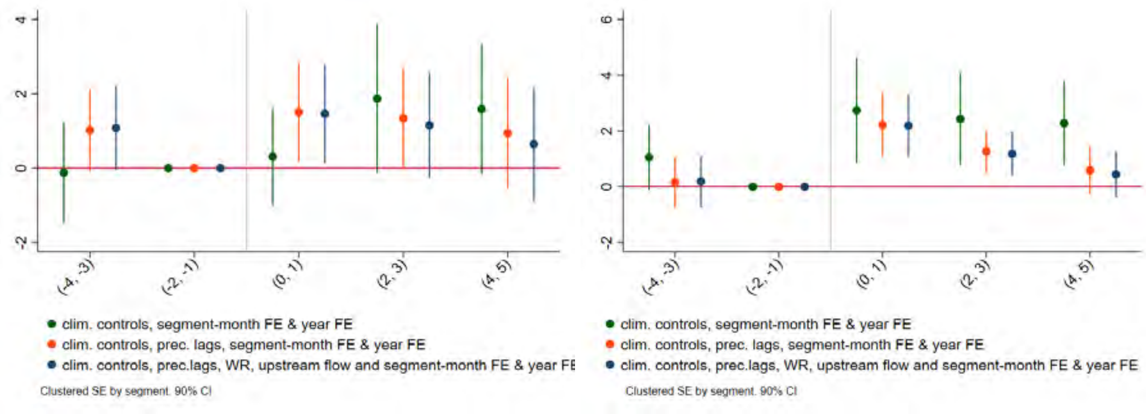
Notes: this figure present estimates of dynamic effects of water boards on water rights issued (measured in m^3/s,) per km^2 of surface of the basin, separately by source: in green, the effect of water boards on surface water rights; in orange, the effect of water boards on groundwater rights. Using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

Figure 7: Effect of board establishments on streamflow within their jurisdiction, by month.



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

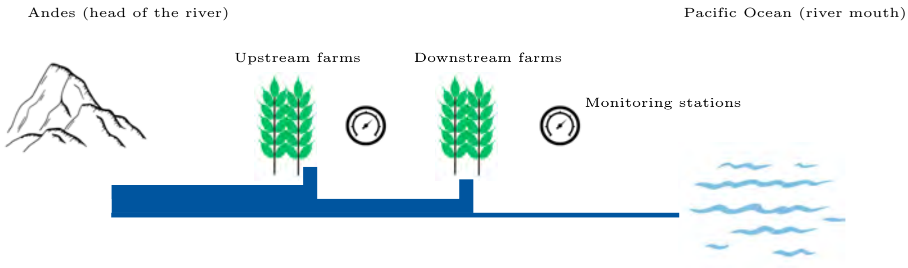
Figure 8: Effect of board establishments on streamflow within their jurisdiction, by relative time (binned years) to the board establishment event.



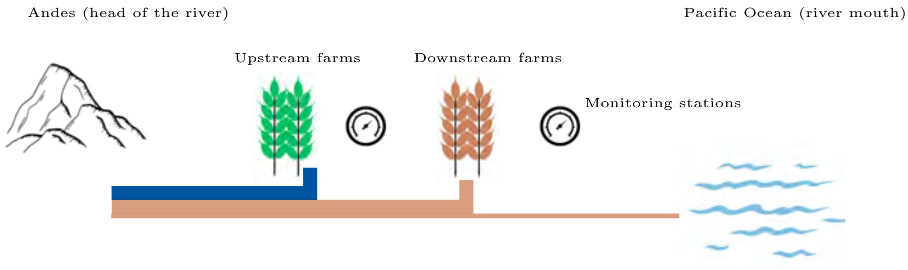
(a) Full year. (b) Dry season.

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

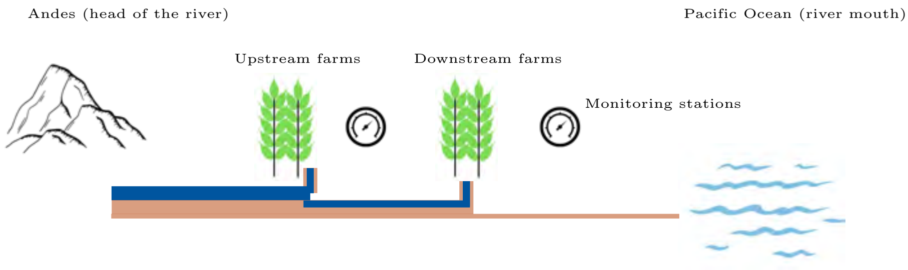
Figure 9: Illustration: how streamflows measurement allows to recover impacts of enforcement by water boards on streamflow.



(a) No drought

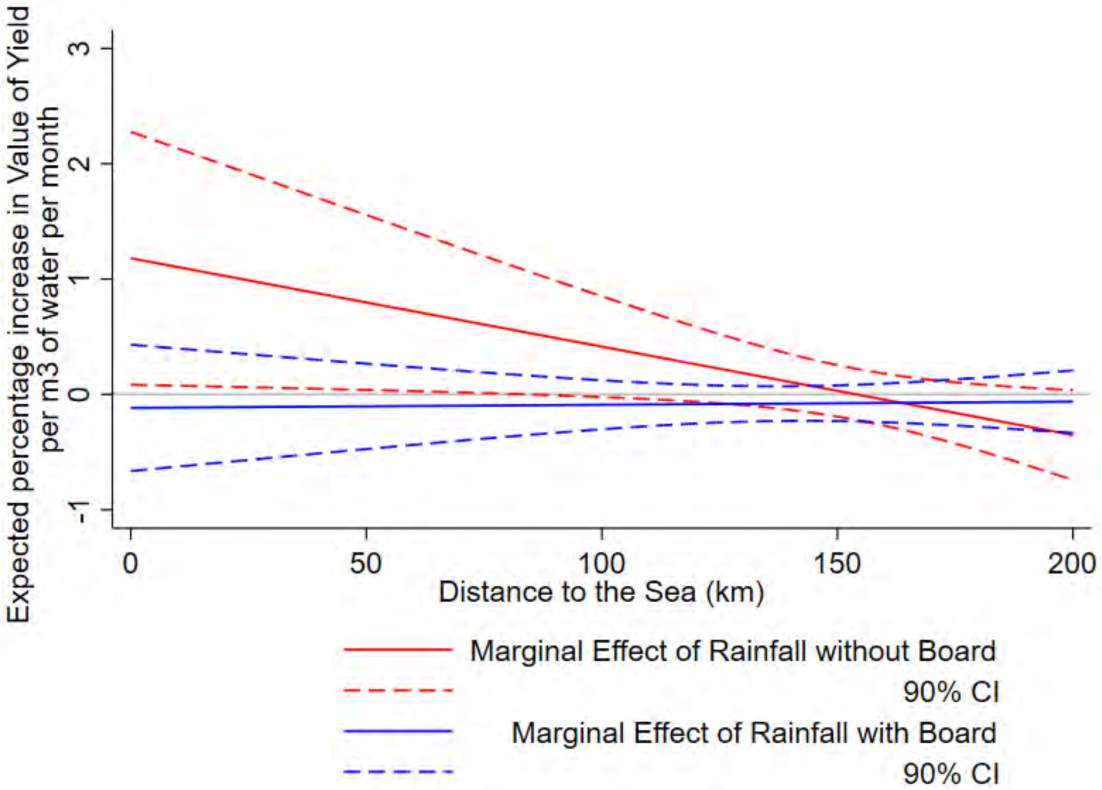


(b) Drought, and no enforcement of water rights



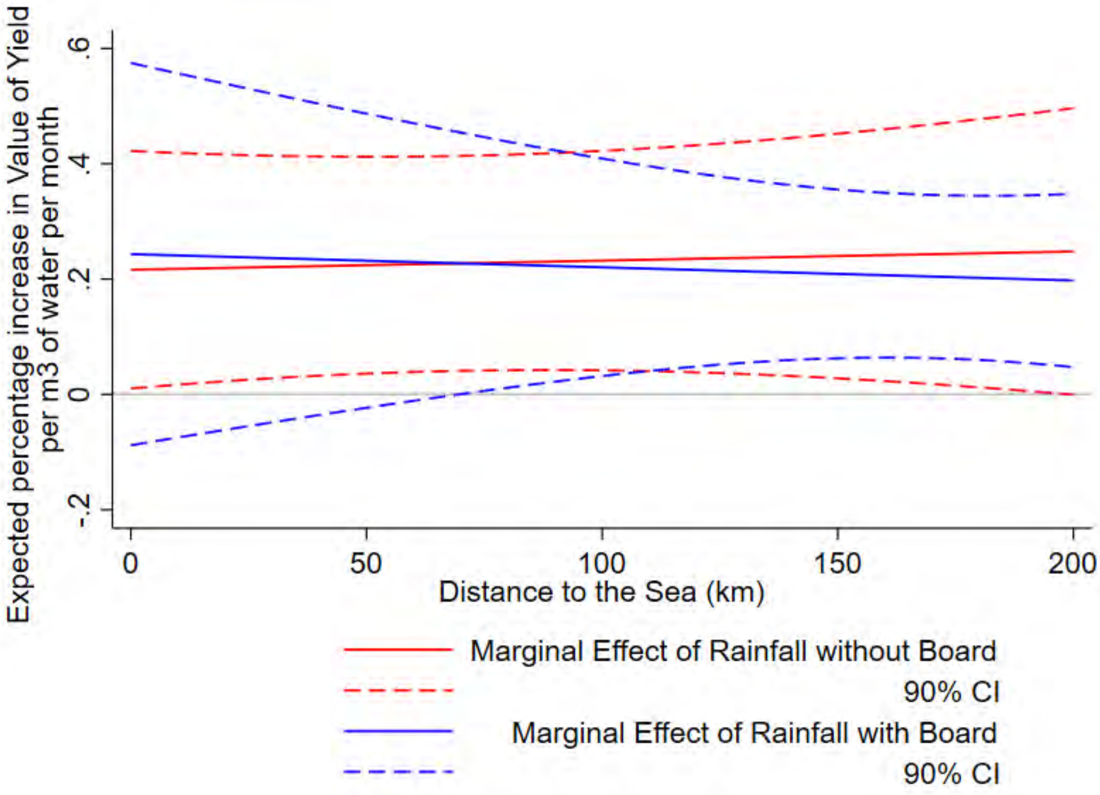
(c) Drought, and Water Boards enforce water rights

Figure 10: Main results: effect on log(Production) of rainfall during the irrigation season by longitude and treatment status for irrigated parcels registered in canal associations.



Notes: Graphical representation of results in Table 9.

Figure 11: 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 10 .

A Model of Agricultural Production and Irrigation under Water Rights

This section discusses a model of agricultural production and irrigation under water rights, that provides the framework to interpret the results in presented in Section 6 as a misallocation test. The first part presents a model of agricultural production, that allows to define the shadow value of water as the marginal productivity of irrigation water. The second part discusses briefly the problem of a Social Planner, and shows that a Social Planner willing to maximize the value of production would equalize the shadow value of water across users. In this environment, an application of the First Welfare Theorem allows to conclude that the solution of the Social Planner would be implemented as the Market Equilibrium under a well-functioning market.

The key insights from this section are that the partial derivative of output with respect to rainfall is equal to the shadow value of water, times the marginal rate of technical substitution between rainfall and water from irrigation, and a definition of short-term misallocation.

Environment

Consider the problem of allocating water across N agricultural users within a basin. 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 have different impacts depending of 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 each stage, 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 of irrigation water, up to a technical rate of substitution constant θ. Rainfall is a random variable with 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 crop, capital and land.

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

time= 2 : Profits are realized

Finally, each production function F_c is continuous, strictly concave and monotone[30].

[30] 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 scenario is certainly realistic, in the area under study -with mostly a dry mediterranean weather with a well marked rainfall season in the winter- is rare, and in fact 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 affect the solution to the farmer's problem by reducing irrigation, in which case the irrigation restriction is not binding. In this scenario, the shadow value of water is zero, and so the problem and the shadow value preserve their meaning.

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:

$$\begin{aligned} \max_{L_i, w_i} \quad & p_c F_i^c(S_i, K_i, L_i, w_i + \theta r_i) - \lambda_i^s (w_i - \bar{w}_i) - c_L L_i \\ FOC(w_i) \quad : \quad & p_c F_{i\ w}^{c\prime} = \lambda_i^w \\ FOC(L_i) \quad : \quad & p_c F_{i\ L}^{c\prime} = c_L \end{aligned}$$

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

$$\begin{aligned} \max_{K_i, S_i} \quad & \mathbb{E}_r \left\{ p F_i^c \left(S_i, K_i, L_i \left(K_i, S_i, \bar{w}_i \right), w_i \left(K_i, S_i, \bar{w}_i \right) + \theta r_i \right) - c_S S_i - c_K K_i | I_0 \right\} \\ FOC(S_i) \quad : \quad & \mathbb{E}_r \left\{ p_c F_{i\ S}^{c\prime} | I_0 \right\} = c_S \\ FOC(K_i) \quad : \quad & \mathbb{E}_r \left\{ p_c F_{i\ K}^{c\prime} | I_0 \right\} = c_K \end{aligned}$$

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

$$\begin{aligned} \pi_i^c(\bar{w}_i) \equiv & \mathbb{E}_r \left\{ p_c F_i^c \left(S_i \left(\bar{w}_i \right), K_i \left(\bar{w}_i \right), L_i \left(\bar{w}_i \right), w_i \left(\bar{w}_i \right) + \theta r_i \right) \right. \\ & \left. - c_S S_i \left(\bar{w}_i \right) - c_K K_i \left(\bar{w}_i \right) - c_L L_i \left(\bar{w}_i \right) - \lambda_i^w \left(w_i \left(\bar{w}_i \right) - \bar{w}_i \right) | I_0 \right\} \end{aligned} \tag{9}$$

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

$$\bar{\pi}_i(\bar{w}_i) \equiv \max \left\{ k : \pi_i^k(\bar{w}_i) \right\} \tag{10}$$

Social Planners' Problem

Lets 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 total production value, subject to the total availability of water:

$$\max_{\{\bar{w}_i\}|_{i=1}^N} \sum_i \bar{\pi}_i(\bar{w}_i) - \lambda^W \left(\sum_i \bar{w}_i - \bar{W} \right) \tag{11}$$

Note that the social planners 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

$$\frac{\partial \Omega}{\partial \bar{w}_i} = 0 \iff \frac{\partial \bar{\pi}_i}{\partial \bar{w}_i} = \lambda^W \tag{12}$$

Therefore, the optimal allocation satisfies $\frac{\partial \bar{\pi}_i}{\partial \bar{w}_i} = \frac{\partial \bar{\pi}_j}{\partial \bar{w}_j}$. 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 the second equality is a consequence of the Envelope Theorem[31][32]. In the socially optimal allocation, therefore, the expected shadow value of water is equal across farmers; any deviation from that imply 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

Consider the effect on welfare of an unexpected rainfall shock over farm j. As the water rights allocation is fixed, then:

$$\frac{\partial \Omega}{\partial r_j} = \mathbb{E}_r \left[\frac{\partial p_k F^{k'}_{j\,w}}{\partial w_i} \right] \times \theta = \theta \mathbb{E}_r \left[\lambda_j \right] = \theta \mathbb{E}_r \left[\lambda^W \right]$$

where the second equality comes from the problem of farmer j and the third comes from the planner FOC. 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[33], which is approximately equal to 1.

We can conclude from the former discussion that

1. the optimal allocation of water rights equalizes the expected marginal productivity of irrigation water across users, and
2. the effect of an unexpected rainfall shock is equal to the marginal productivity of irrigation water.

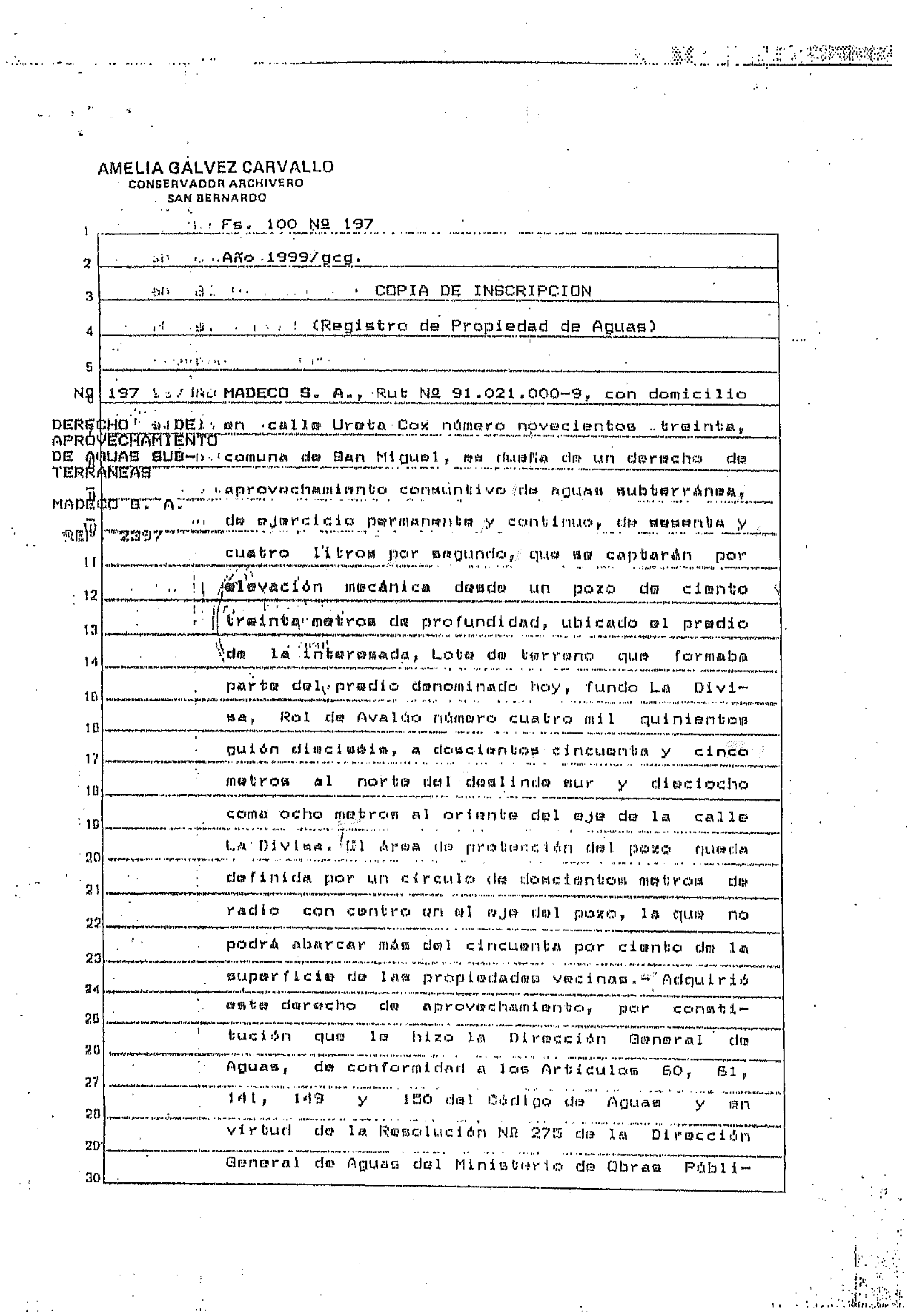
[31] The application is direct in this case; a more general discussion can be found in Hsiang (2016); Deryugina and Hsiang (2017)

[32] The K index here denotes the crop chosen by the farmer; this choice is not affected by an unexpected rainfall shock.

[33] 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.

B Appendix

Figure 12: Example: water right title.



AMELIA GALVEZ CARVALLO
CONSERVADOR ARCHIVERO
SAN BERNARDO

Fs. 100 Nº 197

Año 1999/gcg.

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(Registro de Propiedad de Aguas)

Nº 197

DERECHO DE APROVECHAMIENTO DE AGUAS SUBTERRANEAS

MADECO S. A.

REP 2397

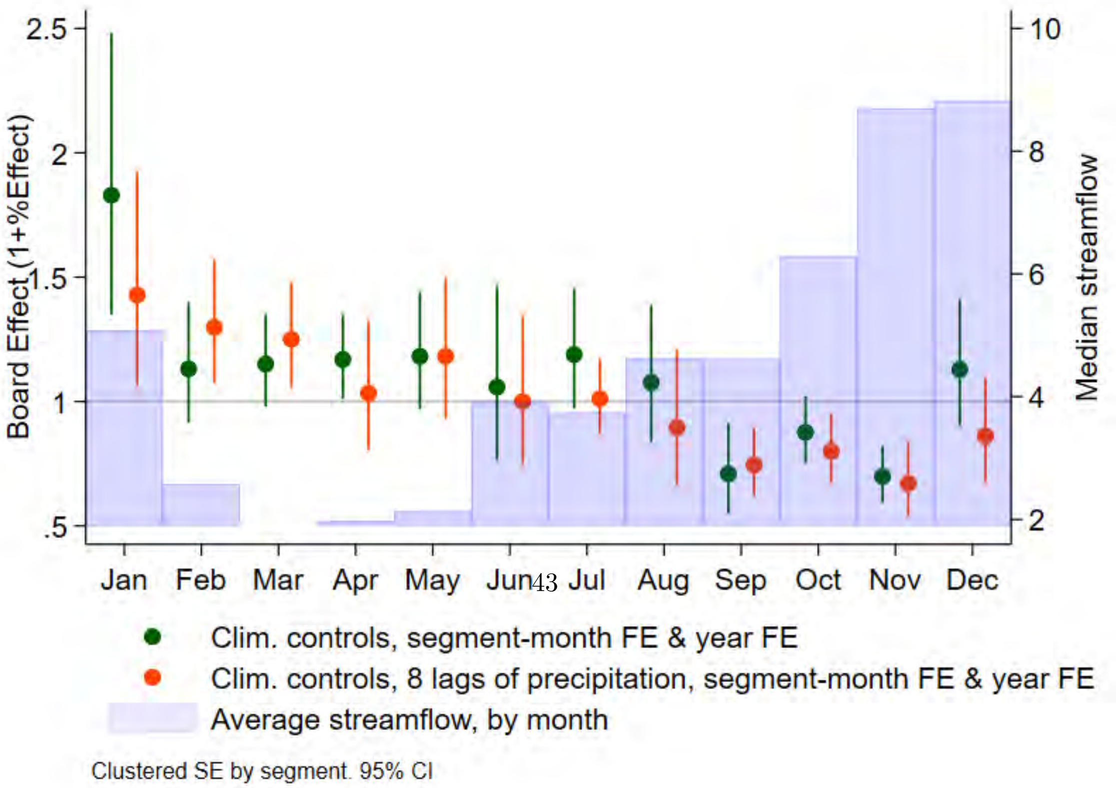
MADECO S. A., Rut Nº 91.021.000-9, con domicilio en calle Ureta Cox número novecientos treinta, comuna de San Miguel, es dueña de un derecho de aprovechamiento consuntivo de aguas subterránea, de ejercicio permanente y continuo, de sesenta y cuatro litros por segundo, que se captarán por elevación mecánica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

Table 11: Years of Board Establishment, by river segment

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

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

Figure 13: Effects by month, estimated using Poisson Regression.



Water Rights created

Panel A: OLS

	Surface WR (m3/s)		Groundwater WR (m3/s)	
	(1)	(2)	(3)	(4)
-4	-0.0118	-0.00571	-0.0142	-0.0125
	(0.0816)	(0.0848)	(0.00700)**	(0.00709)*
-3	0.0249	0.00803	-0.0149	-0.0127
	(0.0304)	(0.0270)	(0.00662)**	(0.00523)**
-2	-0.00436	-0.00358	-0.0150	-0.0147
	(0.00451)	(0.00782)	(0.00587)**	(0.00634)**
-1	0	0	0	0
	(.)	(.)	(.)	(.)
0	-0.00352	-0.0254	-0.0217	-0.0123
	(0.00328)	(0.0162)	(0.0159)	(0.0183)
1	-0.00438	0.00480	0.00248	0.00153
	(0.00414)	(0.0169)	(0.0211)	(0.0210)
2	-0.00835	-0.0229	0.0207	0.0245
	(0.00602)	(0.0162)	(0.0296)	(0.0304)
3	-0.0356	-0.0252	0.0544	0.0562
	(0.0267)	(0.0298)	(0.0424)	(0.0425)
4	-0.0803	-0.0786	0.0729	0.0680
	(0.0379)**	(0.0534)	(0.0492)	(0.0493)
-1	0	0	0	0
	(.)	(.)	(.)	(.)
Climatic controls	No	Yes	No	Yes
Segment FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	1,404	1,404	1,404	1,404
R-squared	0.893	0.896	0.751	0.753
Outcome mean	0.180	0.180	0.062	0.062
Outcome SD	0.686	0.686	0.170	0.170

Panel B: Poisson

	Surface WR (m3/s)		Groundwater WR (m3/s)	
	(1)	(2)	(3)	(4)
-4	0.158	0.184	-0.158	-0.101
	(0.219)	(0.228)	(0.0742)**	(0.0703)
-3	0.209	0.147	-0.204	-0.164
	(0.162)	(0.156)	(0.0517)***	(0.0508)***
-2	0.00204	0.0691	-0.215	-0.154
	(0.0139)	(0.0639)	(0.0403)***	(0.0597)***
-1	0	0	0	0
	(.)	(.)	(.)	(.)
0	-0.0391	-0.0103	0.0467	0.0959
	(0.0262)	(0.106)	(0.0261)*	(0.0809)
1	-0.109	-0.0774	0.306	0.341
	(0.0428)**	(0.0714)	(0.0564)***	(0.0817)***
2	-0.158	-0.110	0.426	0.412
	(0.0522)***	(0.111)	(0.0699)***	(0.0710)***
3	-0.725	-0.676	0.543	0.480
	(0.340)**	(0.317)**	(0.0921)***	(0.103)***
4	-0.790	-0.823	0.350	0.435
	(0.332)**	(0.329)**	(0.209)*	(0.146)***
-1	0	0	0	0
	(.)	(.)	(.)	(.)
Climatic controls	No	Yes	No	Yes
Segment FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	814	814	684	684
R-squared				
Outcome mean	0.311	0.311	0.128	0.128
Outcome SD	0.879	0.879	0.225	0.225

Table 12: Dynamic effects of Water Boards on water rights. Baseline period correspond to the last two years before the boards establishment.

Water Rights per squared Kilometer

Panel A: OLS

	Surface WR per Area		Groundwater WR per Area	
	(1)	(2)	(3)	(4)
-4	-0.0282	-0.0284	-0.0000869	0.0000348
	(0.0304)	(0.0305)	(0.000347)	(0.000334)
-3	-0.00237	-0.00252	-0.000141	-0.0000798
	(0.00398)	(0.00386)	(0.000245)	(0.000245)
-2	-0.00153	-0.00162	-0.000289	-0.000166
	(0.00188)	(0.00205)	(0.000140)**	(0.000146)
-1	0	0	0	0
	(.)	(.)	(.)	(.)
0	-0.00108	-0.000222	-0.000842	-0.000866
	(0.000715)	(0.00128)	(0.000479)*	(0.000537)
1	-0.00147	-0.00207	-0.000172	-0.000114
	(0.000790)*	(0.000892)**	(0.000719)	(0.000780)
2	-0.00237	-0.00137	0.000325	0.000279
	(0.00119)*	(0.00122)	(0.00128)	(0.00128)
3	-0.00641	-0.00662	0.000637	0.000656
	(0.00295)**	(0.00296)**	(0.00167)	(0.00169)
4	-0.0107	-0.0126	-0.00231	-0.00191
	(0.00431)**	(0.00505)**	(0.00326)	(0.00290)
-1	0	0	0	0
	(.)	(.)	(.)	(.)
Climatic controls	No	Yes	No	Yes
Segment FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	1,404	1,404	1,404	1,404
R-squared	0.882	0.882	0.666	0.667
Outcome mean	0.014	0.014	0.003	0.003
Outcome SD	0.062	0.062	0.008	0.008

Panel B: Poisson

	Surface WR per Area		Groundwater WR per Area	
	(1)	(2)	(3)	(4)
-4	0.0561	0.0478	-0.0534	-0.0402
	(0.0480)	(0.0503)	(0.0439)	(0.0431)
-3	0.0463	0.0649	-0.0425	-0.0307
	(0.0193)**	(0.0189)***	(0.0349)	(0.0394)
-2	0.0205	0.0398	-0.0359	-0.0263
	(0.0111)*	(0.0156)**	(0.0306)	(0.0369)
-1	0	0	0	0
	(.)	(.)	(.)	(.)
0	-0.0124	0.0290	0.00687	0.00658
	(0.00755)*	(0.0310)	(0.0101)	(0.0236)
1	-0.0668	-0.0690	-0.0157	-0.0154
	(0.0290)**	(0.0328)**	(0.0158)	(0.0222)
2	-0.0951	-0.0888	-0.0892	-0.107
	(0.0347)***	(0.0380)**	(0.0615)	(0.0639)*
3	-0.179	-0.182	-0.143	-0.172
	(0.0812)**	(0.0836)**	(0.0820)*	(0.0839)**
4	-0.197	-0.212	-0.270	-0.240
	(0.0834)**	(0.0750)***	(0.157)*	(0.132)*
-1	0	0	0	0
	(.)	(.)	(.)	(.)
Climatic controls	No	Yes	No	Yes
Segment FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	814	814	684	684
R-squared				
Outcome mean	0.311	0.311	0.128	0.128
Outcome SD	0.879	0.879	0.225	0.225

Table 13: Dynamic effects of Water Boards on water rights per unit of area. Baseline period correspond to the last two years before the boards establishment.

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

Table 14: Dynamic effects of Water Boards on streamflows. Baseline period correspond to the last two years before the boards establishment.

Rainfall during the crop irrigation season								
	Full Sample				Irrigated fields sample			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Distance to coast (100km)	0.107	0.0121	0.0171	-0.0321	-0.0323	-0.313	-0.240	-0.372
	(0.0321)***	(0.0350)	(0.0208)	(0.0247)	(0.0910)	(0.138)**	(0.0630)***	(0.0943)***
Water Board=1	0.127	0.0398	0.0138	-0.0250	0.0833	-0.146	-0.142	-0.233
	(0.0822)	(0.0544)	(0.0512)	(0.0456)	(0.164)	(0.236)	(0.105)	(0.155)
Water Board=1 × Distance to coast (100km)	-0.106	-0.0376	-0.0174	0.0358	-0.0689	0.0713	0.0775	0.141
	(0.0485)**	(0.0359)	(0.0318)	(0.0301)	(0.105)	(0.146)	(0.0694)	(0.101)
Constant	0.0783	0.192	0.188	0.233	0.315	0.713	0.616	0.791
	(0.0523)	(0.0449)***	(0.0320)***	(0.0344)***	(0.158)**	(0.224)***	(0.101)***	(0.147)***
Agro-climate zone FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Basin FE	Yes	No	Yes	No	Yes	No	Yes	No
0.5 degree cell FE	No	Yes	No	Yes	No	Yes	No	Yes
Crop FE	No	No	Yes	Yes	No	No	Yes	Yes
Observations	220,162	220,162	216,334	216,334	15,908	15,905	15,149	15,147
R-squared	0.238	0.296	0.879	0.900	0.302	0.356	0.922	0.945
Outcome mean	0.204	0.204	0.205	0.205	0.276	0.277	0.278	0.278
Outcome SD	0.314	0.314	0.316	0.316	0.301	0.301	0.304	0.304

Table 15: Balance table: outcome variable is precipitation fell during the irrigation season of the crop planted in the parcel