Interjurisdictional Spatial Externalities in Groundwater Management*

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Abstract

When designing groundwater management policies, it is important to account for spatial externalities that result from the common pool nature of the resource. Spatial externalities may arise not only among individual groundwater users sharing the same aquifer, but also among water managers whose separate jurisdictions do not each cover an entire aquifer. In this paper, we develop a model of interjurisdictional spatial externalities in groundwater management, and apply our model to a detailed spatial panel data set covering the 57 years from 1960 to 2016 that we have collected and constructed from historical records in California. Our econometric analysis of the effects of partial coordination shows that, consistent with the theory, wells that were more interior to their jurisdiction better internalized spatial externalities, while wells that were hydrologically connected to other jurisdictions either through rivers or across a purely political boundary faced interjurisdictional spatial externalities that they did not internalize. Our spatial econometric models show that the split groundwater management mandated under the 1969 Western Judgment did little to correct the effects of these interjurisdictional spatial externalities on groundwater pumping behavior. Our results provide empirical evidence for the presence of interjurisdictional spatial externalities that should be accounted for in the optimal design of groundwater management in California.

Keywords: interjurisdictional spillovers, spatial externalities, groundwater, California
***JEL* Codes:** Q15, Q38, R50
This draft: June 3, 2023

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1 Introduction

The sustainable management of groundwater resources is a critical issue for agriculture and for rural economic activity worldwide (Siebert et al., 2013; Sears and Lin Lawell, 2019; National Groundwater Association, 2020). In California, where both high-value specialty crop production and large residential populations rely on groundwater resources, and where climate change is expected to lead to more extreme weather conditions, the optimal management of groundwater resources is an acute policy problem (Hanak et al., 2012; Hanson et al., 2012; Taylor et al., 2013; Sumner et al., 2015; Diffenbaugh et al., 2015; Cook et al., 2015). When designing groundwater management policies, it is important to account for spatial externalities that result from the common pool nature of the resource. Spatial externalities arise among groundwater users who share the same aquifer because groundwater pumping by one user raises the extraction cost and lowers the total amount available to other nearby users (Provencher and Burt, 1993; Brozović et al., 2010; Pfeiffer and Lin, 2012; Lin Lawell, 2016; Sears et al., 2019).

Spatial externalities may arise not only among individual groundwater users sharing the same aquifer, but also among water managers whose separate jurisdictions do not each fully cover an entire aquifer's groundwater supply. This can occur, for example, when jurisdictional boundaries are determined based on political borders rather than aquifer boundaries, when connected surface water supplies like rivers and streams cross jurisdictional boundaries, or when groundwater is managed under several different sets of regulations based on how it is used.

In this paper, we develop a model of interjurisdictional spatial externalities in groundwater management. We derive theoretical predictions for the effects of economic and hydrological factors on interjurisdictional spatial externalities and on groundwater extraction under partial coordination. We find that if groundwater managers each manage only a subset of an aquifer, and if there is spatial movement of water between the jurisdictions of different groundwater managers, then groundwater will be over-extracted relative to the socially optimal coordinated solution.

We apply our model to a detailed spatial panel data set to analyze and estimate interjurisdictional spatial externalities in groundwater management in California. We focus our empirical analysis on three interconnected basins that were adjudicated as part of the 1969 Western Judgment in San Bernardino and Riverside Counties. The 1969 Western Judgment allowed users to operate under different regulations based on the locations of their wells and the service areas, thereby splitting groundwater management across multiple jurisdictional boundaries and regulatory frameworks. We first estimate the share of spatial externalities that are internalized under the jurisdictional boundaries and design of regulations imposed under the Western Judgment. This provides a measure of the degree to which groundwater management was coordinated between groundwater users in our study region, and how the regulatory framework influenced the level of coordination. We then use a spatial panel dataset covering the 57 years from 1960 to 2016 that we have collected and constructed from historical records to estimate how interjurisdictional spatial externalities affected extraction behavior. Finally, we use an instrumental variable (IV) spatial econometric model to analyze the impact of the 1969 Western Judgment on the spatial effects of groundwater extraction, which we define as the effects of groundwater extraction at nearby wells on groundwater extraction at a particular well.

Our empirical analysis indicates that when a single hydraulically connected groundwater system is managed under several different sets of regulations, there is statistically significant variation across space and between regulatory zones in terms of the share of spatial externalities that are internalized in the extraction decision-making process; and suggests that the effectiveness of groundwater management depends on the degree to which management is fractured across space. Our econometric analysis of the effects of partial coordination shows that, consistent with the theory, wells that were more interior to their jurisdiction better internalized spatial externalities in their own administrative basins after the regulation. In contrast, wells that were hydrologically connected to other jurisdictions either through rivers or across a purely political boundary faced interjurisdictional spatial externalities that they did not internalize.

Results of our spatial econometric models show that the split groundwater management mandated under the Western Judgment did little to correct the effects of these interjurisdictional spatial externalities on groundwater pumping behavior. While pumping behavior appears to have changed in response to the judgment, these changes support a story in which the judgment caused groundwater users to shift their pumping spatially to avoid violating the terms of the judgment but did not mitigate the spatial effect of groundwater extraction by others.

Our results therefore suggest that fragmented regulation may lead to economically inefficient pumping in the face of uninternalized externalities, and provide empirical evidence for the presence of interjurisdictional spatial externalities that should be accounted for in the optimal design of groundwater management in California. These results have important implications for the efficiency of policies designed to prevent groundwater overdraft in California, Texas (Torres, 2012), and other parts of the Western United States and the world where groundwater is managed at the local level. More generally, our results suggest that policies like those used in the Western Judgment that split regulation of a common pool resource across non-physical boundaries such as political borders may not be effective in mitigating the undesirable effects of interjurisdictional spatial externalities. We contribute to the broader literature surrounding common pool resource management, and analyses like ours can be applied to other resources whose physical systems may not align with political and other jurisdictional boundaries.

The balance of our paper proceeds as follows. We review the relevant literature in Section 2. We provide more details about the 1969 Western Judgment in Section 3. Section 4 presents our model of interjurisdictional spatial externalities in groundwater management. We describe our data and how we take our theory model and the predictions that it yields to data in Section 5. We present our empirical analysis of interjurisdictional spatial externalities in Section 6 and our spatial econometric analysis of spatial effects in Section 7. We provide a discussion and conclusion in Section 8.

2 Literature Review

We build on the previous literature on spatial externalities in groundwater extraction. Theoretically, spatial externalities in groundwater use are potentially important causes of welfare loss (Dasgupta and Heal, 1979; Eswaran and Lewis, 1984; Negri, 1989; Provencher and Burt, 1993; Brozović et al., 2002; Rubio and Casino, 2003; Koundouri, 2004; Msangi, 2004; Saak and Peterson, 2007; Brozović et al., 2010; Lin and Pfeiffer, 2015; Lin Lawell, 2016; Sears et al., 2018; Merrill and Guilfoos, 2018; Sears and Lin Lawell, 2019; Sears et al., 2019). Empirically, Pfeiffer and Lin (2012) find that the spatial externality causes over-extraction that accounts for about 2.5 percent of total pumping in western Kansas. Aquifer heterogeneity can affect the extent of the spatial externality: portions of an aquifer where water moves rapidly, those with high hydraulic conductivity, as well as those that receive less yearly recharge, face a more costly common pool problem and therefore receive higher benefits from coordinated management (Edwards, 2016).

Owing in large part to spatial externalities, the issue of managing water resource use across political boundaries is particularly important (Dinar and Dinar, 2016). Substantial anecdotal evidence suggests that political jurisdictions free ride in the allocation of shared water resources (Gleick, 1993). Olmstead and Sigman (2015) find empirical evidence that countries typically take advantage of opportunities to free ride on other countries in water impoundment and withdrawal decisions. Sears et al. (2023b) find that the institution of quantified property rights and the introduction of artificial recharge of water in the Beaumont Basin of Califonia had a positive spillover effect on the level of groundwater stocks in nearby basins. Adopting spatially differentiated groundwater pumping regulations may yield sizable cost savings if regulators wish to decrease damage to streams (Kuwayama and Brozović, 2013). To make optimal spatial management more politically feasible, Pitafi and Roumasset (2009) devise an intertemporal compensation plan that renders switching from the status quo to optimal spatial management Pareto-improving.

Sears et al. (2019) present a dynamic game framework for analyzing spatial groundwater management. In particular, they characterize the Markov perfect equilibrium resulting from non-cooperative behavior and compare it with the socially optimal coordinated solution. Results show that the benefits from coordinated management in California are particularly high under conditions of extreme drought, and also when the possibility of extreme rainfall situations are high. In addition, these benefits vary with the efficiency of irrigation technology, and whether the crop is an annual crop or perennial (Sears et al., 2019).

Our analysis of partial coordination, wherein a groundwater manager only manages a subset of all the patches that constitute an aquifer, builds on the work of Costello et al. (2015), who examine the efficiency, distributional, and environmental consequences of assigning spatial property rights to part of a spatially-connected natural resource while the remainder is competed for by an open access fringe. Ayres et al. (2021) analyze a market for groundwater rights that does not cover the entire aquifer. Drysdale and Hendricks (2018) analyze the impact of a water restriction imposed through local governance.

Common pool resources that span across jurisdictional boundaries have also been studied extensively in the context of international fisheries. For example, so-called "straddling" fisheries contain stocks of fish that migrate across political boundaries, including the border between two exclusive economic zones (EEZs) of individual countries, where fishing is regulated exclusively by individual coastal countries; and the border between an EEZ and the high seas, where fishing can be done by more remote participants. Much like groundwater, straddling fisheries have important dynamic and spatial dimensions that create tensions between the incentives of individual country regulators and the maximization of social welfare as a whole (Henriksen and Hoel, 2011). Research on straddling fisheries has demonstrated the benefits of cooperative management strategies that internalize spatial externalities (Bjørndal et al., 2004; Le and Flaaten, 2011).

There is also extensive research on spatial externalities that span across jurisdictional boundaries. Transboundary pollution externalities have been studied in the context of international environmental agreements (Aldy and Stavins, 2010; Karp and Zhao, 2010; Stavins, 2015; Barrett, 2016; Chan et al., 2016; Chen and Zeckhauser, 2018; Zakerinia and Lin Lawell, 2023b,a), and include carbon leakage problems that arise when international climate agreements do not cover all countries of the world (van der Ploeg and Withagen, 2017). A related literature studies environmental regulations for transboundary pollutants (List and Mason, 2001; Lin, 2010; Kakeu and Johnson, 2018; Keiser et al., 2021). Coria et al. (2021) study interjurisdictional externalities in the context of air pollution control policies.

3 The 1969 Western Judgment

Regulation of groundwater extraction in California has primarily taken place at the local or regional level through so-called groundwater adjudications. The adjudication process has long been the primary process for defining groundwater rights in California. An adjudication comes about either as a result of disputes over water districts drawing beyond surplus water, or as a mechanism to plan additions to the local water supply, such as imports from outside the adjudicated area (Landridge et al., 2016).[1]

To draw lessons from past experience with split groundwater management, we focus our empirical analysis on three interconnected basins that were adjudicated as part of the 1969 Western Judgment: San Bernardino Basin , Riverside Basin, and Colton Basin. The 1969 Western Judgment was brought on by disputes between groundwater users in these basins due to the physical connections between basins, and the appropriation of water between Riverside and San Bernardino Counties, which share the Riverside Basin (Landridge et al., 2016).

Figure B.1 in Appendix B maps these 3 basins. San Bernardino Basin is upstream, while Riverside Basin and Colton Basin are downstream. Groundwater users in this region represent interests in either

[1] For a more detailed discussion of groundwater adjudications, see Sears et al. (2023a).

San Bernardino County or Riverside County.

San Bernardino Basin, Riverside Basin, and Colton Basin are part of the Coastal Basins aquifers, which occupy a number of basins in coastal areas from northern to southern California. Nearly all the large population centers in California are located in the Coastal Basins aquifers. In most of the basins, however, the population has grown to such an extent that local groundwater supplies are no longer adequate, and surface water must be transported from distant sources to meet demand. In nearly all basins that contain more than one aquifer, the aquifers are hydraulically connected to some degree. Interior northern California is sparsely populated, and most groundwater demand there is for agricultural irrigation (U.S. Geological Survey, 1995; Sears et al., 2018).

Figure B.2 in Appendix B maps the basin boundaries, fault lines, and the Santa Ana River. San Bernardino Basin is bordered on the northwest by the San Gabriel Mountains and Cucamonga fault zone; on the northeast by the San Bernardino Mountains and San Andreas Fault zone; on the east by the Banning fault and Crafton Hills; and on the south by a low, east-facing escarpment of the San Jacinto fault and the San Timoteo Badlands (Landridge et al., 2016).

Colton Basin underlies a portion of the upper Santa Ana Valley in southwestern San Bernardino County and northwestern Riverside County. It is bounded by the San Gabriel Mountains in the northwest, the San Jacinto fault in the northeast, the Badlands in the southeast, and the Rialto-Colton fault in the southwest. The basin generally drains to the southeast toward the Santa Ana River that cuts across the southeastern part of the basin and flows to the Pacific Ocean through Riverside and Orange Counties (Landridge et al., 2016).

Riverside Basin does not have any groundwater obstructions or barriers, but was administratively divided at the county line into Riverside North and Riverside South Sub-basins under the Western Judgment. The Riverside North Sub-basin is the portion in San Bernardino County within the San Bernardino Valley Municipal Water District, and the Riverside South Basin is in Riverside County within the service area of the Western Municipal Water District. The Rialto-Colton Basin is located to the north, the Bunker Hill Basin is located to the east, the Arlington Basin is located to the south, and the Chino Basin is located to the west. The Riverside Basin follows the course of the Santa Ana River (Landridge et al., 2016), which flows from North to South (TreeFlow, 2021).

While the regulations under the 1969 Western Judgment were coordinated as part of a single judgment, they allowed users to operate under different regulations based on the locations of their wells and the service areas. As a consequence, the 1969 Western Judgment split groundwater management across multiple jurisdictional boundaries and regulatory frameworks. In particular, the 1969 Western Judgment set up separate upstream and downstream systems of governance.

Upstream in the San Bernardino Basin, groundwater users are divided into two groups: plaintiffs and non-plaintiffs. Each plaintiff faces an individual limit to their groundwater extraction, while non-plaintiffs as a group face an aggregate limit. In particular, each plaintiff is given an individual annual adjusted right based on extraction levels measured between 1960 and 1963, and its groundwater extraction is limited to a 5-year total extraction of 5 times its adjusted right. Non-plaintiffs as a group are limited to a 5-year total extraction of 5 times the average annual base period extraction of 165,407 acre-feet per year, which is based on group extraction between 1960 and 1963 (Landridge et al., 2016).

Users in the downstream Colton Basin are divided into groundwater users who put the water to use in the San Bernardino Valley, and those who put it to use outside of the San Bernardino Valley. Users inside the San Bernardino Valley do not face any groundwater extraction limits, except in the case that the average groundwater stock measurement at three reference wells falls below 1963 groundwater levels. Then replenishment must be provided. Users outside the San Bernardino Valley as a group are limited to 5-year totals of 5 times average annual totals of 3,349 acre-feet, and to annual limits of 120 percent of this total (Landridge et al., 2016).

Users in the downstream Riverside Basin within San Bernardino County (Riverside North) are also divided into users who use the water in the San Bernardino Valley (San Bernardino interests), and those who use it outside of the San Bernardino Valley (Riverside interests). These two regulatory groups within Riverside North are not separated by any political or geographic boundary, but instead differ in the location of use and interest. Users inside the San Bernardino Valley (San Bernardino interests) do not face any groundwater extraction limits, except in the case that the average groundwater stock measurement at three reference wells falls below 1963 groundwater levels. Then replenishment must be provided. Users outside the San Bernardino Valley (Riverside interests) as a group are limited to 5-year totals of 5 times average annual totals of 20,191 acre-feet, and to annual limits of 120 percent of this total (Landridge et al., 2016).

Users in the Riverside Basin within Riverside County (Riverside South) as a group are limited to 5-year totals of 5 times the average annual totals of 30,044 acre-feet, and to annual limits of 120 percent of this total (Landridge et al., 2016).

We can group the users in the 1969 Western Judgment into the following 7 basin subgroups: San Bernardino Basin plaintiffs, San Bernardino Basin non-plaintiffs, Colton Basin users who use the water inside the San Bernardino Valley, Colton Basin users who use the water outside the San Bernardino Valley, users in the Riverside Basin within San Bernardino County (Riverside North) who use the water inside the San Bernardino Valley (San Bernardino interests), users in the Riverside Basin within San Bernardino County (Riverside North) who use the water outside the San Bernardino Valley (Riverside interests), and users in the Riverside Basin within Riverside County (Riverside South). Owners can have wells in multiple basin subgroups. For example, any users who are non-plaintiffs but operate in multiple basins, including water districts that are not treated as plaintiffs, will span multiple basin subgroups.

We can group the basin subgroups by regulation type as follows. Basin subgroups that face a limit for each user in the basin subgroup include the plaintiffs in the San Bernardino Basin. Basin subgroups that face a limit for the group as a whole include non-plaintiffs in San Bernardino Basin, users in Colton Basin that are users outside the San Bernardino Valley, users in the Riverside Basin within San Bernardino County that are users outside the San Bernardino Valley, and users in the

Riverside Basin within Riverside County. Basin subgroups without quantified groundwater extraction limits include users in Colton Basin that are users inside the San Bernardino Valley, and users in the Riverside Basin within San Bernardino County that are users inside the San Bernardino Valley.

Administrative boundaries and different structures of regulation can in theory induce different levels of partial coordination between groundwater users in the region. Groundwater users representing common interest groups (upstream or downstream) would be expected to have greater levels of coordination even prior to the implementation of the Western Judgment's regulations. Following implementation, policies like group extraction caps and stock monitoring-based regulations could in theory help to internalize spatial externalities and lead to better-coordinated extraction. For example, the fact that groundwater users representing the San Bernardino County interests who extracted from wells in Colton and Riverside North were regulated based on a measure of groundwater stock provides significant variation in the degree to which the regulation affected coordination. In theory, groundwater users in this group with wells near the monitoring sites would need to incorporate their expectations about extraction by all other groundwater users, regardless of interest or regulatory group, since any pumping would increase the probability of triggering the regulation and increasing their costs. On the other hand, wells owned by groundwater users in these basins that were not close to the monitoring sites were effectively left unregulated, with no pumping limits and little connection between their pumping and the stock of water at the monitoring sites.

4 Model

We develop a model of interjurisdictional spatial externalities in groundwater management. After characterizing the hydrological system, we begin with the two extremes of optimal spatial management and non-cooperative behavior, respectively, and then examine interjurisdictional spatial externalities that arise under partial coordination. We derive theoretical predictions of the effects of economic and hydrological factors on interjurisdictional spatial externalities and on groundwater extraction under partial coordination.

4.1 The hydrological system

Our model of the hydrological system follows that of Pfeiffer and Lin (2012) and Bertone Oehninger and Lin Lawell (2021). To capture the important characteristics of groundwater movement, while avoiding the complications of a sophisticated hydrological model, each groundwater user can be thought of as owning a "patch" $i \in \{1, ..., I\}$ of the aquifer that has one point of extraction, or well, on it, and that is connected to neighboring patches via a simplified hydrological model.[2]

[2]Although our model is a simplification of the true physical nature of groundwater flows, it has several advantages over the standard groundwater extraction model that assumes that an aquifer is like a bathtub. In the simple bathtub model, a decrease in the level of the aquifer caused by extraction by any individual is transmitted immediately and completely to all other users of the aquifer, and all users are homogeneous (Burt, 1964; Negri, 1989). In reality, however, aquifer systems do not adjust instantaneously to withdrawals, and the response can be complex and heterogeneous, even

The change in groundwater stock s_i for groundwater user i from one period to the next depends on the total amount of water w_i extracted by groundwater user i, recharge, and net flow. Let $\mathbf{s}_t \equiv (s_{1t}, ..., s_{It})$ denote the vector of the groundwater stocks s_i for each groundwater user i. The equation of motion for groundwater stock s_i, which is derived from simplified hydrological mass-balance equations (Freeze and Cherry, 1979), is given by:

$$s_{i,t+1} = s_{it} - w_{it} + g_{it}(w_{it}) + \sum_{j=1}^{I} \theta_{ji}(\mathbf{s}_t) s_{jt}, \tag{1}$$

where $g_{it}(w_{it})$ is recharge and $\theta_{ji}(\cdot)$ is the net flow rate from patch j to patch i. Recharge $g_{it}(w_{it})$ is a function of return flow (the proportion of the amount pumped that returns to the groundwater table) and precipitation, where $0 \leq \frac{\partial g_{it}}{\partial w_{it}} \leq 1$.[3] The net flow rate $\theta_{ji}(\cdot)$ is defined as the proportion of the water that starts in patch j and disperses to patch i by the next period, so $\sum_{j=1}^{I} \theta_{ji}(\cdot) s_{jt}$ is the net amount of water that flows into patch i from all other patches in the system. Groundwater flow is generally stock dependent: the net flow rate $\theta_{ji}(\cdot)$ from patch j to patch i is a function of the stocks of water in all patches, $\mathbf{s}_t$; and the more stock is in patch i, the less the net flow from other patches j: $\frac{\partial \theta_{ji}}{\partial s_i} \leq 0$. The net flow rate $\theta_{ji}(\cdot)$ from patch j to patch i may also depend on the saturated hydraulic conductivity k_j of the material holding the water in patch j, which measures the ability of the sediments or rocks to transmit water (Fryar and Mukherjee, 2021); the distance x_{ji} between patches i and j; and the physical gradients $\frac{s_j - s_i}{x_{ji}}$ between patches (Brutsaert, 2005; Pfeiffer and Lin, 2012; Bertone Oehninger and Lin Lawell, 2021).

A simple yet hydrologically reasonable functional form assumption for the net flow rate $\theta_{ji}(\cdot)$ can be derived from Darcy's Law for water movement through a porous material and is given by Pfeiffer and Lin (2012):

$$\theta_{ji}(\cdot) = k_j \frac{s_j - s_i}{x_{ji}}. \tag{2}$$

The net flow rate $\theta_{ji}(\cdot)$ could also be more complex and consider the effects of aquifer bed topology, continuous cones of depression from pumping, or saltwater intrusion (Janmaat, 2005).

4.2 Non-cooperative behavior

Non-cooperative behavior arises among individual groundwater users extracting groundwater because groundwater users face a common pool resource problem: because groundwater users are sharing the

within a small geographic area (Heath, 1983; Brozović et al., 2002; Pfeiffer and Lin, 2012; Bertone Oehninger and Lin Lawell, 2021; Blomquist, 2020).

[3]We assume that return flow $\frac{\partial g_{it}}{\partial w_{it}}$ and precipitation have additively separable effects on recharge so that return flow $\frac{\partial g_{it}}{\partial w_{it}}$ is not a function of precipitation. Thus, since our first-order conditions below involve return flow $\frac{\partial g_{it}}{\partial w_{it}}$, which we assume is not a function of precipitation, we suppress the dependence of recharge on precipitation in our notation for our analytic model. In our numerical dynamic game in (Sears et al., 2019), we include both groundwater stock and rainfall as state variables, and incorporate the effect of rainfall on groundwater extraction decisions through its effect on recharge.

aquifer with other groundwater users, groundwater pumping by one user raises the extraction cost and lowers the total amount that is available to other nearby users (Pfeiffer and Lin, 2012; Lin Lawell, 2016; Sears et al., 2019; Sears and Lin Lawell, 2019). As a consequence, an individual dynamically optimizing groundwater user may behave non-cooperatively with respect to other groundwater users.

Let $R_{it}(w_{it})$ denote the per-period revenue that can be generated with extracted water w_{it}. For agricultural groundwater users, for example, $R_{it}(w_{it})$ denotes the per-period revenue that can be generated by producing crops with extracted irrigation water w_{it}, assuming crops are chosen optimally to maximize revenue given extracted irrigation water w_{it}. Let $C_{it}(w_{it}, s_{it})$ denote the cost of extracting water and $\frac{\partial C_{it}(w_{it},s_{it})}{\partial w_{it}} = C^w(s_{it})$ denote the marginal cost of extracting water, both of which depend on the distance that the water must be pumped from the aquifer to the surface of the ground. The distance the water must be pumped depends on the stock of water s_{it}; as the stock decreases, pumping cost increases: $\frac{\partial C^w(s_{it})}{\partial s_{it}} < 0$. Let the discount rate be denoted by r.

An individual dynamically optimizing groundwater user behaving non-cooperatively with respect to other groundwater users will choose groundwater extraction w_{it} each period t in order to maximize the expected present discounted value of his entire stream of per-period profits, conditional on the groundwater stocks s_{jt} and water extraction w_{jt} of all his neighbors j.[4] We denote the vector of stocks s_{jt} of all of i's neighbors j as $s_{-i,t} = (s_{1t}, ..., s_{i-1,t}, s_{i+1,t}, ..., s_{It})$. We similarly denote the vector of groundwater extraction w_{jt} of all i's neighbors j as $w_{-i,t}$. The optimization problem faced by an individual dynamically optimizing groundwater user behaving non-cooperatively with respect to other groundwater users is therefore given by:

$$\max_{\{w_{it}\}_t} \sum_{t=0}^{\infty} \left(\frac{1}{1+r} \right)^t E\left[R_{it}(w_{it}) - C_{it}(w_{it}, s_{it})\right], \tag{3}$$

subject to the equation of motion (1) and conditional on the groundwater stocks s_{jt} and groundwater extraction w_{jt} of all of groundwater user i's neighbors j.

The dynamic optimization problem of an individual dynamically optimizing groundwater user behaving non-cooperatively with respect to other groundwater users can be expressed using the following Bellman equation (Bellman, 1957):

$$V_{it}(s_{it}; s_{-i,t}, w_{-i,t}) = \max_{w_{it}} R_{it}(w_{it}) - C_{it}(w_{it}, s_{it}) + \frac{1}{1+r} EV_{i,t+1}(s_{i,t+1}; s_{-i,t+1}, w_{-i,t+1}), \tag{4}$$

[4]Groundwater management, even at the individual level, is generally modeled as a dynamic optimization problem. This is because marginal pumping costs are a function of the stock of groundwater, and that stock is affected by decisions the manager has made in the past. This would more precisely model a groundwater user's decision if an individual were granted a total amount of water (not an allocation per year) to manage as he sees fit; this would pertain to a more complete property rights system like the one described in Anderson et al. (1983). Bertone Oehninger and Lin Lawell (2021) examine whether agricultural groundwater users faced with prior appropriation property rights to groundwater in western Kansas exhibit dynamic, forward-looking behavior consistent with dynamic management, and find evidence that groundwater users manage their groundwater resource dynamically, even if their property rights do not necessarily encourage or incentivize them to do so. Earnhart and Hendricks (2023) similarly find evidence of dynamically optimal behavior groundwater use behavior by groundwater users.

subject to the equation of motion (1).

The first-order conditions of the Bellman equation can be used to derive the following Euler equation for the non-cooperative solution, which holds at all points in time t:[5]

$$\frac{\partial R_{it}(w_{it})}{\partial w_{it}} - C^w(s_{it}) = \mu_{it}(w_{it}, s_{it}; s_{-it}, w_{-it}), \tag{5}$$

where the marginal user cost $\mu_{it}(\cdot)$ is given by:

$$\begin{aligned} &\mu_{it}(w_{it}, s_{it}; s_{-it}, w_{-it}) = \\ &\quad -\tfrac{1}{1+r}\left(1-g'\left(w_{it}\right)\right) E\left[\tfrac{\partial C^w(s_{i,t+1})}{\partial s_{i,t+1}}\right] w_{i,t+1} \\ &\quad +\tfrac{1}{1+r} E\left[\left(\tfrac{1-g'(w_{it})}{1-g'(w_{i,t+1})}\right)\left(\tfrac{\partial R_{i,t+1}}{\partial w_{i,t+1}} - C^w(s_{i,t+1})\right)\right] \\ &\quad +\tfrac{1}{1+r} E\left[\left(\tfrac{1-g'(w_{it})}{1-g'(w_{i,t+1})}\right)\left(\tfrac{\partial R_{i,t+1}}{\partial w_{i,t+1}} - C^w(s_{i,t+1})\right)\textstyle\sum_{j=1}^{I} \tfrac{\partial \theta_{ji}(\mathbf{s}_{t+1})}{\partial s_{i,t+1}} s_{j,t+1}\right]. \end{aligned} \tag{6}$$

The Euler equation (5) is the standard optimality condition for a resource problem; the decision maker will extract until the marginal revenue from pumping water is equal to the marginal cost plus the marginal user cost of the resource. The marginal user cost $\mu_{it}(\cdot)$ is the value to the user of leaving a marginal unit of the resource in the ground for future extraction, and is also known as the shadow price. A marginal unit of the resource left in the ground as groundwater stock has value because it is then available for future extraction, and because it reduces future pumping costs. Owing to spatial externalities, however, a marginal unit of groundwater left in the aquifer has value only in proportion to the amount that the groundwater user can capture in the future. The left-hand side of the Euler equation (5) can be interpreted as the marginal net benefits from consuming one additional unit of the resource in period t, while the marginal user cost $\mu_{it}(\cdot)$ on the right-hand side is what the user gives up in period $t+1$ by consuming that unit in t (Bertone Oehninger and Lin Lawell, 2021).[6]

4.3 Socially optimal coordinated solution

To determine the socially optimal coordinated solution, consider a single owner or social planner who must make pumping decisions for an entire aquifer basin, consisting of multiple patches $i = 1, ..., I$ with groundwater pumps. Assuming there is no flow in or out of the aquifer, a social planner would choose the set of pumping volumes w_{it} on each patch i in each time period t in order to maximize the expected present discounted value of the entire stream of aggregate profit from the aquifer:

$$\max_{\{\{w_{it}\}_t\}_i} \sum_{i=1}^{I} \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t E\left[R_{it}(w_{it}) - C_{it}(w_{it}, s_{it})\right], \tag{7}$$

[5] The derivation is presented in Appendix A.

[6] For a detailed discussion of the intuition behind each term in the marginal user cost $\mu_{it}(\cdot)$ in Equation (6), see Section 3.3 of Bertone Oehninger and Lin Lawell (2021).

subject to the equations of motion (1) for all patches i. The social planner's dynamic optimization problem can be expressed using the following Bellman equation:

$$V_t(s_{1t}, ..., s_{It}) = \max_{\{w_{it}\}_i} \sum_{i=1}^{I} \left(R^{it}(w_{it}) - C_{it}(w_{it}, s_{it})\right) + \frac{1}{1+r} EV_{t+1}(s_{1,t+1}, ..., s_{I,t+1}), \tag{8}$$

subject to the system of equations of motion (1) for all patches i.[7]

The first-order conditions of the Bellman equation can be used to derive the following Euler equation for each patch i at each point in time t under the socially optimal coordinated solution:[8]

$$\frac{\partial R_{it}(w_{it})}{\partial w_{it}} - C^w(s_{it}) = \mu_{it}(w_{it}, s_{it}; s_{-it}, w_{-it}) + \sigma_{it}(w_{it}, s_{it}; s_{-it}, w_{-it}), \tag{9}$$

where the marginal social cost $\sigma_{it}(\cdot)$ to nearby patches of pumping an additional unit of groundwater from patch i at time period t, which is a measure of the spatial externality, is given by:

$$\begin{aligned} &\sigma_{it}(w_{it}, s_{it}; s_{-it}, w_{-it}) = \\ &\quad \tfrac{1}{1+r} E\left[\sum_{j=1}^{I} \left(\tfrac{1-g'(w_{it})}{1-g'(w_{j,t+1})}\right)\left(\tfrac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^w(s_{j,t+1})\right)\left(\tfrac{\partial \theta_{ij}(\mathbf{s}_{t+1})}{\partial s_{i,t+1}} s_{i,t+1} + \theta_{ij}(\mathbf{s}_{t+1})\right)\right]. \end{aligned} \tag{10}$$

According to the Euler equation for the socially optimal coordinated solution in Equation (9), we find that at the social optimum, marginal revenue is now equal to the sum of marginal cost, marginal user cost $\mu_{it}(\cdot)$, and the marginal social cost $\sigma_{it}(\cdot)$ to nearby patches. Comparing the Euler equation (5) under non-cooperative behavior and the Euler equation (9) for the socially optimal coordinated solution, we see that there is an additional term on the right-hand side of Equation (9) in the socially optimal coordinated solution, $\sigma_{it}(\cdot)$, that reflects the marginal social cost to nearby patches, and therefore measures the spatial externality. Since the marginal social cost $\sigma_{it}(\cdot)$ to nearby patches is an additional cost of extracting water in time t, the groundwater users behaving non-cooperatively will over-extract water relative to the socially optimal coordinated solution if there is spatial movement of water between patches owned by different groundwater users. The magnitude of this spatial externality $\sigma_{it}(\cdot)$ is intuitively greater for patches j that are closer to patch i, since the distance x_{ji} to patct i is relatively smaller. Similarly, more transmissive patches, or patches j in which the saturated hydraulic conductivity k_j is relatively large, are also expected to be susceptible to larger spatial externalities, since water will flow more easily into or out of the patch.

Using Darcy's Law in Equation (2) as the functional form for the net flow rate $\theta_{ji}(\cdot)$ in the social marginal cost, the marginal social cost $\sigma_{it}(\cdot)$ to nearby patches of pumping an additional unit of

[7] This program is identical to the single owner/social planner problem normally analyzed using a bathtub aquifer model if we assume that saturated hydraulic conductivity is infinite, the aquifer is parallel sided and flat bottomed, return flow is zero, and parcels are perfectly homogeneous (Negri, 1989). In this case, it would not matter where the wells are located or how many there are, as long as water can be transported costlessly to the entire surface of the parcel (Pfeiffer and Lin, 2012).

[8] The derivation is presented in Appendix A.

groundwater from patch i at time period t, which is a measure of the spatial externality, simplifies to:

$$\sigma_{it}(w_{it}, s_{it}; s_{-it}, w_{-it}) = \frac{1}{1+r} E\left[\sum_{j=1}^{I} \left(\frac{1-g'(w_{it})}{1-g'(w_{j,t+1})}\right)\left(\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^w(s_{j,t+1})\right)\left(\frac{k_i(2s_{i,t+1}-s_{j,t+1})}{x_{ij}}\right)\right]. \quad (11)$$

4.4 Partial coordination

Partial coordination occurs if the groundwater manager only manages a subset of all the patches that constitute an aquifer. Let's suppose a groundwater manager manages a subset $\{1, ..., I'\}$ of patches, where $I' < I$. Such a groundwater manager's dynamic optimization problem is given by the following Bellman equation:

$$V_t(s_{1t}, ..., s_{I't}; s_{I'+1,t}, ..., s_{It}) = \max_{\{w_{it}\}_{i=1}^{I'}} \sum_{i=1}^{I'} \left(R^{it}(w_{it}) - C^w(s_{it})w_{it}\right) + \frac{1}{1+r} EV_{t+1}(s_{1,t+1}, ..., s_{I',t+1}; s_{I'+1,t+1}, ..., s_{I,t+1}), \quad (12)$$

subject to the system of equations of motion (1) for the patch $i \in \{1, ..., I'\}$ in the groundwater manager's jurisdiction.

The Euler equation for the partially coordinated solution is then given by:

$$\frac{\partial R_{it}(w_{it})}{\partial w_{it}} - C^w(s_{it}) = \mu_{it}(w_{it}, s_{it}; s_{-it}, w_{-it}) + \frac{1}{1+r} E\left[\sum_{j=1}^{I'} \left(\frac{1-g'(w_{it})}{1-g'(w_{j,t+1})}\right)\left(\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^w(s_{j,t+1})\right)\left(\frac{\partial \theta_{ij}(\mathbf{s}_{t+1})}{\partial s_{i,t+1}} s_{i,t+1} + \theta_{ij}(\mathbf{s}_{t+1})\right)\right]. \quad (13)$$

Comparing the Euler equation (13) under partial coordination and the Euler equation (9) for the socially optimal coordinated solution, we see that partial coordination does not account for the full marginal social cost, since the Euler equation (13) under partial coordination can be rewritten as:

$$\frac{\partial R_{it}(w_{it})}{\partial w_{it}} - C^w(s_{it}) = \mu_{it}(w_{it}, s_{it}; s_{-it}, w_{-it}) + \sigma_{it}(w_{it}, s_{it}; s_{-it}, w_{-it}) - \delta_{it}(w_{it}, s_{it}; s_{-it}, w_{-it}), \quad (14)$$

where the **interjurisdictional spatial externality** $\delta_{it}(\cdot)$, which we define as the component of the marginal social cost (or spatial externality) $\sigma_{it}(\cdot)$ of pumping an additional unit of groundwater from patch i that the groundwater manager does not internalize, is equal to:

$$\delta_{it}(w_{it}, s_{it}; s_{-it}, w_{-it}) = \frac{1}{1+r} E\left[\sum_{j=I'+1}^{I} \left(\frac{1-g'(w_{it})}{1-g'(w_{j,t+1})}\right)\left(\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^w(s_{j,t+1})\right)\left(\frac{\partial \theta_{ij}(\mathbf{s}_{t+1})}{\partial s_{i,t+1}} s_{i,t+1} + \theta_{ij}(\mathbf{s}_{t+1})\right)\right]. \quad (15)$$

The interjurisdictional spatial externality $\delta_{it}(\cdot)$ – the component of the marginal social cost $\sigma_{it}(\cdot)$

that the groundwater manager does not internalize – is the marginal social cost of extracting from patch i at time t to those outside the manager's jurisdiction. Thus, groundwater managers who each manage a subset of the patches that constitute an aquifer and who behave non-cooperatively with respect to other groundwater managers will over-extract water relative to the socially optimal coordinated solution if there is spatial movement of water between patches that are managed by different groundwater managers.

Using Darcy's Law in Equation (2) as the functional form of the net flow rate $\theta_{ij}(\cdot)$ the from patch i to patch j, the interjurisdictional spatial externality $\delta_{it}(\cdot)$ simplifies to:

$$\begin{aligned}&\delta_{it}(w_{it}, s_{it}; s_{-it}, w_{-it}) = \\ &\quad \tfrac{1}{1+r} E\left[\sum_{j=I'+1}^{I} \left(\tfrac{1-g'(w_{it})}{1-g'(w_{j,t+1})}\right)\left(\tfrac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^w(s_{j,t+1})\right)\left(\tfrac{k_i(2s_{i,t+1}-s_{j,t+1})}{x_{ij}}\right)\right].\end{aligned} \tag{16}$$

4.5 Determinants of interjurisdictional spatial externalities

We now derive theoretical predictions of the effects of economic and hydrological factors on the interjurisdictional spatial externality $\delta_{it}(\cdot)$ and on groundwater extraction under partial coordination. The extent to which the groundwater manager fails to account for the social cost of extraction depends critically on both the jurisdictional boundaries that govern the manager's authority, and the physical properties of the hydrological system. As in the case of the individual groundwater user, the groundwater manager's uninternalized social cost increases with k_i, the saturated hydraulic conductivity of patch i. So, all else equal, more transmissive aquifer systems are more susceptible to over-extraction when they are shared by multiple groundwater managers. In addition, $\frac{\partial \delta_{it}(\cdot)}{\partial x_{ij}} \leq 0$, meaning that patches nearest to jurisdictional boundaries are more likely to be used inefficiently. The extent of the inefficiency also depends on the share $\frac{I'}{I}$ of the aquifer system that the manager controls.

Let's assume that recharge $g_{it}(w_{it})$ is a linear function of extracted water w_{it}, with a constant slope $g'_{it}(w_{it}) = \gamma_{it}$, where the recharge rate γ_{it} satisfies $0 \leq \gamma_{it} \leq 1$. The recharge rate γ_{it} may be higher in the case of flood irrigation, for example, where water is applied evenly throughout the field, leaving some unused water to recharge the aquifer. In the case of more efficient irrigation techniques, however, there will be little return flow, so the recharge rate γ_{it} may be closer to zero. Under the assumption that recharge $g_{it}(w_{it})$ is linear in extracted water w_{it}, we can simplify the expression for the interjurisdictional spatial externality $\delta_{it}(\cdot)$ to:

$$\delta_{it}(w_{it}, s_{it}; s_{-it}, w_{-it}) = \frac{1-\gamma_{it}}{1+r} E\left[\sum_{j=I'+1}^{I} \left(\frac{\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^w(s_{j,t+1})}{1-\gamma_{j,t+1}}\right)\left(\frac{k_i(2s_{i,t+1}-s_{j,t+1})}{x_{ij}}\right)\right]. \tag{17}$$

Assuming that each groundwater user j does not extract to the point that private marginal cost $C^w(s_{j,t+1})$ exceeds marginal revenue $\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}}$, the sign of the interjurisdictional spatial externality $\delta_{it}(\cdot)$ will depend on the relative expected elevation of groundwater at each of the patches. If net flows between neighboring stocks are assumed to keep the stock values relatively close, then δ_{it} is unambiguously positive, and increasing in the number $I - I'$ of patches in the aquifer outside the groundwater manager's jurisdiction.

Under the same assumptions, we can differentiate the expression with respect to the economic and hydrological variables of interest and find the following comparative statics for the interjurisdictional spatial externality $\delta_{it}(\cdot)$. These predicted effects are summarized in Table 1.

Differentiating the expression with respect to the physical variables of interest – saturated hydraulic conductivity k_j and the distance x_{ji} between patches i and j – we find the following comparative statics for the interjurisdictional spatial externality $\delta_{it}(\cdot)$:

$$\frac{\partial \delta_{it}(\cdot)}{\partial k_i} = \frac{1-\gamma_{it}}{1+r} E\left[\sum_{j=I'+1}^{I} \left(\frac{\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^w(s_{j,t+1})}{1-\gamma_{j,t+1}}\right)\left(\frac{(2s_{i,t+1} - s_{j,t+1})}{x_{ij}}\right)\right] \geq 0 \tag{18}$$

$$\frac{\partial \delta_{it}(\cdot)}{\partial x_{ij}} = -\frac{1-\gamma_{it}}{1+r} E\left[\left(\frac{\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^w(s_{j,t+1})}{1-\gamma_{j,t+1}}\right)\left(\frac{k_i(2s_{i,t+1} - s_{j,t+1})}{{x_{ij}}^2}\right)\right] \leq 0. \tag{19}$$

Thus, the factors that increase flow between the two stocks (greater saturated hydraulic conductivity k_j, shorter distance x_{ji}) will tend to increase the size of the uninternalized social cost for the manager. This captures the idea that pumping from one patch draws water away from neighboring patches that are closer and in more transmissive areas, increasing the marginal cost of pumping for neighboring groundwater users.

Variables related to the expected future marginal cost and marginal revenue of groundwater users on patches in the aquifer outside the groundwater manager's jurisdiction have the following effects on the interjurisdictional spatial externality $\delta_{it}(\cdot)$. The effects of an increase in expected future marginal revenue $\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}}$ on patches in the aquifer outside the groundwater manager's jurisdiction is positive, since the marginal social costs are higher when marginal revenue is higher in other jurisdictions, for example due to higher value crops on patches in other jurisdictions. On the other hand, higher expected future marginal costs $C^w(s_{j,t+1})$ of extraction on patches in the aquifer outside the groundwater manager's jurisdiction have a negative effect on the interjurisdictional spatial externality $\delta_{it}(\cdot)$, since the marginal social costs are lower when the foregone profits on patches in other jurisdictions are lower.

The discount rate r has a negative effect on the interjurisdictional spatial externality $\delta_{it}(\cdot)$:

$$\frac{\partial \delta_{it}(\cdot)}{\partial r} = -\frac{1-\gamma_{it}}{(1+r)^2} E\left[\sum_{j=I'+1}^{I} \left(\frac{\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^w(s_{j,t+1})}{1-\gamma_{j,t+1}}\right)\left(\frac{k_i(2s_{i,t+1} - s_{j,t+1})}{x_{ij}}\right)\right] \leq 0. \tag{20}$$

A higher discount rate means that groundwater users in all jurisdictions care less about the future. As a consequence, the future effects of extraction in one jurisdiction matter less to groundwater users in other jurisdictions.

The recharge rate γ_{it} also has a negative effect on the interjurisdictional spatial externality $\delta_{it}(\cdot)$:

$$\frac{\partial \delta_{it}(\cdot)}{\partial \gamma_{it}} = -\frac{1}{1+r} E\left[\sum_{j=I'+1}^{I}\left(\frac{\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^w(s_{j,t+1})}{1-\gamma_{j,t+1}}\right)\left(\frac{k_i(2s_{i,t+1} - s_{j,t+1})}{x_{ij}}\right)\right] \leq 0. \tag{21}$$

Greater recharge rates on one's patch has the effect of raising the expected stock in the next period, making groundwater in the future less scarce, and lowering its shadow price. Intuitively, if the groundwater user receives full recharge, then his pumping decision has no effect on the patch's state in the next period and so there is no effect on costs for other groundwater users. Thus the spatial externality, along with the portion that is not internalized, disappears. At the other extreme, when there is no recharge on the patch, the effect of his pumping is unmitigated by recharge and is fully passed on as an externality to his neighbors. In this case, the marginal social cost (or spatial externality) increases, and the uninternalized marginal social cost (or interjurisdictional spatial externality) rises.

In contrast, the future recharge rate $\gamma_{j,t+1}$ on patches in the aquifer outside the groundwater manager's jurisdiction has the opposite effect:

$$\frac{\partial \delta_{it}(\cdot)}{\partial \gamma_{j,t+1}} = \frac{1-\gamma_{it}}{1+r} E\left[\left(\frac{\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^w(s_{j,t+1})}{(1-\gamma_{j,t+1})^2}\right)\left(\frac{k_i(2s_{i,t+1} - s_{j,t+1})}{x_{ij}}\right)\right] \geq 0. \tag{22}$$

The intuition for this can be seen through the expected differences in outcomes for neighboring agricultural groundwater users who flood irrigate and neighboring agricultural groundwater users who use drip irrigation. The recharge rate is higher under flood irrigation than under drip irrigation, since in the latter the water is used efficiently to water crops so less is returned to the aquifer. Suppose that a farmer extracts water using drip irrigation from a patch i managed by the groundwater manager, and has a single neighbor who extracts water using flood irrigation from a patch j outside the groundwater manager's jurisdiction. The drip irrigated patch i has a low recharge rate γ_{it}, while the flood irrigated patch j has a high recharge rate γ_{jt}. If patch j does not fall under the groundwater manager's plan, then farmer i will not internalize damage done to the profits of his neighbor j through the use of groundwater from their shared source. If farmer i extracts water from the shared source using drip irrigation, relatively little of it is returned to the ground below his land, since it is used efficiently to irrigate his crops. If his neighbor j uses flood irrigation, then a relatively larger share of the water farmer j pumps each period will be returned to the ground below patch j. This will in turn raise the stock below the patch j relative to patch i and some of this returned water will flow to patch i, raising the neighboring farmer j's cost of extraction in the following period. This raises the uninternalized spatial externality imposed by farmer i.

Finally, examining the effects of groundwater stock levels in patch i inside the manager's jurisdiction and patch j outside the manager's jurisdiction, we find:

$$\frac{\partial \delta_{it}(\cdot)}{\partial s_{i,t+1}} = \frac{1-\gamma_{it}}{1+r} E\left[\sum_{j=I'+1}^{I} \left(\frac{\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^w(s_{j,t+1})}{1-\gamma_{j,t+1}}\right)\left(\frac{2k_i}{x_{ij}}\right)\right] \geq 0 \tag{23}$$

$$\frac{\partial \delta_{it}(\cdot)}{\partial s_{j,t+1}} = -\frac{1-\gamma_{it}}{1+r} E\left[\left(\frac{\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^w(s_{j,t+1})}{(1-\gamma_{j,t+1})}\right)\left(\frac{k_i}{x_{ij}}\right) + \left(\frac{\frac{\partial C^w(s_{j,t+1})}{\partial s_{j,t+1}}}{(1-\gamma_{j,t+1})}\right)\left(\frac{k_i(2s_{i,t+1}-s_{j,t+1})}{x_{ij}}\right)\right]. \tag{24}$$

A high future groundwater stock in a patch i insider the manager's jurisdiction increases the interjurisdictional spatial externality, since the manager expects to lose water that he has access to now if he leaves it available to neighboring users outside his jurisdiction. The effect of the future groundwater stock in a neighboring patch j outside the manager's jurisdiction on the interjurisdictional spatial externality, or the marginal social cost of the manager extracting from patch i to those outside the manager's jurisdiction, is ambiguous. While neighboring patches with higher future groundwater stocks lose more stock to the manager's patch, they also tend to have lower pumping costs. As a result, the change in expected future profits on neighboring patch j outside the manager's jurisdiction as a result of the manager extracting from patch i may be smaller if patch j has a higher stock.

Using Darcy's Law in Equation (2), the share $\frac{\sigma_{it}(\cdot)-\delta_{it}(\cdot)}{\sigma_{it}(\cdot)}$ of the marginal social cost (or spatial externality) $\sigma_{it}(\cdot)$ that is internalized under partial coordination is given by:

$$\frac{\sigma_{it}(\cdot)-\delta_{it}(\cdot)}{\sigma_{it}(\cdot)} = \frac{E\left[\sum_{j=1}^{I'}\left(\frac{\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^w(s_{j,t+1})}{1-\gamma_{j,t+1}}\right)\left(\frac{k_i(2s_{i,t+1}-s_{j,t+1})}{x_{ij}}\right)\right]}{E\left[\sum_{k=1}^{I}\left(\frac{\frac{\partial R_{k,t+1}}{\partial w_{k,t+1}} - C^w(s_{k,t+1})}{1-\gamma_{k,t+1}}\right)\left(\frac{k_i(2s_{i,t+1}-s_{k,t+1})}{x_{ik}}\right)\right]}, \tag{25}$$

which can be expressed using conditional expectations as follows:

$$\frac{\sigma_{it}(\cdot)-\delta_{it}(\cdot)}{\sigma_{it}(\cdot)} = \frac{I'}{I}\frac{E\left[\left(\frac{\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^w(s_{j,t+1})}{1-\gamma_{j,t+1}}\right)\left(\frac{k_i(2s_{i,t+1}-s_{j,t+1})}{x_{ij}}\right)\middle| j \in I'\right]}{E\left[\left(\frac{\frac{\partial R_{k,t+1}}{\partial w_{k,t+1}} - C^w(s_{k,t+1})}{1-\gamma_{k,t+1}}\right)\left(\frac{k_i(2s_{i,t+1}-s_{k,t+1})}{x_{ik}}\right)\middle| k \in I\right]}. \tag{26}$$

Thus, the degree to which partial coordination ameliorates spatial externalities depends both on the share of the basin that is coordinated $\frac{I'}{I}$ and the relative values of the conditional expectations. Clearly if coordinated fields are more profitable at the margin, then partial coordination internalizes more of the marginal social cost. Additionally, if recharge is relatively lower in coordinated fields, and water table levels are higher, then partial coordination also does a better job of approximating a socially efficient outcome.

If we make the assumption that the profit function for each groundwater user is strictly concave in groundwater extracted w_{it} (or in turn that marginal net revenue $\frac{\partial R_{it}(w_{it})}{\partial w_{it}} - C^w(s_{it})$ is strictly decreasing in groundwater extracted w_{it}) then Equation (14) implies that for a given marginal social cost (or spatial externality) $\sigma_{it}(\cdot)$, any factor that increases the component $\delta_{it}(\cdot)$ of the marginal social cost $\sigma_{it}(\cdot)$ that the groundwater manager does not internalize will in turn lead to higher extraction w_{it} under partial coordination. This thus creates a channel through which the effects identified in equations (18)-(24) may be expected to influence pumping in a partial coordination environment. These predicted effects are summarized in Table 1. We explore these channels empirically in Section 6.

4.6 Spatial effects of groundwater extraction

Our theory model also yields several predictions for the spatial effects of groundwater extraction, which we define as the effects of groundwater extraction at nearby wells on groundwater extraction at a particular well.

First, our theory shows that extraction at one well will increase if extraction at nearby hydrologically connected wells increases. The intuition is as follows. Nearby extraction at hydrologically connected wells lowers the expected future stock at the well, thereby increasing expected future costs and decreasing the shadow price (or marginal user cost) $\mu_{it}(\cdot)$. All else equal, this should raise current period extraction at the well.

Second, our theory shows that if nearby wells are managed by the same owner, then the effects on groundwater extraction at one well of groundwater extraction at other nearby wells owned by the same owner would likely differ from the effects if there were no coordination, and may possibly be less positive or even negative. If an owner's wells are clustered in areas where water is cheaper to extract, then the own-pumping effect may be positive. On the other hand, if there are relative cost differences between wells, an owner may find it advantageous to substitute between wells when one is cheaper to extract from than another, leading to a negative own-pumping effect. If an owner's revenue is concave in total extraction across all the owner's wells, then extraction at one well would lower the marginal revenue at all the owners' wells, which all else equal would decrease current period extraction at other wells owned by the same owner.

Third, our theory shows that under partial coordination, the effects on groundwater extraction at one well of groundwater extraction at other nearby coordinated wells would likely differ from the effects if there were no coordination, and may possibly be less positive or even negative. For example, if an owner's revenue is concave in total extraction across all the wells in the owner's regulatory group, then extraction at one well in the regulatory group would lower the marginal revenue at all the wells in the regulatory group, which all else equal would decrease current period extraction at all other wells in the regulatory group.

The spatial effects under partial coordination may differ by the type of regulation. Nevertheless, regardless of regulation type, the effects on groundwater extraction at one well of groundwater extraction at other nearby coordinated wells within one's regulatory group would likely differ from the effects of extraction at other nearby uncoordinated wells outside of one's regulatory group, and may possibly be less positive or even negative. One type of regulation under partial coordination is individual quantity regulation, wherein individual users are each faced with individual limits to their groundwater extraction. Under individual quantity regulation, extraction by other users would not affect the regulation faced by an individual user.

A second type of regulation under partial coordination is group quantity regulation, wherein users in a regulatory group are faced with a group limit to their aggregate groundwater extraction. Under group quantity regulation, extraction at wells outside of one's regulatory group would not affect the regulation faced by the regulatory group. On the other hand, since extraction at another well inside of one's regulatory group would affect the aggregate groundwater extraction for the entire group, extraction at one well in the regulatory group would lower the marginal revenue at all the wells in the regulatory group, which all else equal would decrease current period extraction at all other wells in the regulatory group.

A third type of regulation under partial coordination is stock monitoring-based regulation, wherein users in a regulatory group do not face any groundwater extraction limits unless the average groundwater stock measurement at certain designated monitoring site reference wells falls below a certain level. Under stock monitoring-based regulation, extraction at other wells that are not near any monitoring site reference well has no impact on the regulation faced by the regulatory group. On the other hand, since extraction at other wells that are near a monitoring site reference well may potentially impact the regulation faced by the regulatory group, pumping at coordinated wells near a monitoring site reference well would increase the expected regulatory cost and therefore decrease current period extraction at all other wells in the regulatory group. Pumping at uncoordinated wells outside the regulatory group but near a monitoring site reference well would similarly increase the expected regulatory cost and therefore decrease current period extraction at all wells in the regulatory group, but the effect would likely be less negative since these wells are outside the regulatory group and are therefore uncoordinated.

We empirically examine these spatial effects of groundwater extraction in Section 7.

5 Data and Empirical Application

5.1 Data

To draw lessons from past experience with split groundwater management, we focus our empirical analysis on three interconnected basins that were adjudicated as part of the 1969 Western Judgment. In addition to providing an example of split groundwater management, the Western Judgment also mandated meticulous record keeping of extraction at each well in the judgment area on an annual basis. We collect detailed historical records on extraction at each well in the judgment area from the adjudication's annual reports, including the owner, regulatory grouping, and annual extraction at each well for the years 1960 to 2016, covering the periods before and after implementation of the regulations.

We merge location data from a well completion report dataset from the California Department of Water Resources with the well's state well identification number to determine the location of each the wells, as shown in Figure B.3 in Appendix B.

There are three monitoring sites used to determine if extraction in Colton Basin and North Riverside Basin by non-plaintiff users is in compliance. Basically, if the groundwater level measured at the three sites falls below 1963 levels, then the non-plaintiffs are responsible for importing water.

We include data on State Water Project (SWP) deliveries, which are imports of surface water from outside the counties used either to deliver directly to customers or to recharge the basins. The availability of State Water Project water is determined by snowpack levels at the start of the year, and by each water district's allocation, called the "Table A" allocation (California Department of Water Resources, 2015a). The quantities vary year to year and are determined by weather conditions outside of Southern California (California Department of Water Resources, 2015a). San Bernardino Valley Water District (SBVWD) signed a contract in 1960 to receive imported water from the northern part of the state starting in 1972 (San Bernardino Valley Municipal Water District, 2018). Between the start of the program and the present, SBVWD has increased its "Table A" allocation in the SWP from 46,000 acre-feet per year to 102,600 acre-feet (San Bernardino Valley Municipal Water District, 2018). SWP deliveries vary from year to year due to both the purchasing decision of the contractor, and the availability of water supplies. For example, at the height of the recent drought, the SWP announced an initial availability of 0% of Table A allocations at the start of 2014 (California Department of Water Resources, 2015a). SWP water is purchased from the contractor, SBVWD, and then sold to customers, or spread for recharge in the basin by water retailers in each of the basins under adjudication. We make use of the recorded amount of SWP water delivered to the basins, and the total amount SWP water used for recharge in the basins, which is recorded in the Western Watermaster's Annual Report (Western-San Bernardino Watermaster, 2018).

We use historical precipitation data, at a 4 km resolution, from the PRISM Climate Group (PRISM Climate Group and Oregon State University, 2018). Since many groundwater users included in the adjudication use water either for agricultural or landscaping irrigation, precipitation variability has an impact on the amount of groundwater that is required in a given year. In addition, precipitation is correlated with the availability of surface water supplies, which act as a substitute for groundwater, and help to replenish groundwater supplies. Finally, variability in precipitation also determines the expected amount of recharge to the groundwater stock, through sub-surface infiltration.

To capture variation in the cost of groundwater extraction and the level of groundwater stock across time and space, we make use of groundwater depth data from the U.S. Geological Survey (USGS) during the period of our sample. Since monitoring sites are often only available for part of the sample period, we use inverse-distance weighted changes in depth to groundwater at all available sites to interpolate the depth to groundwater for a given site in years in which data are unavailable.

Finally, we capture spatial and temporal variation in the marginal profitability of water using a combination of data on historical land use and farmland value. Agricultural farmland has been mapped by the California Department of Conservation Farmland Mapping and Monitoring Program (FMMP) since 1984 (California Department of Conservation, 2018). This allows us to have a measure of how much of the land surrounding a well was used for cropland, grazing land, or urban development over time, and since the FMMP divides farmland into several classifications based on the relative soil quality, we can differentiate between areas with higher value agriculture, and areas with lower value agriculture (California Department of Conservation, 2018). We capture common changes in the profitability of agriculture through changes in the real value of cropland, which is tracked by the U.S. Department of Agriculture at a state-wide level on an annual basis (U.S. Department of Agriculture, 2018).

5.2 Taking theory to data

We take our theory model and the predictions that it yields to data gathered as part of the 1969 Western Judgment in San Bernardino and Riverside Counties. For our empirical analysis, we conduct three separate exercises.

First, in Section 6.1 we measure the share $\frac{\sigma_{it}(\cdot)-\delta_{it}(\cdot)}{\sigma_{it}(\cdot)}$ of the spatial externality $\sigma_{it}(\cdot)$ that is internalized under partial coordination at each well in our sample for the three years (2007-2009) for which we have sufficient data by applying our data to Equation (26) from Section 4.5. This allows us to measure the variation in the severity of interjurisdictional spatial externalities arising from the jurisdictional boundaries and design of regulations imposed under the Western Judgment. We justify our use of the Western Judgment for our empirical setting by demonstrating that interjurisdictional spatial externalities were prevalent in the region, and varied among wells in our dataset.

Second, in Section 6.2 we use fixed effects regressions applied to a spatial panel dataset covering the 57 years from 1960 to 2016 that we have collected and constructed from historical records to test some of the predictions from our theory model from Section 4.5 about the effects of interjurisdictional spatial externalities on extraction behavior. Here we leverage variation in location of wells in relation to the jurisdictional boundaries imposed under the Western Judgment, as well variation in the hydrological interconnections at these boundaries. This approach allows us to demonstrate that interjurisdictional spatial externalities had significant impacts on extraction behavior which, according to our theory model, would translate to social welfare losses relative to coordinated behavior.

Third, in Section 7 we use a panel instrumental variables (IV) spatial econometric model to estimate the impact of the Western Judgment on the spatial effects of groundwater extraction. Here we are primarily concerned with changes in how extraction was influenced by other nearby extraction and empirically examining the predictions for the spatial effects of groundwater extraction from Section 4.6. Spatial effects are one particular channel through which we expect to see the impact of spatial externalities on extraction. Our approach allows us to analyze the effect of the policies imposed under the Western Judgment on coordination and on patterns of extraction across space. We examine if the regulations helped to ameliorate the impact of uninternalized interjurisdictional spatial externalities. We also compare spatial effects across different types of regulations.

6 Empirical Analysis of Interjurisdictional Spatial Externalities

6.1 Share of spatial externality that is internalized under partial coordination

The first way in which we take our theory model and the predictions that it yields to data is to use data gathered as part of the 1969 Western Judgment in San Bernardino and Riverside Counties to estimate the share of externalities internalized when a common pool of groundwater is managed under multiple regulatory frameworks.

In particular, to analyze the extent of interjurisdictional spatial externalities in the Western Judgment, we apply our data to Equation (26) to calculate the share $\frac{\sigma_{it}(\cdot)-\delta_{it}(\cdot)}{\sigma_{it}(\cdot)}$ of the spatial externality that is internalized under partial coordination in the Western Judgment over the years 2007 to 2009.[9] This enables us to measure the variation in the severity of interjurisdictional spatial externalities arising from the jurisdictional boundaries and design of regulations imposed under the Western Judgment.

6.1.1 Empirical calibration

Since regulation in the Western Judgment was not done using spatial boundaries within a basin, but instead by grouping different types of groundwater users, we use the share of wells operating in the basin in each regulatory grouping as a proxy for the number of patches in the manager's jurisdiction I'; and we use the total number of wells operating in the year as the total number of patches in the entire aquifer basin I. We use the share of wells for each regulatory group to calculate the share of the basin internalized since the groups are not spatially defined.

For marginal revenue $\frac{\partial R_{i,t+1}}{\partial w_{i,t+1}}$, we differentiate based on the type of user: municipal water districts and agricultural producers. For water districts and municipal water companies, the marginal revenue from water extraction is the price of water for either municipal or irrigation use in that year. For the price of water, we use 2010 water prices from either the company itself, or from the Western Municipal Water District, which was given watermaster duties for overseeing the regulation.

For agricultural producers, the marginal revenue $\frac{\partial R_{i,t+1}}{\partial w_{i,t+1}}$ from water extraction is the per-period marginal revenue that can be generated by producing crops with extracted irrigation water, assuming crops are chosen optimally to maximize revenue given extracted irrigation water. Thus: $\frac{\partial R_{i,t+1}}{\partial w_{i,t+1}} = P_{i,t+1}\frac{\partial Q_{i,t+1}}{\partial w_{i,t+1}}$, where $P_{i,t+1}$ are crop prices and $\frac{\partial Q_{i,t+1}}{\partial w_{i,t+1}}$ is the marginal effect of applied water on crop yield.

To estimate marginal revenue $\frac{\partial R_{i,t+1}}{\partial w_{i,t+1}}$ for the agricultural producers, we use satellite data to determine if crops were grown in the Public Land Survey System section in which the well was found. For

[9] Unfortunately, since our crop, groundwater elevation, and groundwater depth data does not cover the entire 1960-2016 time range of our panel data set, we cannot estimate interjurisdictional spatial externalities in each year over the entire the entire 1960-2016 time period.

crop prices P_{it}, we use historical values of production per unit price for California at planting time in the period for that crop from the state department of food and agriculture, for each year t. We use the contemporaneous price (i.e., we use the price at year t for P_{it}; and the price in year $t+1$ for $P_{i,t+1}$), which assumes rational expectations. For each year t, we use the crop price for the crop that used in the parcel in which the well is located, or the majority crop in the township/range/section/subsection in which the well is located.

To estimate $\frac{\partial Q_{i,t+1}}{\partial w_{i,t+1}}$, the marginal effect of applied water on crop yield, we apply an evapotranspiration-based equation from Doorenbos and Kassam (1979):

$$\left(1 - \frac{Y_a}{Y_x}\right) = K_y \left(1 - \frac{ET_a}{ET_x}\right), \tag{27}$$

where Y represents yield, ET represents evapotranspiration, K_y represents a yield response factor that is crop specific, and x and a denote the maximum and actual values of the variables. Equation (27) can be re-written as: $Y_a = \left(1 - K_y \left(1 - \frac{ET_a}{ET_x}\right)\right) Y_x$. Differentiating with respect to the actual evapotranspiration ET_a should give the marginal effect of applied water on crop yield:

$$\frac{\partial Q}{\partial w} = \frac{\partial Y_a}{\partial ET_a} = \frac{K_y Y_x}{ET_x}. \tag{28}$$

We use data on evapotranspiration ET from CIMIS weather stations and yield response factor K_y values from Steduto et al. (2012), and use seasonal conversion factors from Allen et al. (1998).

For marginal cost, following Rogers and Alam (2006), Hendricks and Peterson (2012), and Sears et al. (2019), we model the marginal cost $C^w(d_{i,t+1})$ of extraction as the cost of pumping an acre-inch of water to the surface as the following function of the price P_E of energy used for pumping, depth to groundwater $d_{i,t+1}$ (in feet), and the amount of energy E_L required to lift 1 acre inch of water by 1 foot:

$$C^w(d_{i,t+1}) = P_{E_{i,t+1}} E_L d_{i,t+1}. \tag{29}$$

For the relevant energy price $P_{E_{i,t+1}}$, we use electricity prices from Southern California Edison, the local electricity utility, since groundwater pumping in California is primarily powered with electricity (Sears and Lin Lawell, 2019).

Our depth to groundwater values are spatially interpolated using inverse-distance weighting of a sample of values from April of each year taken at monitoring site wells in the basins. Our groundwater stock s_{it} value is based on the elevation of groundwater which is again spatially interpolated using inverse-distance weighting. We take recharge rate γ_{it} values from estimates submitted by groundwater agencies as part of alternative groundwater sustainability plan submissions, and saturated hydraulic conductivity k_i values from the USGS Soil Survey.

6.1.2 Calibration results

Table 2 presents our results for the share $\frac{\sigma_{it}(\cdot)-\delta_{it}(\cdot)}{\sigma_{it}(\cdot)}$ of the spatial externality that is internalized under partial coordination in the Western Judgment data using the entire Western Judgment data set, as well as for municipal water districts versus agricultural producers, for each basin, for each basin subgroup, and for each regulation type. We find that there is wide variation between the types of groundwater users, between the basins, within each basin, between regulation subgroups, and between each type of regulation in the share of externalities that is internalized under partial coordination.

Under partial coordination, agricultural producers on average internalize a slightly larger share of the marginal social cost of their groundwater use than do water districts. The marginal revenue for agricultural producers from groundwater extraction is the per-period marginal revenue that can be generated by producing crops with extracted irrigation water, assuming crops are chosen optimally to maximize revenue given extracted irrigation water. In contrast, the marginal revenue for water districts and municipal water companies from water extraction is the price of water for either municipal or irrigation use in that year. Some reasons why agricultural producers might internalize more of the marginal social cost of their groundwater use than water districts do may include the benefits of doing so on the current and future marginal revenue; and perhaps also social norms amongst farmers (Smith, 2018) that may not exist amongst water districts.

Users in the San Bernardino and Colton Basins each internalize a larger share of the externality under partial coordination than do users in the Riverside Basin, who only internalize around half the share of their counterparts in the other two basins. This is driven by the fractured regulation of the Riverside Basin, where regulations differ on either side of the county border, and within the northern part of the basin between interest groups representing San Bernardino County and Riverside County.

In both Colton and San Bernardino Basins, there is a wide discrepancy in the share $\frac{\sigma_{it}(\cdot)-\delta_{it}(\cdot)}{\sigma_{it}(\cdot)}$ of the spatial externality that is internalized under partial coordination between users who were regulated as plaintiffs or non-plaintiffs. Plaintiffs, who in each case were regulated more strictly, internalize relatively less of their extraction, probably due to their smaller share in the number of wells used in the area. In Riverside Basin, there is relatively little difference in magnitude between the shares for plaintiffs and non-plaintiffs in Riverside North, but a large difference between Riverside North and Riverside South, with users in Riverside South internalizing a much larger share of their externalities. Finally, unsurprisingly, given the number of users in each group, those who were regulated by group limits on extraction internalized the largest share of externalites, while those who were given individual limits internalized the least. It is worth noting here that we assume that the users who were left unregulated as long as groundwater elevation levels remained above 1963 static levels are treated as a group with a common regulation. In practice, however, if the regulation is unlikely to bind, as was the case, these users would internalize only their own individual share of the externalities. This makes our estimate likely an optimistic upper bound for the share of externality internalized for these users.

We next evaluate whether the differences between these groups are statistically significant by conducting two-sample t-tests that compare pairwise the share of the spatial externality that is internalized under partial coordination for different groups in each category. In Table B.1 in Appendix B, we present the differences in the share of the spatial externality that is internalized between different groups in each category, and indicate their statistical significance based on the two-sample t-test.

We find that while the difference in the share of the spatial externality that is internalized under partial coordination between agricultural producers and water districts is statistically significant, it is small in magnitude. As mentioned above, this may in fact be an underestimate of this difference, since agricultural producers are more likely to be included in the unregulated group, making their share of internalized externality likely much lower.

In other cases, we generally find highly significant differences in the share of the spatial externality that is internalized under partial coordination. We see large magnitudes in the differences between Riverside Basin and the other two basins, as mentioned above. We also find the differences are large between plaintiff and non-plaintiff groups in each of the three basins, but not large in magnitude between plaintiffs in neighboring basins. Finally, we find that those in group quantity regulations internalized a much larger share of the externality than those in other forms of regulation.

Our findings suggest the importance of choosing regulatory divisions that are economically meaningful and of encouraging coordination among agents. For example, our finding that a relatively small share of externalities were internalized in Riverside Basin is a direct result of the fact that this basin's management structure was split by the political boundary between Riverside and San Bernardino Counties. Thus, groundwater users faced separate management structures for wells on either side of the boundary, despite the fact that water was used for similar purposes on either side, and even though there was no discontinuity in the flow of groundwater between plots of land on either side of the boundary.

We also find that we find that the type of regulation may also affect the degree of coordination. According to our results, those in group quantity regulations internalized a much larger share of the externality than those in other forms of regulation. Group limits that encompassed groundwater users with wells clustered closely together helped bring these users under a common management structure and helped to limit the theoretical efficiency losses in extraction. In contrast, while indirect regulations like monitoring well measurements may be cheaper to administer, they may lead to more fractured management if they do not encompass all groundwater users in the area. Similarly, individual limits that do not encompass all groundwater users in the area may lead to more fractured management when these users are not naturally isolated. Here it is important to note that coordination between wells in the same interest group may have existed prior to the regulation. For example, growth in towns on either side of the county border may have had spillover benefits for other nearby towns represented by different water districts. In order to measure the impact of the regulation itself on coordination, and to evaluate our theoretical predictions, we examine differences between extraction behavior before and after the regulation was imposed in our empirical analyses in Section 6.2 and Section 7.

6.2 Panel regression analysis of interjurisdictional spatial externalities

The second way in which we take our theory model and the predictions that it yields to data from the 1969 Western Judgment is to use fixed effects regressions to test some of the predictions from our theory model from Section 4.5 about the effects of interjurisdictional spatial externalities on extraction behavior. Here we leverage variation in location of wells in relation to the jurisdictional boundaries imposed under the Western Judgment, as well variation in the hydrological interconnections at these boundaries. This approach allows us to demonstrate that interjurisdictional spatial externalities had significant impacts on extraction behavior which, according to our theory model, would translate to social welfare losses relative to coordinated behavior.

6.2.1 Fixed effects regression model

Unfortunately, since our crop, groundwater elevation, and groundwater depth data does not cover the entire 1960-2016 time range of our panel, we cannot estimate interjurisdictional spatial externalities in each year. Instead, we estimate an econometric model to examine how partial coordination induced by the 1969 Western Judgment affected determinants of the spatial externality. We apply our econometric model to our panel dataset covering the years 1960-2016 that we collected and constructed from historical records.

Our regression equation is given by:

$$w_{ibt} = \beta_0 + (1 - I\{post_t\}) (\beta_1 x_{it} + \beta_2 L_{ib} x_{it}) + I\{post_t\} (\beta_3 x_{it} + \beta_4 L_{ib} x_{it}) + \mu_{bt} + \alpha_i + \varepsilon_{it}, \quad (30)$$

where w_{ibt} is groundwater extraction at well i in basin b at time t; $I\{post_t\}$ is a post-regulation dummy for being after the 1969 Western Judgment; x_{it} is depth to groundwater at well i at time t; L_{ib} is the share of the 1-mile radius surrounding circle area around well i that lies inside the same administrative basin b as well i; μ_{bt} is an administrative basin-year effect; α_i is a well fixed effect; and ε_{it} is the error term.

We control for time-invariant variation between wells using well fixed effects. We account for time-varying factors within the basin by including basin-year effects in our models. Therefore our identifying assumption is that any remaining variation in the conditional expectation of extraction left outside our model, ε_{it}, is uncorrelated with our regressors of interest related to depth to groundwater and the share of hydrologically connected nearby land outside of one's administrative region.

Since the regulation in theory should have aligned the users under one management structure, the number of wells $I - I'$ that are not internalized by the groundwater users in their decision making should shrink after the regulation; according to our theory model as summarized in Table 1, this would reduce the interjurisdictional spatial externality $\delta_{it}(\cdot)$. Under complete coordination, the number of patches in the manager's jurisdiction I' would equal the total number of patches in the aquifer basin I, and the interjurisdictional spatial externality $\delta_{it}(\cdot)$ would go to 0.

As seen in Equation (23) and summarized in Table 1, our theory model predicts that having a greater depth to groundwater (lower stock) should decrease the interjurisdictional spatial externality $\delta_{it}(\cdot)$ and therefore decrease extraction. The reasoning for this is that when there is less groundwater stock, the expected additional future net benefits gained from coordinated or partially coordinated behavior are expected to be smaller. Therefore, uncoordinated behavior creates smaller social damages that are not internalized. Thus, if the regulation were effective in increasing coordination and reducing spatial externalities among wells within a jurisdiction, then the marginal effect of depth to groundwater on pumping would be less negative (or more positive) after the regulation for wells within that jurisdiction that are not near hydrologically connected wells from any other jurisdiction.

We take advantage of variation in the share of hydrologically connected land within one's regulatory boundary created by the structure of the regulation, and in the hydrology of the region. In particular, we focus on hydrologically connected wells near the administrative border between the two Riverside basins: Riverside North and Riverside South. The boundary between Riverside North and Riverside South is just a county line, and should not impact hydrology at all. Thus, Riverside Basin is a single groundwater basin with an administrative split between Riverside North and Riverside South. In contrast, the administrative borders between other basins coincide with fault lines in the region that create discontinuities in the flow of groundwater. The exception to this are wells that are on land that lie near the Santa Ana River. This river spans across boundaries and we should expect subsurface connections between the river and wells nearby it (Landridge et al., 2016). Figure B.2 in Appendix B maps the basin boundaries, fault lines, and the Santa Ana River.

Our hypotheses are that, if the regulation were effective in increasing coordination and reducing spatial externalities among wells within a jurisdiction, we would expect to see the following. First, the marginal effect of depth to groundwater on pumping would be more positive after the regulation for wells located in the interior of the jurisdiction that are not near hydrologically connected wells from any other jurisdiction. Second, for wells near the administrative border of the two Riverside basins, since only a fraction of the nearby land is under the same jurisdiction, after the regulation their response to depth to groundwater would be more negative than the response for wells that are located in the interior of the jurisdiction. Third, since wells that are near administrative boundaries that are fault lines but are not near rivers have limited spatial flows to land outside the jurisdiction's boundaries, the spatial externalities are attenuated for these wells so they should also have a less negative response to depth to groundwater than wells at administrative borders that are hydrologically connected. Fourth, since wells that are near administrative boundaries that are fault lines and that are also near the river have spatial flows of water to basins outside the jurisdiction, these wells should also have a less negative response to depth to groundwater than wells at administrative borders that are not fault line boundaries, but may have somewhat more of a negative response to depth to groundwater than wells at administrative borders that are hydrologically connected.

6.2.2 Panel regression results

To examine our hypotheses, we estimate several variants of the regression in Equation (30), each of which estimates the pumping response to variation in depth to groundwater at the individual well level. Specifications (1)-(3) in Table 3 use only observations from wells in Riverside Basin (either Riverside North or Riverside South) for years after the 1969 Western Judgment. This allows us to compare the pumping response between interior wells (i.e., wells for which a larger share of neighboring land is in the same jurisdiction) and wells near the jurisdictional boundary, during the years after the regulation (when coordination within a jurisdiction would have increased if the regulation were effective). Specifications (4)-(5) in Table 4 use only observations from wells in Riverside Basin (either Riverside North or Riverside South) for all years over the entire 1960-2016 time period of our data set, and therefore includes observations both before and after the 1969 Western Judgment. This allows us to compare the pumping response before the regulation (when all users behaved non-cooperatively) with that after the regulation (when coordination within a jurisdiction would have increased if the regulation were effective). Specifications (6)-(8) in Table B.2 in Appendix B use all observations from all wells in our data for all years over the entire 1960-2016 time period of our data set, and therefore includes observations both before and after the 1969 Western Judgment. This allows us to assess the effect of interjurisdictional hydrological linkages on pumping response.

Our empirical results are consistent with our hypotheses. As seen in Specification (1), the marginal effect of depth to groundwater on pumping is more positive after the regulation for interior wells. Specifications (2), (4), and (6) show that the marginal effect of depth to groundwater on pumping is more positive (or less negative) after the regulation for interior wells, negative for wells near the administrative border of the two Riverside basins, and statistically insignificant for wells near administrative borders that are fault lines and therefore are not hydrologically connected with wells from other jurisdictions. Specifications (3), (5), and (7), which interact the terms with a dummy for being within 1 mile of the Santa Ana River, show that the marginal effect of depth to groundwater on pumping is less negative after the regulation for interior wells; negative for wells near the administrative border of the two Riverside basins; statistically insignificant for wells that are near administrative borders that are fault lines and are not near the river, and therefore are not hydrologically connected with wells from any other jurisdiction; and, a somewhat negative response to depth to groundwater after the regulation for wells that are near administrative borders that are fault lines but are also near the river, and therefore have spatial flows of water to basins outside the jurisdiction. In Specification (8), we treat area in other basins that is not hydrologically connected as area outside the model, and therefore exclude it from the 1 mile radius circle's area in both the numerator and denominator of our area share variables. Specification (8) similarly shows that the marginal effect of depth to groundwater on pumping is less negative after the regulation for interior wells; negative for wells near the administrative border of the two Riverside basins; and a somewhat negative response to depth to groundwater after the regulation for wells that are near administrative borders that are fault lines but are also near the river, and therefore have spatial flows of water to basins outside the jurisdiction.

Our findings therefore support our hypothesis that wells that were more interior to their jurisdiction better internalized spatial externalities in their own administrative basins after the regulation. In contrast, wells that were hydrologically connected to other jurisdictions either through rivers or across the political boundary in Riverside faced interjurisdictional spatial externalities that they did not internalize.

Our panel regression results indicate that the regulation did indeed have an impact on pumping response to changes in the stock of groundwater, but that this impact was weaker for wells near hydrologically connected jurisdictional borders. When there is little coordination between jurisdictions, and hydrological connections that enable the flow of water across boundaries, the owners of wells that are closest to the jurisdictional boundary internalize less of the effect of their pumping on the stock of groundwater for their neighbors. This is consistent with our finding in Section 6.1 that there is a great deal of heterogeneity in the share of externalities that the users in each of the regulatory groups internalize. Our panel regression results suggest that a mechanism through which interjurisdictional externalities may have weakened the effect of the regulation is through groundwater stock levels. Our theory model predicts that higher groundwater stocks would increase the interjurisdictional spatial externality $\delta_{it}(\cdot)$ and therefore increase extraction. Our panel regression results show that pumping responses to higher levels of stock were much stronger for wells near the hydrologically connected boundary than for interior wells, even after the regulation was imposed, suggesting these well owners did not expect to be able to take advantage of this higher stock in future periods. This is consistent with a story of limited coordination between owners on either side of these boundaries, where pumping effects on neighboring stocks are not internalized.

7 Spatial Econometric Analysis of Spatial Effects

The third way in which we take our theory model and the predictions that it yields to data from the 1969 Western Judgment is to use a panel instrumental variables (IV) spatial econometric model to estimate the impact of the Western Judgment on the spatial effects of groundwater extraction. Here we are primarily concerned with changes in how extraction was influenced by other nearby extraction and empirically examining the theoretical predictions for the spatial effects of groundwater extraction from Section 4.6. Spatial effects are one particular channel through which we expect to see the impact of spatial externalities on extraction. Our approach allows us to analyze the effect of the policies imposed under the Western Judgment on coordination and on patterns of extraction across space. We examine if the regulations helped to ameliorate the impact of uninternalized interjurisdictional spatial externalities. We also compare spatial effects across different types of regulations.

Results from our panel regression analysis in Section 6.2 indicate that wells that were more interior to their jurisdiction better internalized spatial externalities in their own administrative basins after the regulation, while wells that were hydrologically connected to other jurisdictions either through rivers or across the political boundary in Riverside faced interjurisdictional spatial externalities that they did not internalize. We now analyze how these interjurisdictional externalities impact groundwater extraction and the spatial effects of groundwater extraction, which we define as the effects of groundwater extraction at nearby wells on groundwater extraction at a particular well. In particular, we examine how individual users responded to pumping at nearby wells, and the effects of the regulation group and the degree to which spatial externalities were internalized on these spatial effects. Unfortunately, since our crop, groundwater elevation, and groundwater depth data does not cover the entire 1960-2016 time range of our panel, we cannot estimate interjurisdictional spatial externalities in each year. We instead use panel regression techniques to examine each of these effects, and provide suggestive evidence.

As explained in more detail in Section 4.6, our theory model yields several predictions for the spatial effects of groundwater extraction. First, extraction at one well will increase if extraction at nearby hydrologically connected wells increase. Second, if nearby wells are managed by the same owner, then the effects on groundwater extraction at one well of groundwater extraction at other nearby wells owned by the same owner would likely differ from the effects if there were no coordination, and may possibly be less positive or even negative. Third, if nearby wells are managed in a coordinated fashion, then the effects on groundwater extraction at one well of groundwater extraction at other nearby coordinated wells would likely differ from the effects if there were no coordination, and may possibly be less positive or even negative.

7.1 IV fixed effects spatial econometric model

We estimate an instrumental variables (IV) fixed effects spatial econometric model to measure the spatial and strategic drivers of groundwater extraction, and how these factors are affected by the split regulation of the basins, using the panel dataset covering the years 1960-2016 that we collected and constructed from historical records. In particular, we measure the effect of extraction at neighboring wells within one mile, both in the same basin and in other basins, and distinguish between extraction done by the same owner, and extraction done by other owners. We then examine how the degree to which the basin is controlled by each form of regulation affects these spatial effects. This gives us a measure of how split regulation can affect spatial externalities in extraction.

Our regression equation is given by:

$$w_{ibt} = (1 - I\{post_t\}) \left(W'_{-i,t}\beta^{pre} + \gamma_G^{pre} G_{it}\right) + I\{post_t\} \left(W'_{-i,t}\beta^{post} + \gamma_G^{post} G_{it}\right) + S'_{bt}\gamma_S + \tau_t + \alpha_i + \varepsilon_{it}, \tag{31}$$

where w_{ibt} is groundwater extraction at well i in basin b at time t; $I\{post_t\}$ is a post-regulation dummy for being after the 1969 Western Judgment; $W_{-i,t}$ is a vector of weighted sums of the extraction from various sets of neighboring wells; G_{it} is the regulatory grouping the well would have been assigned to in t according to the regulatory framework imposed after 1969; S_{bt} is the vector of precipitation, State Water Project (SWP) deliveries, and SWP recharge within basin b at time t; τ_t captures all common time-variant factors; α_i is a well fixed effect, which controls for unobserved time invariant factors that may affect extraction at the well; and ε_{it} is the error term.

Let B_i denote the basin of well i and O_i denote the owner of well i. The vector $W_{-i,t}$ of weighted sums of the extraction from various sets of neighboring wells includes: the weighted sum $\sum_{j|B_j=B_i \wedge O_j=O_i} \frac{k_j}{x_{ji}} w_{jt}$ of extraction from wells in the same basin as i and owned by the same owner as i; the weighted sum $\sum_{j|B_j \neq B_i \wedge O_j=O_i} \frac{k_j}{x_{ji}} w_{jt}$ of extraction from wells from a different basin from i and owned by the same owner as i; the weighted sum $\sum_{j|B_j=B_i \wedge O_j \neq O_i} \frac{k_j}{x_{ji}} w_{jt}$ of extraction from wells in the same basin as i and owned by a different owner from i; and the weighted sum $\sum_{j|B_j \neq B_i \wedge O_j \neq O_i} \frac{k_j}{x_{ji}} w_{jt}$ of extraction from wells from a different basin from i and owned by a different owner from i. The vector $W_{-i,t}$ of weighted sums also includes these same weighted sum terms interacted with the share of wells in the basin that are included as part of the same regulatory group as well i. Following Pfeiffer and Lin (2012), the weights $\frac{k_j}{x_{ji}}$ used in the weighted sums of the extraction from various sets of neighboring wells come from Equation (2) for Darcy's Law describing the movement of a fluid through porous material, and adjust the amount pumped at a neighboring well by the effect that it should have based on hydrology. For example, if the distance x_{ji} between two wells is greater, the effect should be smaller. On the other hand, if the saturated hydraulic conductivity k_j of the material holding the water in neighboring patch j is greater, then the effect of pumping at neighboring well j on patch i should be greater.

Measuring the effects of pumping at neighboring wells is difficult owing to two sources of endogeneity. One source is of endogeneity is simultaneity: if groundwater extraction at well i is affected by groundwater extraction at its neighboring well j, then groundwater extraction at well j is affected by its groundwater extraction at its neighboring well i. The other arises from spatially correlated unobservable variables (Manski, 1993, 1995; Brock and Durlauf, 2001; Conley and Topa, 2002; Glaeser et al., 1996; Moffitt, 2001; Lin, 2009; Robalino and Pfaff, 2012; Pfeiffer and Lin, 2012; Morrison and Lin Lawell, 2016; Rojas Valdés et al., 2023). It is therefore important to address these endogeneity problems in order to measure the effects of pumping at neighboring wells.

To address the endogeneity of groundwater extraction at neighboring wells, we use the average annual extraction limit imposed by the regulation on the neighboring well as an instrument for the neighboring well's extraction. The neighboring well's regulatory limit is correlated with the extraction at the neighboring well, but does not affect a well's own groundwater extraction except through its effect on the neighboring well's groundwater extraction.

In order to calculate the average annual extraction limit imposed by the regulation on the neighboring well, we take the regulated quantity specified in the Western Judgment, either at the individual or group level, and divide it by the number of operating wells subject to that regulation in the given year. For wells that were indirectly regulated through measurements at monitoring sites, we use the difference between the groundwater level in 1963 and the previous year's lowest recorded elevation as the instrument. These instruments are relevant due to the fact that a less restrictive regulation allows for greater levels of pumping at each individual well. We argue that they satisfy the exclusion restriction since the regulations were determined based on several years of pumping prior to either the regulation being implemented or the case being brought to court. In the case of the monitoring site measurements, by using the previous year's levels, pumping in the current year cannot influence the instrument.

Our Angrist-Pischke first-stage F-statistics are presented in Table B.3 in Appendix B. The Angrist-Pischke first-stage F-statistics are tests of weak identification of individual endogenous regressors, and are constructed by 'partialling-out' linear projections of the remaining endogenous regressors (Angrist and Pischke, 2009). As seen in Table B.3, the Angrist-Pischke first-stage F-statistics are all greater than the threshold of 10 used in current practice (Staiger and Stock, 1997; Stock and Yogo, 2005; Andrews et al., 2019), and 34 out of 36 Angrist-Pischke first-stage F-statistics are also greater than the threshold of 104.7 for a true 5 percent test (Lee et al., 2021).

7.2 IV fixed effects spatial regression results

In the first specification of our IV fixed effects spatial econometric model, presented in Table 5, we divide wells into two groups: plaintiffs and non-plaintiffs. Plaintiffs are well owners who were specified in the judgment and given specified rights to extraction, either individually, or as a group. This excludes the group of groundwater users in South Riverside and non-plaintiffs in San Bernardino, who while given group limits on extraction, were not specified by name or function of extraction in the judgment.

We first note that both plaintiffs and non-plaintiffs extracted significantly more prior to the regulation than after. Thus, the regulation led to a decrease in pumping by all users.

We next examine the effect of nearby extraction in the same basin. We find that extraction was positively influenced by nearby extraction from the same owner before but not after regulation. The positive own-pumping effect prior to the regulation could be due to common shocks affecting nearby wells of the same owner; returns to scale from extracting from nearby wells; and/or an owner learning information about nearby wells, such as the cost of extraction, from extracting at one of his wells. The regulation appears to have worked in the opposite direction to dampen this effect, however. After the regulation, pumping limits for the individual owner or regulatory group within each basin were put in place, which would limit the ability of well owners to capitalize on cheaper water in one basin relative to the others, and thus attenuate the positive effect of own nearby extraction in the same basin.

Prior to the regulation, we see that nearby pumping by the same owner outside the basin had a negative effect, providing evidence for some substitution. This suggests that cost disparities likely exist between wells in different basins, even when they are nearby, making it more advantageous to substitute between wells when one is cheaper than another. This effect is dampened by the share of wells in the basin that are included as part of the same regulatory group as well i, likely due to correlation between the share of nearby wells in one's regulatory group and the share of one's own wells in the immediate area. When a well owner has many nearby wells in the basin, each well in the basin may substitute less for pumping at wells outside of the basin, and therefore have a less elastic negative response, which mitigates the negative effect. After the regulation, we see that the negative effect of nearby pumping by the same owner outside the basin becomes much stronger, although it is ultimately insignificant when we control for common shocks within each year. This suggests some additional substitution across basins, which may vary across years. This makes sense under the hypothesis that the main causes of inter-basin substitution are likely time-variant factors such as relative cost differences and regulatory pressure brought on by one's pumping history. The magnitude of these factors may then be strongly correlated with unobservable factors that vary from year to year, and thus would be captured by the year dummies included in our main specification.

We next note that the effect of extraction by other nearby users in the basin is significantly negative both before and after the regulation. This suggests that the drawdown effect of other owners' pumping negatively influences each owner's pumping decision more than the dynamic effect of lower future stocks and higher future costs, likely due to strong sub-surface flows that cause drawdowns to be transmitted quickly within the system and which may also make owners expect faster inflows of water from elsewhere in the system to recharge the stock in future years. The negative effect of other nearby users in the basin goes away when the owner's regulatory group owns a large share of nearby wells; this dampening effect of the share of wells is likely due to correlation between the share of nearby wells in one's regulatory group and the share of one's own wells in the immediate area. Well owners who could not substitute for pumping at wells which faced drawdown from their neighbor's pumping would likely have a less elastic negative response, which mitigates the negative effect. Finally, we note that the regulation does not seem to have had an effect on this spatial externality.

In the second specification of our IV fixed effects spatial econometric model, presented in Table B.4 in Appendix B, we divide groundwater users into groups based on the type of regulation they face. Here they are either faced with an individual quantity cap, a group cap, or no regulation. We find that pumping was higher prior to the regulation for each group. In addition, we find that nearby pumping in the basin by the owner has a positive effect on pumping prior to the regulation, but the point estimate switches sign after the regulation. Conversely, pumping by the owner at nearby wells outside the basin does not have a statistically significant effect on pumping before the regulation, but has a significantly negative effect after. Finally, both before and after the regulation, nearby pumping in the basin by other owners has a negative effect on pumping. This effect disappears both before and after the regulation, however, when a large share of nearby wells are controlled by owners in the same regulation group.

For our third specification of our IV fixed effects spatial econometric model, shown in Table B.5 in Appendix B, we demean separately by basin and regulation group. Our results are generally similar to those in the previous two cases, making them robust to how we demean by group. Here we see that, as in our regulatory group model, the effect of an owner's own pumping at nearby wells in the basin actually switches sign from positive to negative after the regulation is instituted. As in the plaintiff model, the magnitude of the effect of own extraction at nearby wells outside the basin increases after the regulation, but so does the variance in the point estimate, making the coefficient insignificant.

We also run additional versions of each of our three specifications of our IV fixed effects spatial econometric model in which we add controls related to the size of the groundwater stock, the level of expected recharge, and the marginal revenue of water at both the well itself, and at neighboring wells owned by others. As summarized in Table 1, our theory model predicts that greater marginal revenue on neighboring farmland should lead to greater pumping when there is less coordination. Thus, if the regulation were effective in increasing coordination and reducing spatial externalities, the marginal effect of marginal revenue on neighboring farmland on pumping would be less positive after the regulation.

We attempt to capture marginal revenue on farmland through an interaction of land-use and land value. In particular, we interact land use share with the value of farmland per acre. The marginal revenue on neighboring farmland is captured by terms that interact agricultural land use with the value of farmland per acre. We expect that land used for prime farmland or other designations of farmland should have a higher marginal revenue for groundwater than pasture land. Our results provide some support for the idea that the regulation dampened the positive effect of the neighboring farmland marginal revenue on extraction.

In particular, as seen in Table B.6 in Appendix B, when we use the type of regulation as our grouping mechanism, we find that, as a result of the regulation, after controlling for common time effects, both farmland of state-wide importance and prime farmland either switched from a positive significant effect to an ambiguous effect on extraction, or switched from an ambiguous effect to a significant negative effect, respectively. After controlling for time effects, only the effect of farmland of statewide importance remains significantly different between periods, although prime farmland comes the next closest. These are the top two designations in terms of farmland quality in the survey, and so, they would be expected to produce the sharpest effects since marginal revenue should be highest on these two types of farmland. Thus it appears that the regulation did seem to dampen the competition for water due to the marginal revenue of groundwater for irrigation.

Examining our results from the perspective of plaintiff groups vs. non-plaintiff groups we find generally similar results. As seen in Table B.7 in Appendix B, the main difference is that instead of just farmland of state-wide importance, prime farmland's effect also changed significantly between periods after controlling for common time effects. We again see some evidence that farmers nearby other farmers with better land had a more negative effect from higher farmland values after the regulation than before.

Finally, when we group wells based both on the type of regulation they received, and on the basin in which they were located, we find similar results as in the case of plaintiff vs. non-plaintiff groups. Our results, found in Table B.8 in Appendix B, indicate that after controlling for common time shocks in the second model, both neighboring prime farmland and farmland of statewide importance had their effects become significantly more negative after the regulation was introduced. This again suggests that the pumping response to greater marginal revenue on neighboring plots of land was lower after the regulation.

7.3 Spatial econometric analysis of jurisdictional boundaries

In order to better understand how hydrology influences the effect of the regulation, we supplement our spatial econometric analysis by examining the effects of changes in nearby pumping on extraction behavior near the different jurisdictional boundaries imposed under the adjudication. In our study area, jurisdictional boundaries were based on fault lines which correspond to the basins' boundaries, and political boundaries (county borders) which do not. In addition, a river with subsurface flows connecting it to the groundwater basins flows across the jurisdictional boundaries. In theory, boundaries that do not correspond to physical boundaries separating distinct groundwater basins create the opportunity for interjurisdictional spatial externalities to exist and not be internalized. Results from our panel regression analysis in Section 6.2 indicate that the type of boundary plays a significant role in determining how the regulation impacted pumping response to groundwater stock. Results from our IV fixed effects spatial econometric model in Sections 7.1-7.4 indicate that groundwater users responded differently to their own nearby pumping versus the pumping of other groundwater users, and that the pumping response changed after the regulation was imposed. In this section, we focus on the response to pumping within 1 mile of the well of interest and examine how the response to different types of nearby pumping across different types of boundaries changed after the regulation was imposed. We attempt to difference out common trends unrelated to the regulation's effect on coordination between different groundwater users, in order to measure of the effect of increased coordination on the spatial effects of groundwater extraction.

We use a slightly modified version of our previous IV fixed effects spatial econometric model in Section 7.1. Since our geographic region is much smaller, we do not have sufficient variation in precipitation and SWP deliveries to include these in our model, and instead account for spatio-temporal variation by including administrative basin-year effects.

Our regression equation is given by:

$$\begin{aligned} w_{iobt} = \\ & (1 - I\{post_t\}) \left(W'_{-i,obt}\beta^{pre}_{ob} + W'_{-i,o,-b,t}\beta^{pre}_{o,-b} + W'_{-i,-o,bt}\beta^{pre}_{-o,b} + W'_{-i,-o,-b,t}\beta^{pre}_{-o,-b} + \gamma^{pre} G_{it} \right) + \\ & I\{post_t\} \left(W'_{-i,obt}\beta^{post}_{ob} + W'_{-i,o,-b,t}\beta^{post}_{o,-b} + W'_{-i,-o,b,t}\beta^{post}_{-o,b} + W'_{-i,-o,-b,t}\beta^{post}_{-o,-b} + \gamma^{post} G_{it} \right) + \\ & + \mu_t + \alpha_i + \varepsilon_{it}, \end{aligned} \tag{32}$$

where w_{iobt} is groundwater extraction at well i owned by user o in basin b at time t; $I\{post_t\}$ is a post-regulation dummy for being after the 1969 Western Judgment; $W_{-i,o,b,t}$ is a vector of sums of the extraction from various sets of neighboring wells within 1 mile that are owned by the same owner o and located in the same basin b; $W_{-i,o,-b,t}$ is a vector of sums of the extraction from various sets of neighboring wells within 1 mile that are owned by the same owner o and located in a different basin from basin b; $W_{-i,-o,b,t}$ is a vector of sums of the extraction from various sets of neighboring wells within 1 mile that are owned by a different owner from owner o and located in the same basin

b; $W_{-i,-o,-b,t}$ is a vector of sums of the extraction from various sets of neighboring wells within 1 mile that are owned by a different owner from owner o and located in a different basin from basin b; G_{it} is the regulatory grouping the well would have been assigned to in t according to the regulatory framework imposed after 1969; μ_{bt} is an administrative basin-year effect; α_i is a well fixed effect, which controls for unobserved time invariant factors that may affect extraction at the well; and ε_{it} is the error term.

As before, to address the endogeneity of groundwater extraction at neighboring wells, we use the average annual extraction limit imposed by the regulation on the neighboring well as an instrument for the neighboring well's extraction. The neighboring well's regulatory limit is correlated with the extraction at the neighboring well, but does not affect a well's own groundwater extraction except through its effect on the neighboring well's groundwater extraction. Our first-stage F-statistics are presented in Table B.9. Overall we find our instruments deliver strong first-stage results, indicating relevance.

The regression in Equation (32) allows us to examine whether the pumping response to neighboring pumping in the immediate area differed based on ownership of the nearby well and inclusion in the same regulatory boundary. We focus in particular on the effect of extraction at nearby wells in the same basin owned by other owners after the regulation is imposed. As explained in more detail in Section 4.6, our theory model predicts that extraction at one well will increase if extraction at nearby hydrologically connected wells increase, but if nearby wells are managed in a coordinated fashion, then the effects on groundwater extraction at one well of groundwater extraction at other nearby coordinated wells may possibly be less positive or even negative. Thus, under partial coordination (e.g., after the regulation is imposed), we would expect pumping response to be less positive (and therefore more negative) for neighboring wells owned by others in one's own basin with whom one may be coordinating, and therefore with whom our pumping may be viewed as substitutes, compared to that for neighboring wells owned by others on the other side of an administrative boundary with whom we may be competing for a common resource rather than coordinating.

Our results are presented in Table B.10. Specifications (1)-(3) use wells from Riverside Basin only, while Specifications (4) and (5) use the full sample of wells in our data set. We then introduce an additional level to our model to account first for changes around political boundaries in extraction response. To examine whether it is easier to coordinate at wells that are more "internal" to one's regulatory basin, since managing a shared stock might more possible when the stock is less susceptible to drawdown from other wells that are not coordinating, Specifications (2) and (5) distinguish between nearby wells that are near a political border (e.g., the political border between Riverside North and Riverside South), and wells that are not. Since there might be multiple regulatory groups within a basin, and since wells within the same basin may only coordinate with other wells within the same regulatory group in that basin, to examine the role that regulatory heterogeneity played within Riverside Basin, and how this interacted with spatial regulation, Specification (3) distinguishes between extraction at nearby wells owned by others that are within the same basin and in the same regulatory group, and extraction at nearby wells owned by others that are within the same basin, but in a different regulatory group. Consistent with the results from our IV fixed effects spatial econometric model in Sections 7.1-7.4 that show that the effects of extraction by others in same basin after the regulation are negative, our results in Table B.10 show that the effects of extraction by others within 1 mile in same basin after the regulation are also negative, which is evidence for at least some partial coordination after the regulation is imposed.

We next further examine Riverside Basin (both North and South administrative zones), since Riverside North wells were divided into two regulatory groups, and since the political boundary separating Riverside North from Riverside South was political and thus allowed for the flow of groundwater across administrative lines. Riverside North lies upstream of Riverside South on the Santa Ana River. Thus extraction North of the border would impact the availability of groundwater south of the border both through groundwater flows, and by diminishing river flows. Riverside North was also split into two regulatory groupings. Wells in the Riverside North side of this border were divided into two separate groups and thus faced the most fractured regulation, while wells in Riverside South were all grouped into one regulatory group. In Table B.11 we show the first-stage F-statistics for each endogenous variable included in our regressions. Our results are presented in Table B.12. Specifications (1), (2), (5), (6), and (8) use only border wells, which we define as wells that are within 1 mile of the administrative border separating Riverside North and Riverside South. To examine behavior at wells facing a combination of intrajurisdictional and interjurisdictional regulatory fracturing, Specifications (1) use only border wells from Riverside Basin. To examine whether there were any differences between Riverside North and Riverside South, Specifications (3)-(6) use only wells in Riverside North, while Specifications (7)-(8) use only wells in Riverside South.

Our results for Riverside Basin in Table B.12 show that the effects of other nearby extraction in same basin after the regulation are negative if the wells are in the same regulatory group (Specifications (2), (4), and (6)), which is evidence for partial coordination within a regulatory group. Results show that the effects of other nearby extraction in same basin after the regulation are also negative if the well is in Riverside North (Specifications (3) and (5)), which is evidence for partial coordination within Riverside North. On the other hand, we find that the effects of other nearby extraction in same basin after the regulation are positive if the well is in Riverside South (Specification (7)), which is evidence for continued competition, rather than partial coordination, within Riverside South even after the regulation is imposed. Thus, in Riverside South there appears to have been more competition further from the border, both before and after the regulation was imposed. The regulation did not appear to affect the spatial effects of groundwater extraction on the Southern side of the Riverside border. This result suggests that regulatory heterogeneity did limit the success of the regulation around the administrative basin boundaries.

To better understand the effect the regulation had on the spatial effects of groundwater extraction, we next break our sample into groups based on the form of regulation imposed after the adjudication. As explained in more detail in Section 4.6, our theory model predicts that the spatial effects of groundwater extraction under partial coordination may differ by whether the regulation type is individual quantity regulation, group quantity regulation, or stock monitoring-based regulation. Wells owned by Riverside interests were given group pumping limits, with separate group quantity limits for wells on either side of the administrative boundary. Wells owned by San Bernardino interests were regulated based on the groundwater stock measurements at specific monitoring sites.

We separate our sample by regulation type, and then examine pumping responses to neighboring groundwater pumping, and to variables representing the likelihood that the regulatory mechanism imposed on the group becomes binding in the coming year. For the wells in the group quantity regulation group, we use the share of the maximum five-year group pumping limit that was extracted by the group in the previous three years to measure the likelihood that the group limit becomes binding in the coming year. When this share is higher, groundwater pumping in the current year is more likely to trigger the regulation, and also makes the triggering of the regulation more likely in the next year. For the wells regulated based on monitored groundwater elevation, we use the depth to groundwater at the monitoring site interacted with the inverse distance between the extraction well and the nearest monitoring site to measure the likelihood that the stock monitoring-based regulation becomes binding in the coming year. When depth to groundwater is high, elevation of groundwater is low, and continued pumping is more likely to trigger the regulation in the current and next year. Similarly, when distance is small, pumping has a greater impact on groundwater elevation at the monitoring site. Our results are presented in Table B.13. Specifications (1) and (3) use wells in the group quantity limit regulatory groups; while Specifications (2) and (4) use wells in the San Bernardino interest group, which were regulated based on the elevation of groundwater at specific monitoring sites. Specifications (3) and (4) focus on border wells only.

As seen in Table B.13, for wells in the group quantity limit regulatory groups, our results show that, further from the border, the pumping response to wells in one's regulatory group (on either side of the administrative boundary) is more positive than the pumping response to nearby wells owned by San Bernardino interests, suggesting that competition between groups remained after the regulation. For wells in the group quantity limit regulatory groups, we do not find that the regulation directly impacted pumping behavior.

For wells in the San Bernardino interest group, which were regulated based on the elevation of groundwater at specific monitoring sites, we find the regulation does appear to have had an impact, as pumping responses to all nearby pumping became more negative after the regulation. Furthermore, we see that when the interaction between depth to groundwater at the monitoring site and inverse distance to the monitoring site is large, this has a negative and significant impact on pumping. Thus, wells that faced a more binding form of the regulation did reduce pumping in response. Near the border, however, pumping became significantly more competitive between owners in different interest groups, and the regulation's probability of being binding does not appear to affect pumping in a significant way.

7.4 Discussion of spatial econometric results

At first pass, the results of our IV fixed effects spatial econometric regressions in Section 7.2 and Tables 5-B.5 appear to show that pumping did generally decrease after the regulation was put into place. Relative to prior pumping, there was significant groundwater conservation after the regulation. The effect of rapid population growth on demand for groundwater appears to have been mitigated by deliveries of imported water through the State Water Project. On closer inspection, however, our spatial results also indicate that the regulation led to changes in the balancing of extraction across each owner's wells.

In particular, our results in Section 7.2 indicate that the regulation had important effects on how individual owners spatially and dynamically managed their extraction. The change in sign of the effect of nearby pumping within a basin may reflect the differences of the regulation's direct and indirect caps on extraction by basin. Prior to the regulation, owners may have pumped where water was cheapest in the present, and thus pumping by an owner would be likely to cluster in certain areas, leading to positive own-pumping effects. After the regulation, however, pumping at wells in the same basin would bring the owner closer to their individual or group cap, or draw down monitored levels in the basin, decreasing the availability of groundwater in the future. Owing to the split regulation, after the regulation was imposed, users who were close to their caps on extraction in a basin in a given year may have lowered their extraction from regulated wells and simply substituted with increased extraction at nearby wells that were not under the same regulation. The strong negative coefficient on nearby pumping at wells outside the basin illustrates the effect of the split regulation.

The regulation did not materially impact the spatial and dynamic effects of pumping by other owners. Both before and after the regulation was imposed, pumping by other nearby owners had a significant negative effect which vanished as the share of nearby wells controlled by the same group increased. This negative impact indicates that the immediate spatial drawdown effect of nearby pumping on groundwater levels, and thus cost, was likely stronger than the dynamic effect on costs in the future. This could be due to the relatively high rate of transmissivity or flow of water spatially in the area, since pumping externalities would be transmitted quickly. Some of this drawdown may also be mitigated over the course of the longer term by inflow of water from elsewhere in the basin, which would dampen the impact on lift height in future years. The mitigating impact of the share of nearby wells owned by owners in the same regulation group is likely due to correlation between this variable and the relative level of clustering of one's own wells. If an owner has many of their own wells in the same location they may not be able to avoid the effects of a neighbor's pumping in the short term, and thus may have a less elastic response to nearby pumping.

While pumping was generally reduced, the regulation appears to have created incentives for owners to re-allocate their pumping in order to comply with the regulation. Instead of clustering their pumping in the areas in which it is most profitable to do so, owners appear to have limited this practice after the regulation in order to remain within their legal limits, and have also started to substitute pumping across basin boundaries. While regulation may limit pumping in a given location, the fact that groundwater flows between basins means that this substitution of extraction across basins may limit the effectiveness of the within-basin conservation.

We also find the substitution of extraction across basins was mitigated when the share of the basin under the same regulation grouping was large. Consistent with our theory model, results of our IV fixed effects spatial econometric regressions suggest that if much of the basin was under a single regulatory framework, owners would internalize a larger share of pumping externalities. Thus, while the splinters in regulation created incentives to strategically shift one's own pumping, when the regulation encompassed a higher share of the basin, this strategic effect was mitigated, leading to more socially efficient outcomes.

As summarized in Table 1, our theory model predicts that greater marginal revenue on neighboring farmland should lead to greater pumping when there is less coordination. Thus, if the regulation were effective in increasing coordination and reducing spatial externalities, the marginal effect of marginal revenue on neighboring farmland on pumping would be less positive after the regulation. Our empirical results provide some support for the idea that the regulation dampened the competition for water due to the marginal revenue of groundwater for irrigation, and therefore that the regulation was at least somewhat effective in increasing coordination and reducing spatial externalities.

Our spatial econometric analysis of jurisdictional boundaries in Section 7.3 shows that the regulation did lead to greater coordination within one's basin, but that this coordination did not extend to wells outside of one's basin. Furthermore, this coordination had no effect nearby the borders of the basins, even for nearby wells inside of one's administrative basin. Fractured regulation within the basin further hampered this effort around the jurisdictional borders of the regulation. While coordination did improve at internal wells, even when management was split between groups, this was not the case for wells near the basin's boundaries. At wells near the basin's boundaries, groundwater users treated other groundwater users differently depending on whether or not they were in the same regulatory group. The direction of flow of water between basins through the Santa Ana River and the different regulatory groupings imposed on either side of the Riverside border also appear to have limited the effectiveness of the regulation. The regulation did not affect extraction on the Southern side of the border, where there is a single group of groundwater users limited to a group quantity. In contrast, the regulation did affect extraction at wells upstream on the Northern side of the border, where there were both stock monitoring-based regulations and group extraction limits. In addition, results support the idea that changes in pumping patterns in the interior of the basin lowered competition for groundwater resources for the San Bernardino interest group, which faced a regulation based on the state of the physical stock of groundwater, rather than a fixed limit on extraction. These changes were not present for wells near the administrative boundary, however, where regulation was split both at the basin line, and between interest groups.

Taken together, results from our spatial econometric analyses show that the effectiveness of the regulation was severely hampered by the fractured management structure that was imposed.

8 Discussion and Conclusion

When designing groundwater management policies, it is important to account for spatial externalities that result from the common pool nature of the resource. Spatial externalities may arise not only among individual groundwater users sharing the same aquifer, but also among water managers whose separate jurisdictions do not each cover an entire aquifer. In this paper, we develop a model of interjurisdictional spatial externalities in groundwater management. We find that if groundwater managers each manage only a subset of an aquifer, and if there is spatial movement of water between the jurisdictions of different groundwater managers, then groundwater will be over-extracted relative to the socially optimal coordinated solution. Our model generates theoretical predictions of the effects of economic and hydrological factors on interjurisdictional spatial externalities and on groundwater extraction under partial coordination.

We apply our model to analyze interjurisdictional spatial externalities in groundwater management in California. We first use data gathered as part of the 1969 Western Judgment in San Bernardino and Riverside Counties to estimate the share of spatial externalities that are internalized when a common pool of groundwater is managed under multiple regulatory frameworks. Our findings suggest the importance of choosing regulatory divisions that are economically meaningful and encourage coordination between agents. For example, our finding that a relatively small share of externalities were internalized in the Riverside Basin is a direct result of the fact that this basin's management structure was split by the political boundary between Riverside and San Bernardino Counties. Thus, groundwater users faced separate management structures for wells on either side of the boundary, despite the fact that water was used for similar purposes on either side, and even though there was no discontinuity in the flow of groundwater between plots of land on either side of the boundary.

Using a panel regression analysis applied to a spatial panel dataset covering the 57 years from 1960 to 2016 that we collected and constructed from historical records, we then provide econometric evidence that wells that were more interior to their jurisdiction better internalized spatial externalities in their own administrative basins after the regulation. In contrast, wells that were hydrologically connected to other jurisdictions either through rivers or across the political boundary in Riverside faced interjurisdictional spatial externalities that they did not internalize.

We next estimate the effects of policy and spatial dynamics on extraction using an instrumental variables (IV) spatial econometric model applied to our panel dataset covering the years 1960 to 2016. According to the results of our IV fixed effects spatial econometric regressions, we find that while the regulation generally reduced extraction, it appears to have created incentives for owners to re-allocate their pumping in order to comply. After the regulation was imposed, in order to remain within their legal limits, owners limited the practice of clustering their pumping in the areas in which it is most profitable to do so, and instead started to substitute pumping across basin boundaries. Users who were close to their caps on extraction in a basin in a given year may have lowered their extraction from regulated wells and simply substituted with increased extraction at nearby wells that were not under the same regulation. While regulation may limit pumping in a given location, the fact that groundwater flows between basins means that this substitution of extraction across basins may limit the effectiveness of the within-basin conservation.

We also find in our IV fixed effects spatial econometric analysis that, consistent with our theory model, the substitution of extraction across basins was mitigated when the share of the basin under the same regulation grouping was large. If much of the basin was under a single regulatory framework, owners would internalize a larger share of pumping externalities. Thus, while the splinters in regulation created incentives to strategically shift one's own pumping, when the regulation encompassed a higher share of the basin, this strategic effect was mitigated, leading to more socially efficient outcomes. This result points to a problem that fractured management creates for common pool property rights systems more generally. In a well functioning property rights system with trading of extraction rights, trading between resource users should allocate extraction to the uses and locations where extraction is most profitable. When administrative boundaries create frictions to trading extraction rights within the common pool resource system, resource users cannot make the full set of profitable property rights trades, and must use other tools to profit maximize under the rules of the property rights system. This can lead to socially inefficient balancing of extraction around administrative boundaries.

Results of our empirical calibration and IV spatial econometric models also show that the type of regulation may also affect the degree of coordination. We find that group quantity regulations have the potential to internalize a much larger share of the spatial externality than other forms of regulation. Group limits that encompassed groundwater users with wells clustered closely together helped bring these users under a common management structure and helped to limit the theoretical economic efficiency losses from spatial externalities. In contrast, individual limits that do not encompass all groundwater users in the area may lead to more fractured management when these users are not naturally isolated. Nevertheless, the degree to which extraction limits can actually impact extraction behavior depends on whether these extraction limits are likely to bind. In the case of the Western Judgment, we see evidence that the group extraction limits were not binding and therefore may have been higher than necessary, as the probability of triggering the regulation does not appear to have influenced behavior. This is likely due to the extraction limits set by the regulation, their recurring nature, and the spatial fractures of the regulation which allowed groundwater users to simply shift extraction between regulatory basins year to year to avoid hitting the group or individual limit on extraction. More effective were stock monitoring-based regulations which forced some coordination on groundwater users who had wells located near the monitoring sites used to administer the regulation. Although the regulation was never triggered, we see evidence that groundwater users with wells included in this regulation responded to changes in stock levels at the monitoring site. A major weakness of this regulation was that there were only a few monitoring sites used to administer the regulation, and thus many wells in this group faced little regulation in practice. Improvements in hydrological monitoring and modeling may make stock-based regulations easier to expand across space, and thus more effective.

Our results therefore provide empirical evidence that split management of a common pool resource can lead to heterogeneity in the degree to which well owners internalize spatial extraction externalities. We also find that fragmented regulation can also lead to changes in how groundwater users respond to nearby pumping. Groundwater users in more fragmented areas reduce their pumping more in response to nearby pumping by others, and cluster their own extraction less than groundwater users who are in a more concentrated regulation group. Our results suggest that fragmented regulation may lead to economically inefficient pumping in the face of uninternalized externalities, and provide empirical evidence for the presence of interjurisdictional spatial externalities that should be accounted for in the optimal design of groundwater management in California. Policies like those used in the Western Judgment that split regulation of a common pool resource across non-physical boundaries such as political borders may not be effective in mitigating the undesirable effects of interjurisdictional spatial externalities. In order to achieve the socially optimal coordinated solution, the jurisdictions of local agencies should instead be large enough to internalize all spatial externalities, so that there are no transboundary issues between jurisdictions. Our results illustrate a potential inefficiency of local-level policies designed to prevent groundwater overdraft in other parts of the Western United States and the world.

For example, our results have important implications for the policy framework created by California's 2014 Sustainable Groundwater Management Act (SGMA), wherein groundwater is managed by local agencies that do not each cover an entire groundwater basin. In particular, as stipulated in the Strategic Plan that the California Department of Water Resources developed in 2015 for the implementation of SGMA, each groundwater basin is to be managed at the local level by locally-controlled Groundwater Sustainability Agencies (California Department of Water Resources, 2015b). These local agencies do not each cover an entire groundwater basin; on the contrary, there are many basins in which multiple Groundwater Sustainability Agencies operate. SGMA stipulates that if a basin with multiple GSAs develops multiple Groundwater Sustainability Plans (GSPs), then a single Coordination Agreement must be submitted with the GSPs to the Department of Water Resources to ensure that GSPs are developed and implemented using consistent data, methodologies, and objectives (**?**California Code of Regulations, 2016). On the other hand, Interbasin Agreements, or agreements between adjacent basins, are not required under SGMA (Groundwater Exchange, 2023).

Our results in this paper show that interjurisdictional externalities emerged even in a regulated environment with legally binding rules addressing adverse impacts between users, and formalizing common tools and methods to reconcile water budgets, since the methods used to define the jurisdictions (political boundaries, rather than hydrological boundaries in some cases), define the water budgets (single year extraction rather than long term extraction), and adverse impacts (users were somewhat arbitrarily split into groups) limited the benefits delivered by the regulations. SGMA faces similar risks if inter- and intra-basin regulations are designed in this way.

Our analysis both builds on existing research and suggests possible extensions for future analysis of other common pool resources that span across jurisdictional boundaries. For example, in the realm of tuna fisheries, regional fishing agreements frequently may only allocate catch limits for a subset of fish (Seto et al., 2021). Future research can harness an approach similar to ours to examine fishing effort across allocated and unallocated parts of the fishery, and the response to changes in allocation over time and across space in the fishery.

Previous research on cooperative natural resource and environmental regulations demonstrates that regulations are most likely to succeed when private abatement and compliance costs are outweighed by the beneficial effects of limiting overproduction on revenues (Espínola-Arredondo and Muñoz García, 2012; Akhundjanov and Muñoz García, 2019). Thus, in the context of agriculture in California, we would expect groundwater regulations to have most support in regions where impacts on crop production have a significant impact on prices, or where local production represents a significant share of the market. For example, Sears et al. (2019) find that the benefits from coordinated groundwater management in California are particularly high for specialty crops with high prices, and are expected to be higher under conditions of extreme drought, and also when the possibility of extreme rainfall situations are high. Future research can harness the heterogeneity in crop production and weather conditions across California to better understand the expected impact of the different sets of local groundwater regulations imposed under SGMA. Examining interactions between agricultural production and trade policy in cases in which shared water resources span across national borders could be another useful context for studying interjurisdictional externalities.

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Table 1: Theoretical predictions of effects of economic and hydrological factors on the interjurisdictional spatial externality and on groundwater extraction under partial coordination

	Predicted effect under partial coordination on:	
	Interjurisdictional spatial externality $\delta_{it}(\cdot)$	Groundwater extraction w_{it}
Number $I - I'$ of patches in the aquifer outside of jurisdiction	↑	↑
Saturated hydraulic conductivity k_i	↑	↑
Distance to patches outside of jurisdiction x_{ij}	↓	↓
Future marginal revenue from extraction $\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}}$ on patches outside of jurisdiction	↑	↑
Future marginal costs of extraction $C^w(s_{j,t+1})$ on patches outside of jurisdiction	↓	↓
Recharge rate γ_{it}	↓	↓
Discount rate r	↓	↓
Future recharge rate $\gamma_{j,t+1}$ on patches outside jurisdiction	↑	↑
Groundwater stock $s_{i,t+1}$	↑	↑
Groundwater stock $s_{j,t+1}$ of patches outside jurisdiction	Ambiguous	Ambiguous

Note: Table presents the theoretical predictions of the effects of economic and hydrological factors on the interjurisdictional spatial externality $\delta_{it}(\cdot)$, which we define as the component of the marginal social cost (or spatial externality) $\sigma_{it}(\cdot)$ to nearby patches of pumping an additional unit of groundwater from patch i that the groundwater manager does not internalize; and on groundwater extraction w_{it} under partial coordination. The interjurisdictional spatial externality $\delta_{it}(\cdot)$ is the marginal social cost of the manager extracting from patch i to patches outside the manager's jurisdiction.

Table 2: Share of the spatial externality that is internalized under partial coordination

Group	**# Obs**	**Mean**	**Std.Dev.**	**Min**	**Max**
Full Sample	1,088	0.574	0.335	0.000	0.823
Water right					
Municipal water districts	692	0.549	0.353	0.000	0.823
Agricultural producers	396	0.619	0.296	0.000	0.823
Basin					
San Bernardino	805	0.662	0.314	0.002	0.823
Riverside	231	0.261	0.229	0.000	0.561
Colton	52	0.615	0.203	0.104	0.775
Basin Subgroup					
San Bernardino, plaintiffs	149	0.004	0.002	0.002	0.009
San Bernardino, non-plaintiffs	656	0.811	0.008	0.769	0.823
Colton, plaintiffs	4	0.122	0.019	0.104	0.140
Colton, non-plaintiffs	48	0.656	0.149	0.241	0.775
Riverside North, plaintiffs	44	0.005	0.003	0.000	0.012
Riverside North, non-plaintiffs	68	0.050	0.036	0.000	0.111
Riverside South	119	0.475	0.074	0.304	0.561
Regulation type					
Individual limit	149	0.004	0.002	0.002	0.009
Group limit	823	0.716	0.213	0.000	0.823
Unlimited	116	0.301	0.316	0.000	0.775

Note: Table presents our results for the share $\frac{\sigma_{it}(\cdot)-\delta_{it}(\cdot)}{\sigma_{it}(\cdot)}$ of the spatial externality that is internalized under partial coordination in the Western Judgment data using the entire Western Judgment data set, as well as for municipal water districts versus agricultural producers, for each basin, for each basin subgroup, and for each regulation type.

Table 3: Effects of Partial Coordination: Riverside Basin wells, post-regulation

	Dependent variable is groundwater extraction (acre-feet)		
	(1)	(2)	(3)
Depth to groundwater (feet)	-9.012**	3.482*	3.920**
	(2.961)	(1.490)	(1.506)
Depth to groundwater (feet) X Share of nearby land in:			
Own jurisdiction	13.22***		
	(3.181)		
Other Riverside Basin across political boundary		-16.21***	-17.03***
		(3.539)	(3.565)
Other basins across fault boundary		-0.188	
		(5.175)	
Other basins across fault boundary and not near river			-4.007
			(6.288)
Other basins across fault boundary but connected by river			-5.169
			(6.653)
Constant	277.4*	325.3*	311.4*
	(140.6)	(141.1)	(142.5)
Well fixed effects	YES	YES	YES
Basin-year effects	YES	YES	YES
p-value (Pr>F)	0.0018	0.0002	0.0003
# Observations	4,644	4,647	4,644
# Wells	199	200	199

Notes: Specifications use only observations from wells in Riverside Basin (either Riverside North or Riverside South) for years after the 1969 Western Judgment (i.e., for the years 1970-2016). Regressions are estimated at the well-year level. Each estimation includes well fixed effects, as well as administrative basin-year dummy variables. Nearby represents all land within 1 mile of the well's location. Standard errors in parentheses. We obtain the same point estimates, the same significance levels, and similar standard errors when we estimate the regressions using a Huber/White/sandwich estimator of the variance for the standard errors. Significance codes: *** p<0.001, ** p<0.01, * p<0.05.

Table 4: Effects of Partial Coordination: Riverside Basin wells, all years

Dependent variable is groundwater extraction (acre-feet)	(4)	(5)
Pre-regulation dummy interacted with:		
Depth to groundwater (feet)	0.905	1.456
	(1.445)	(1.465)
Depth to groundwater (feet) X Share of nearby land in:		
Other Riverside Basin across political boundary	-11.09***	-11.82***
	(3.305)	(3.325)
Other basins across fault boundary	3.839	
	(4.996)	
Other basins across fault boundary and not near river		-1.956
		(5.898)
Other basins across fault boundary but connected by river		5.654
		(7.499)
Post-regulation dummy interacted with:		
Depth to groundwater (feet)	3.040*	3.398*
	(1.308)	(1.320)
Depth to groundwater (feet) X Share of nearby land in:		
Other Riverside Basin across political boundary	-15.09***	-15.87***
	(3.215)	(3.239)
Other basins across fault boundary	-0.461	
	(4.698)	
Other basins across fault boundary and not near river		-4.954
		(5.668)
Other basins across fault boundary but connected by river		-4.643
		(6.188)
Constant	461.8***	443.6***
	(125.2)	(126.7)
Well fixed effects	YES	YES
Basin-year effects	YES	YES
p-value (Pr>F) from test that coefficients on the following are equal for pre-regulation and post-regulation:		
Depth to groundwater (feet)	0.000570***	0.00238**
Depth to groundwater (feet) X Share of nearby land across:		
Political boundary	0.0100**	0.00911**
Fault boundary	0.123	
Fault boundary and not near river		0.312
Fault boundary but connected by river		0.0771
p-value (Pr>F)	0.0000	0.0000
# Observations	5,468	5,460
# Wells	258	257

Notes: Specifications use only observations from wells in Riverside Basin (either Riverside North or Riverside South) for all years over the entire 1960-2016 time period of our data set, and therefore includes observations both before and after the 1969 Western Judgment. Regressions are estimated at the well-year level. Each estimation includes well fixed effects, as well as administrative basin-year dummy variables. Nearby represents all land within 1 mile of the well's location. Standard errors in parentheses. We obtain the same point estimates, the same significance levels, and similar standard errors when we estimate the regressions using a Huber/White/sandwich estimator of the variance for the standard errors. Significance codes: *** p<0.001, ** p<0.01, * p<0.05.

Table 5: IV Fixed Effects Spatial Regression Results: Plaintiff groups

Dependent variable is groundwater extraction (acre-feet)	(1)	(2)
Pre-regulation dummy interacted with:		
Own extraction in basin (acre-feet)	0.000851*	0.000762*
	(0.000336)	(0.000327)
Other user extraction in basin (acre-feet)	-0.00518**	-0.00624***
	(0.00182)	(0.00178)
Own extraction outside basin (acre-feet)	-0.0311*	-0.0302**
	(0.0123)	(0.0116)
Own extraction in basin (acre-feet) x share of basin in group	-0.0014	-0.0008
	(0.0008)	(0.0008)
Other user extraction in basin (acre-feet) x share of basin in group	0.00574**	0.00757***
	(0.00218)	(0.00212)
Own extraction outside basin (acre-feet) x share of basin in group	0.0513*	0.0462*
	(0.0238)	(0.0231)
Non-plaintiffs	223.1***	363.1***
	(25.74)	(50.20)
Plaintiffs	192.4***	385.0***
	(23.02)	(47.93)
Post-regulation dummy interacted with:		
Own extraction in basin (acre-feet)	-0.0006	-0.0005
	(0.0003)	(0.0003)
Other user extraction in basin (acre-feet)	-0.00605***	-0.00541***
	(0.000626)	(0.000591)
Own extraction outside basin (acre-feet)	-0.698*	-0.236
	(0.303)	(0.299)
Own extraction in basin (acre-feet) x share of basin in group	0.0000	0.0006
	(0.0006)	(0.0006)
Other user extraction in basin (acre-feet) x share of basin in group	0.00627***	0.00629***
	(0.000811)	(0.000768)
Own extraction outside basin (acre-feet) x share of basin in group	0.645	0.0970
	(0.467)	(0.461)
Non-plaintiffs	162.4***	120.6***
	(24.62)	(24.49)
Total direct SWP deliveries to customers in basin	-0.00196***	0.000587
	(0.000287)	(0.000419)
Total SWP water used to recharge basin	-0.00348***	-0.00213***
	(0.000348)	(0.000559)
Precipitation, inches	-2.348***	-0.435
	(0.669)	(8.431)
Well fixed effects	YES	YES
Year effects	NO	YES
p-value (Pr>F)	0.000	0.000
# Observations	48,319	48,319
# Wells	1,229	1,229

Notes: Robust standard errors in parentheses. We instrument for groundwater extraction at a neighboring well with the average annual extraction limit imposed by the regulation on that well. Significance codes: *** p<0.001, ** p<0.01, * p<0.05.

A Euler Equation Derivations

In this Appendix, we derive the Euler equations (5) and (9) for the non-cooperative solution and the socially optimal coordinated solution, respectively.

A.1 Non-cooperative behavior

An individual dynamically optimizing groundwater user behaving non-cooperatively with respect to other groundwater users will choose groundwater extraction w_{it} each period t in order to maximize the expected present discounted value of his entire stream of per-period profits, conditional on the groundwater stocks s_{jt} and water extraction w_{jt} of all his neighbors j. His dynamic programming problem is given by the Bellman equation (4) subject to the equation of motion (1).

The first-order conditions of the Bellman equation (4) can be used to derive the Euler equation (5) for the non-cooperative solution, which holds at all points in time t. Taking the derivative of the value function $V_{it}(s_{it}; s_{-i,t}, w_{-i,t})$ with respect to the choice variable w_{it} and setting it equal to zero yields:

$$\frac{\partial R_{it}(w_{it})}{\partial w_{it}} - C^w(s_{it}) = \frac{1}{1+r}\left(1 - \frac{\partial g_{it}}{\partial w_{it}}\right) EV'_{i,t+1}(s_{i,t+1}; s_{-i,t+1}, w_{-i,t+1}), \tag{A.1}$$

which can also be written in terms of the previous period as:

$$\frac{\partial R_{i,t-1}(w_{i,t-1})}{\partial w_{i,t-1}} - C^w(s_{i,t-1}) = \frac{1}{1+r}\left(1 - \frac{\partial g_{i,t-1}}{\partial w_{i,t-1}}\right) EV'_{it}(s_{it}; s_{-i,t}, w_{-i,t}), \tag{A.2}$$

where $V'_{it}(s_{it}; s_{-i,t}, w_{-i,t}) = \frac{\partial V_{it}(s_{it}; s_{-i,t}, w_{-i,t})}{\partial s_{it}}$ is the derivative of the value function with respect to groundwater user i's own state variable.

The derivative $V'_{it}(s_{it}; s_{-i,t}, w_{-i,t})$ of the value function with respect to groundwater user i's own state variable produces what is known as the Benveniste-Scheinkman condition (Benveniste and Scheinkman, 1979), yielding the following relationship for groundwater levels between time periods along the optimal extraction path:

$$V'_{it}(s_{it}; s_{-i,t}, w_{-i,t}) = -\frac{\partial C^w(s_{it})}{\partial s_{it}} w_{it} + \frac{1}{1+r} EV'_{i,t+1}(s_{i,t+1}; s_{-i,t+1}, w_{-i,t+1})\left(1 + \sum_{j=1}^{I} \frac{\partial \theta_{ji}(\mathbf{s}_t)}{\partial s_{it}} s_{jt}\right). \tag{A.3}$$

By substituting Equations (A.1) and (A.2) into Equation (A.3), the Euler equation (5) for the non-cooperative solution is obtained.

A.2 Socially optimal coordinated solution

Assuming there is no flow in or out of the aquifer, a social planner would choose the set of pumping volumes w_{it} on each patch i in each time period t in order to maximize the expected present discounted value of the entire stream of aggregate profit from the aquifer. The social planner's dynamic programming problem is given by the Bellman equation (8) subject to the system of equations of motion (1) for all patches i.

The first-order conditions of the Bellman equation (8) can be used to derive the Euler equation (9) for each patch i at each point in time t under the socially optimal coordinated solution. By setting the derivative of the social planner's value function $V_t(s_{1t}, ..., s_{It})$ with respect to the choice variables w_{it} equal to zero we find, for each patch i:

$$\frac{\partial R_{it}(w_{it})}{\partial w_{it}} - C^w(s_{it}) = \frac{1}{1+r}\left(1 - \frac{\partial g_{it}}{\partial w_{it}}\right)\frac{\partial EV_{i,t+1}(s_{1,t+1}, ..., s_{I,t+1})}{\partial s_{i,t+1}}, \tag{A.4}$$

which also holds for the previous time period:

$$\frac{\partial R_{i,t-1}(w_{i,t-1})}{\partial w_{i,t-1}} - C^w(s_{i,t-1}) = \frac{1}{1+r}\left(1 - \frac{\partial g_{i,t-1}}{\partial w_{i,t-1}}\right)\frac{\partial EV_{it}(s_{1t}, ..., s_{It})}{\partial s_{it}}. \tag{A.5}$$

Once again we can derive the Benveniste-Scheinkman condition by taking the derivative of the value function with respect to each state variable s_{it} to obtain the following condition for each patch i:

$$\begin{aligned}\frac{\partial V_t(s_{1t},...,s_{It})}{\partial s_{it}} &= -\frac{\partial C^w(s_{it})}{\partial s_{it}} w_{it} + \frac{1}{1+r}\frac{\partial EV_{t+1}(s_{1,t+1},...,s_{I,t+1})}{\partial s_{i,t+1}}\left(1 + \sum_{j=1}^{I}\frac{\partial \theta_{ji}(s_{1t},...,s_{It})}{\partial s_{it}} s_{jt}\right) \\ &+ \frac{1}{1+r}\sum_{j=1}^{I}\frac{\partial EV_{t+1}(s_{1,t+1},...,s_{I,t+1})}{\partial s_{j,t+1}}\left(\frac{\partial \theta_{ij}(s_{1t},...,s_{It})}{\partial s_{it}} s_{it} + \theta_{ij}(s_{1t}, ..., s_{It})\right) \quad .\end{aligned} \tag{A.6}$$

By substituting Equations (A.4) and (A.5) into Equation (A.6), the Euler equation (9) for the socially optimal coordinated solution is obtained.

B Supplementary Figures and Tables

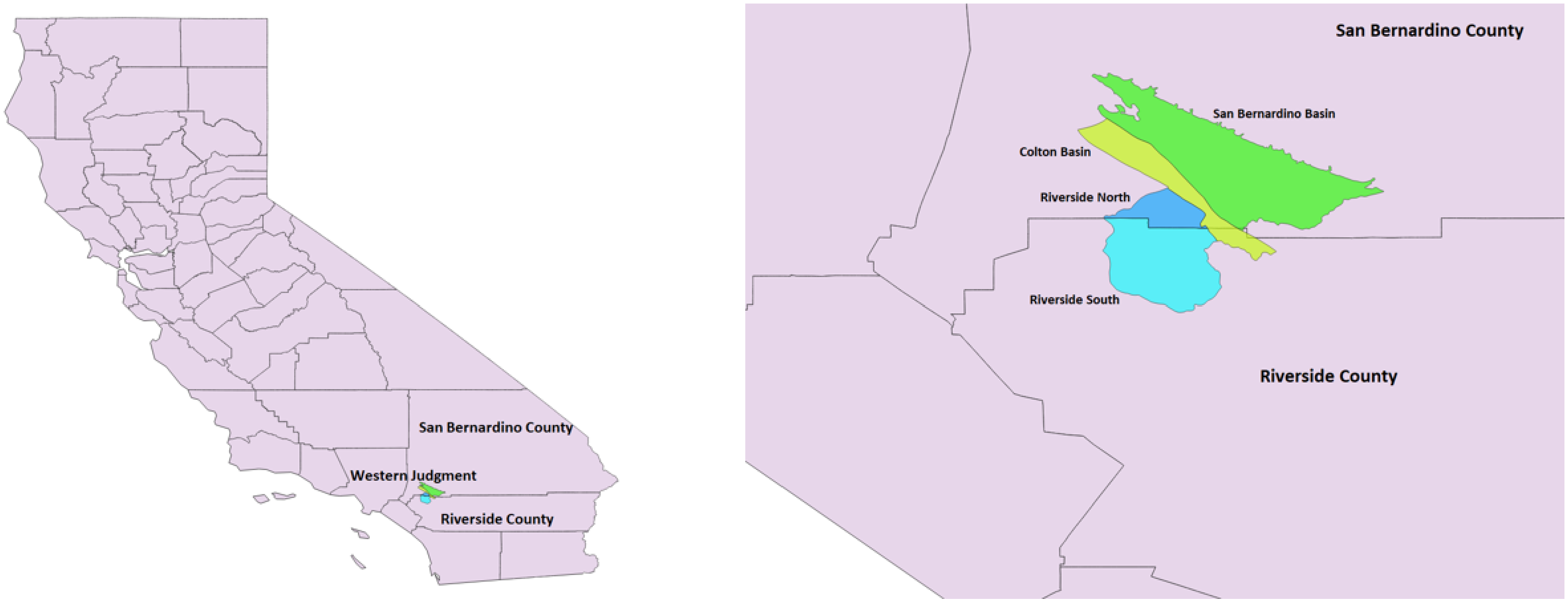

Figure B.1: Western Judgment Regulatory Boundaries
Data Source: Western Municipal Water District

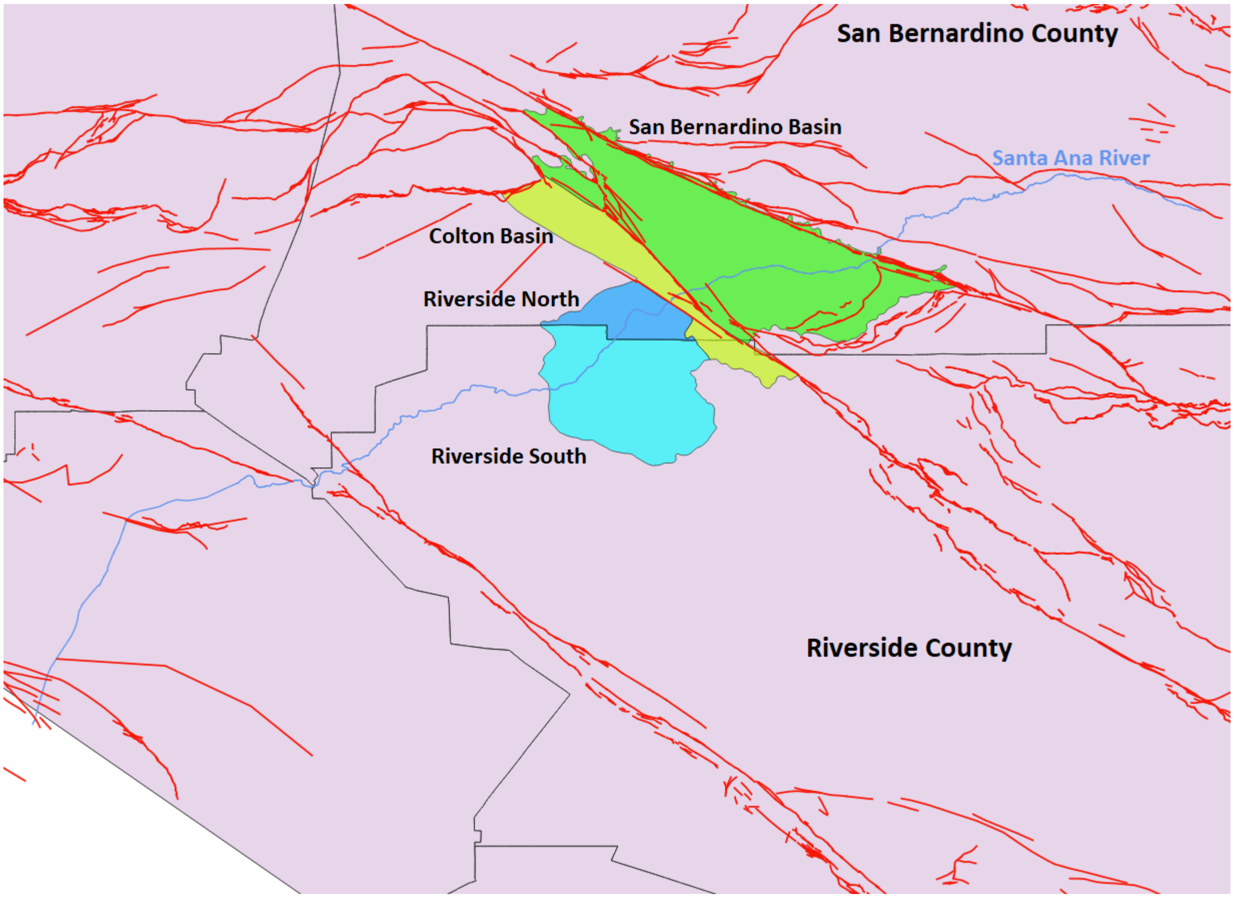

Figure B.2: Basin Boundaries, Fault Lines, and Santa Ana River

Notes: Fault lines are in red. The Santa Ana River is in blue.
Data Sources: U.S. Geological Survey (2021a); U.S. Geological Survey (2021b)

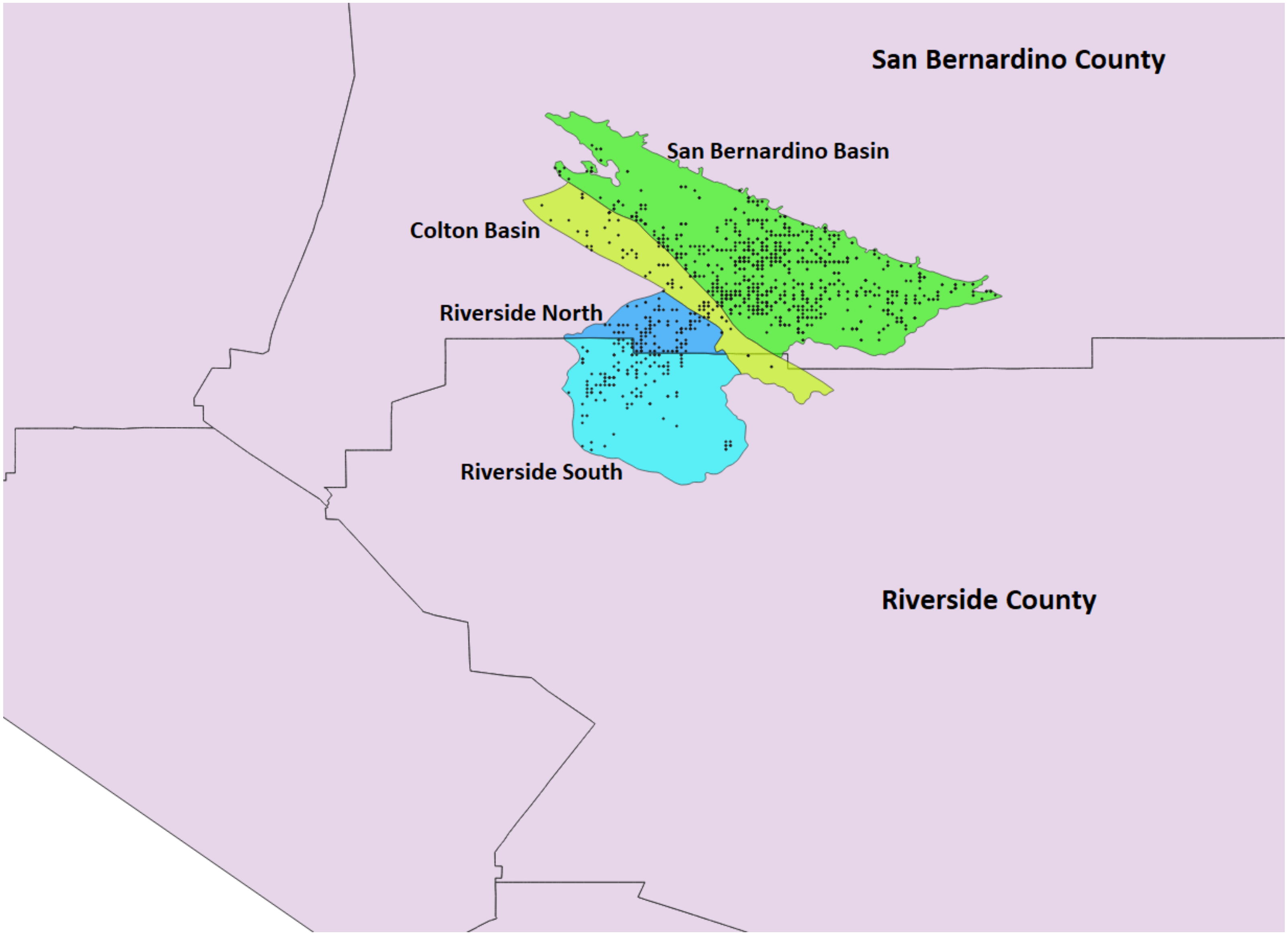

Figure B.3: Western Judgment Monitored Production Wells
Data Source: Western Municipal Water District

Table B.1: Two-sample t-tests comparing share of the spatial externality that is internalized under partial coordination in Western Judgment

Group 1 name	Group 2 name	Difference, Group 1 minus Group 2
Water right		
Municipal water districts	Agricultural producers	-0.0701***
Basin		
San Bernardino	Riverside	0.4012***
San Bernardino	Colton	0.047
Riverside	Colton	-0.3541***
Basin subgroup		
San Bernardino, plaintiffs	San Bernardino, non-plaintiffs	-0.8067***
San Bernardino, plaintiffs	Colton, plaintiffs	-0.1178***
San Bernardino, plaintiffs	Colton, non-plaintiffs	-0.6514***
San Bernardino, plaintiffs	Riverside North, plaintiffs	-0.0011**
San Bernardino, plaintiffs	Riverside North, non-plaintiffs	-0.0459***
San Bernardino, plaintiffs	Riverside South	-0.4707***
San Bernardino, non-plaintiffs	Colton, plaintiffs	0.6889***
San Bernardino, non-plaintiffs	Colton, non-plaintiffs	0.1553***
San Bernardino, non-plaintiffs	Riverside North, plaintiffs	0.8056***
San Bernardino, non-plaintiffs	Riverside North, non-plaintiffs	0.7608***
San Bernardino, non-plaintiffs	Riverside South	0.3359***
Colton, plaintiffs	Colton, non-plaintiffs	-0.5336***
Colton, plaintiffs	Riverside North, plaintiffs	0.1167***
Colton, plaintiffs	Riverside North, non-plaintiffs	0.0719***
Colton, plaintiffs	Riverside South	-0.353***
Colton, non-plaintiffs	Riverside North, plaintiffs	0.6503***
Colton, non-plaintiffs	Riverside North, non-plaintiffs	0.6055***
Colton, non-plaintiffs	Riverside South	0.1806***
Riverside North, plaintiffs	Riverside North, non-plaintiffs	-0.0448***
Riverside North, plaintiffs	Riverside South	-0.4697***
Riverside North, non-plaintiffs	Riverside South	-0.4248***
Regulation type		
Individual limit	Group limit	-0.7117***
Individual limit	Unlimited	-0.2964***
Group limit	Unlimited	0.4152***

Notes: Table reports the share of the spatial externality that is internalized under partial coordination for Group 1 and Group 2, as well as the difference (Group 1 minus Group 2). Significance stars next to the difference between share of marginal social cost that is internalized under partial coordination Group 1 and Group 2 indicate the significance from two-sample t-tests comparing share of marginal social cost that is internalized under partial coordination. Significance codes: * p <0.05, ** p<0.01, *** p< 0.001

Table B.2: Effects of Partial Coordination: Full sample, all years

Dependent variable is groundwater extraction (acre-feet)	(6)	(7)	(8)
Pre-regulation dummy interacted with:			
Depth to groundwater (feet)	-1.563***	-0.996***	-1.283***
	(0.282)	(0.261)	(0.230)
Depth to groundwater (feet) X Share of nearby land in:			
Other Riverside Basin across political boundary	-10.42**	-11.95***	-11.56***
	(3.557)	(2.826)	(2.820)
Other basins across fault boundary	4.958		
	(5.270)		
Other basins across fault boundary and not near river		-1.901*	
		(0.826)	
Other basins across fault boundary but connected by river		-3.844	-3.214
		(3.225)	(3.212)
Post-regulation dummy interacted with:			
Depth to groundwater (feet)	-1.152***	-0.841***	-0.858***
	(0.228)	(0.218)	(0.185)
Depth to groundwater (feet) X Share of nearby land in:			
Other Riverside Basin across political boundary	-11.85***	-13.19***	
	(3.450)	(2.747)	
Other basins across fault boundary	4.191		-13.16***
	(5.004)		(2.740)
Other basins across fault boundary and not near river		-0.0379	
		(0.769)	
Other basins across fault boundary but connected by river		-9.589**	-9.562**
		(3.002)	(2.992)
Constant	535.7***	474.0***	476.6***
	(54.83)	(44.82)	(44.27)
Well fixed effects	YES	YES	YES
Basin-year effects	YES	YES	YES
p-value (Pr>F) from test that coefficients pre- and post-regulation are equal on:			
Depth to groundwater (feet)	0.0405*	0.386	0.0107**
Depth to groundwater (feet) X Share of nearby land across:			
Political boundary	0.357	0.313	0.355
Fault boundary	0.788		
Fault boundary and not near river		0.00005***	0.0134*
Fault boundary but connected by river		0.0253*	0.189
p-value (Pr>F)	0.0000	0.0000	0.0000
# Observations	23,161	22,724	22,724
# Wells	1,071	1,043	1,043

Notes: Specifications use all observations from all wells in our data for all years over the entire 1960-2016 time period of our data set, and therefore includes observations both before and after the 1969 Western Judgment. Regressions are estimated at the well-year level. Each estimation includes well fixed effects, as well as administrative basin-year dummy variables. Nearby represents all land within 1 mile of the well's location. In Specification (8), we treat area in other basins that is not hydrologically connected as area outside the model, and therefore exclude it from the 1 mile radius circle's area in both the numerator and denominator of our area share variables. Standard errors in parentheses. We obtain the same point estimates, the same significance levels, and similar standard errors when we estimate the regressions using a Huber/White/sandwich estimator of the variance for the standard errors. Significance codes: *** p<0.001, ** p<0.01, * p<0.05.

Table B.3: Angrist-Pischke First-Stage F-statistics

Angrist-Pischke First-Stage F-statistics	Plaintiff groups	Regulation groups	Basin sub-groups
Pre-regulation			
Own extraction in basin (acre-feet)	468	399	406
Other user extraction in basin (acre-feet)	121	78	78
Own extraction outside basin (acre-feet)	16,661	15,041	15,320
Own extraction in basin (acre-feet) x share of basin in group	800	682	713
Other user extraction in basin (acre-feet) x share of basin in group	1,032	1,133	1,189
Own extraction outside basin (acre-feet) x share of basin in group	15,878	16,766	15,841
Post-regulation			
Own extraction in basin (acre-feet)	453	400	397
Other user extraction in basin (acre-feet)	1,291	1,238	1,247
Own extraction outside basin (acre-feet)	154	189	170
Own extraction in basin (acre-feet) x share of basin in group	1,515	1,506	1,467
Other user extraction in basin (acre-feet) x share of basin in group	3,751	3,654	3,522
Own extraction outside basin (acre-feet) x share of basin in group	318	348	292

Table B.4: IV Fixed Effects Spatial Regression Results: Regulation groups

Dependent variable is groundwater extraction (acre-feet)	(1)	(2)
Pre-regulation dummy interacted with:		
Own extraction in basin (acre-feet)	0.000974**	0.000881**
	(0.000331)	(0.000322)
Other user extraction in basin (acre-feet)	-0.00348	-0.00476*
	(0.00210)	(0.00205)
Own extraction outside basin (acre-feet)	-0.0171	-0.0148
	(0.0111)	(0.0108)
Own extraction in basin (acre-feet) x share of basin in group	-0.0015	-0.0009
	(0.0008)	(0.0008)
Other user extraction in basin (acre-feet) x share of basin in group	0.00366	0.00575*
	(0.00251)	(0.00244)
Own extraction outside basin (acre-feet) x share of basin in group	0.0361	0.0293
	(0.0232)	(0.0228)
Individual quantity regulation	148.1***	348.1***
	(34.66)	(53.36)
Group quantity regulation	-87.80***	137.2**
	(26.35)	(50.48)
Unregulated	61.08***	242.0***
	(13.25)	(45.66)
Post-regulation dummy interacted with:		
Own extraction in basin (acre-feet)	-0.000673*	-0.000618*
	(0.000324)	(0.000314)
Other user extraction in basin (acre-feet)	-0.00611***	-0.00546***
	(0.000631)	(0.000595)
Own extraction outside basin (acre-feet)	-1.067***	-0.628*
	(0.319)	(0.310)
Own extraction in basin (acre-feet) x share of basin in group	0.0001	0.0008
	(0.0006)	(0.0006)
Other user extraction in basin (acre-feet) x share of basin in group	0.00636***	0.00638***
	(0.000816)	(0.000773)
Own extraction outside basin (acre-feet) x share of basin in group	1.075*	0.557
	(0.489)	(0.477)
Group quantity regulation	-162.0***	-121.3***
	(24.66)	(24.52)
Total direct SWP deliveries to customers in basin	-0.00194***	0.000643
	(0.000287)	(0.000419)
Total SWP water used to recharge basin	-0.00342***	-0.00189***
	(0.000349)	(0.000566)
Precipitation, inches	-2.345***	0.366
	(0.669)	(8.436)
Well fixed effects	YES	YES
Year effects	NO	YES
p-value (Pr>F)	0.000	0.000
# Observations	48,319	48,319
# Wells	1,229	1,229

Notes: Robust standard errors in parentheses. We instrument for groundwater extraction at a neighboring well with the average annual extraction limit imposed by the regulation on that well. Significance codes: *** p<0.001, ** p<0.01, * p<0.05.

Table B.5: IV Fixed Effects Spatial Regression Results: Basin sub-groups

Dependent variable is groundwater extraction (acre-feet)	(1)	(2)
Pre-regulation dummy interacted with:		
Own extraction in basin (acre-feet)	0.000862**	0.000773*
	(0.000332)	(0.000322)
Other user extraction in basin (acre-feet)	-0.00335	-0.00467*
	(0.00211)	(0.00206)
Own extraction outside basin (acre-feet)	-0.0325*	-0.0318**
	(0.0130)	(0.0123)
Own extraction in basin (acre-feet) x share of basin in group	-0.0014	-0.0009
	(0.0008)	(0.0008)
Other user extraction in basin (acre-feet) x share of basin in group	0.00364	0.00576*
	(0.00252)	(0.00245)
Own extraction outside basin (acre-feet) x share of basin in group	0.0500*	0.0458
	(0.0244)	(0.0237)
Colton Basin, non-plaintiff	82.38***	261.9***
	(19.84)	(48.33)
Colton Basin, plaintiff	263.0**	440.9***
	(88.01)	(96.85)
Riverside North, non-plaintiff	211.2***	353.6***
	(28.76)	(51.98)
Riverside North, plaintiff	225.4***	416.8***
	(28.04)	(51.00)
Riverside South	83.35***	262.5***
	(14.55)	(46.21)
San Bernardino Basin, non-plaintiff	54.81***	240.3***
	(11.34)	(44.34)
San Bernardino Basin, plaintiff	152.6***	352.9***
	(34.71)	(53.45)
Post-regulation dummy interacted with:		
Own extraction in basin (acre-feet)	-0.000680*	-0.000622*
	(0.000324)	(0.000314)
Other user extraction in basin (acre-feet)	-0.00612***	-0.00547***
	(0.000630)	(0.000595)
Own extraction outside basin (acre-feet)	-0.553	-0.125
	(0.298)	(0.298)
Own extraction in basin (acre-feet) x share of basin in group	0.0001	0.0007
	(0.0006)	(0.0006)
Other user extraction in basin (acre-feet) x share of basin in group	0.00634***	0.00635***
	(0.000816)	(0.000773)
Own extraction outside basin (acre-feet) x share of basin in group	0.477	-0.0305
	(0.460)	(0.459)
Riverside North, non-plaintiff	163.9***	121.9***
	(24.74)	(24.61)
Total direct SWP deliveries to customers in basin	-0.00197***	0.000548
	(0.000287)	(0.000420)
Total SWP water used to recharge basin	-0.00356***	-0.00233***
	(0.000353)	(0.000580)
Precipitation, inches	-2.370***	-1.109
	(0.669)	(8.441)
Well fixed effects	YES	YES
Year effects	NO	YES
p-value (Pr>F)	0.000	0.000
# Observations	48,319	48,319
# Wells	1,229	1,229

Notes: Robust standard errors in parentheses. We instrument for groundwater extraction at a neighboring well with the average annual extraction limit imposed by the regulation on that well. Significance codes: *** p<0.001, ** p<0.01, * p<0.05.

Table B.6: IV Fixed Effects Spatial Regression Results: Regulation groups, marginal revenue

Dependent variable is groundwater extraction (acre-feet)	(1)	(2)
Pre-regulation dummy interacted with:		
Other share of land prime farmland x value of farmland per acre	2.22	5.21
Other share of land farmland of statewide importance x value of farmland per acre	17.81*	20.38*
Other share of land farmland of local importance x value of farmland per acre	5.288*	-0.42
Other share of land unique farmland x value of farmland per acre	31.60*	36.17
Other share of land grazing x value of farmland per acre	2.69	0.50
Other share of land urban x value of farmland per acre	4.627*	6.51
Own precipitation (inches)	16.53*	19.18*
Other precipitation (inches)	-17.50*	135.30
Own depth to groundwater (feet)	-0.503***	-0.652***
Other depth to groundwater (feet)	2.44	12.63
Post-regulation dummy interacted with:		
Other share of land prime farmland x value of farmland per acre	-1.436***	-3.965**
Other share of land farmland of statewide importance x value of farmland per acre	7.306**	-20.04
Other share of land farmland of local importance x value of farmland per acre	-2.176***	4.25
Other share of land unique farmland x value of farmland per acre	-1.08	24.55*
Other share of land grazing x value of farmland per acre	-1.066***	-0.29
Other share of land urban x value of farmland per acre	0.02	-0.24
Other share of land surface water x value of farmland per acre	-17.12	57.12
Own precipitation (inches)	7.407*	7.81
Other precipitation (inches)	-4.92	16.99
Own depth to groundwater (feet)	-0.435***	-0.623***
Other depth to groundwater (feet)	-1.237***	-0.96
Pre- and post-regulation interactions in Table B.4	YES	YES
Own land use share x value of farmland per acre pre- and post-regulation	YES	YES
Well fixed effects	YES	YES
Year effects	NO	YES
p-value (Pr>chi2) from test that coefficients pre- and post-regulation are equal on:		
Other share of land prime farmland x value of farmland per acre	0.043*	0.057
Other share of land farmland of statewide importance x value of farmland per acre	0.214	0.023*
Other share of land farmland of local importance x value of farmland per acre	0.003**	0.433
Other share of land unique farmland x value of farmland per acre	0.016*	0.602
p-value (Pr>F)	0.00	0.00
# Observations	47,250	47,250
# Wells	1,196	1,196

Notes: Regressions include all the regressors involving pre- and post-regulation interactions in the respective regressions in Table B.4, the additional controls reported in this Table, as well as own land use share interacted with value of farmland per acre both pre- and post-regulation. We instrument for groundwater extraction at a neighboring well with the average annual extraction limit imposed by the regulation on that well. Significance codes based on robust standard errors: *** p<0.001, ** p<0.01, * p<0.05.

Table B.7: IV Fixed Effects Spatial Regression Results: Plaintiff groups, marginal revenue

Dependent variable is groundwater extraction (acre-feet)	(1)	(2)
Pre-regulation dummy interacted with:		
Other share of land prime farmland x value of farmland per acre	2.893	5.544
Other share of land farmland of statewide importance x value of farmland per acre	16.43*	20.66*
Other share of land farmland of local importance x value of farmland per acre	5.794*	0.582
Other share of land unique farmland x value of farmland per acre	29.13*	36.28
Other share of land grazing x value of farmland per acre	2.987	1.533
Other share of land urban x value of farmland per acre	5.176**	6.951
Own precipitation (inches)	20.77*	21.54*
Other precipitation (inches)	-21.16**	81.99
Own depth to groundwater (feet)	-0.463***	-0.650***
Other depth to groundwater (feet)	2.552	6.293
Post-regulation dummy interacted with:		
Other share of land prime farmland x value of farmland per acre	-1.458***	-3.968**
Other share of land farmland of statewide importance x value of farmland per acre	7.306**	-20.19
Other share of land farmland of local importance x value of farmland per acre	-2.165***	3.948
Other share of land unique farmland x value of farmland per acre	-0.870	24.83*
Other share of land grazing x value of farmland per acre	-1.064***	-0.328
Other share of land urban x value of farmland per acre	0.0207	-0.280
Other share of land surface water x value of farmland per acre	-16.35	69.27
Own precipitation (inches)	7.263*	7.741
Other precipitation (inches)	-4.753	21.32
Own depth to groundwater (feet)	-0.468***	-0.647***
Other depth to groundwater (feet)	-1.202***	-0.612
Pre- and post-regulation interactions in Table 5	YES	YES
Own land use share x value of farmland per acre pre- and post-regulation	YES	YES
Well fixed effects	YES	YES
Year effects	NO	YES
p-value (Pr>chi2) from test that coefficients pre- and post-regulation are equal on:		
Other share of land prime farmland x value of farmland per acre	0.015*	0.049*
Other share of land farmland of statewide importance x value of farmland per acre	0.277	0.021*
Other share of land farmland of local importance x value of farmland per acre	0.001**	0.572
Other share of land unique farmland x value of farmland per acre	0.026*	0.608
p-value (Pr>F)	0.000	0.000
# Observations	47,250	47,250
# Wells	1,196	1,196

Notes: Regressions include all the regressors involving pre- and post-regulation interactions in the respective regressions in Table 5, the additional controls reported in this Table, as well as own land use share interacted with value of farmland per acre both pre- and post-regulation. We instrument for groundwater extraction at a neighboring well with the average annual extraction limit imposed by the regulation on that well. Significance codes based on robust standard errors: *** p<0.001, ** p<0.01, * p<0.05.

Table B.8: IV Fixed Effects Spatial Regression Results: Basin sub-groups, marginal revenue

Dependent variable is groundwater extraction (acre-feet)	(1)	(2)
Pre-regulation dummy interacted with:		
Other share of land prime farmland x value of farmland per acre	2.637	5.820
Other share of land farmland of statewide importance x value of farmland per acre	16.53*	21.62*
Other share of land farmland of local importance x value of farmland per acre	5.711*	1.466
Other share of land unique farmland x value of farmland per acre	28.81*	35.39
Other share of land grazing x value of farmland per acre	2.797	1.784
Other share of land urban x value of farmland per acre	4.929*	7.237
Own precipitation (inches)	21.74*	22.09*
Other precipitation (inches)	-22.18*	97.25
Own depth to groundwater (feet)	-0.499***	-0.679***
Other depth to groundwater (feet)	2.529	8.174
Post-regulation dummy interacted with:		
Other share of land prime farmland x value of farmland per acre	-1.461***	-3.900**
Other share of land farmland of statewide importance x value of farmland per acre	7.282**	-20.51
Other share of land farmland of local importance x value of farmland per acre	-2.181***	3.915
Other share of land unique farmland x value of farmland per acre	-0.829	24.86*
Other share of land grazing x value of farmland per acre	-1.067***	-0.349
Other share of land urban x value of farmland per acre	0.0203	-0.289
Other share of land surface water x value of farmland per acre	-16.26	71.60
Own precipitation (inches)	7.229*	7.714
Other precipitation (inches)	-4.713	21.96
Own depth to groundwater (feet)	-0.470***	-0.654***
Other depth to groundwater (feet)	-1.198***	-1.137
Pre- and post-regulation interactions in Table B.5	YES	YES
Own land use share x value of farmland per acre pre- and post-regulation	YES	YES
Well fixed effects	YES	YES
Year effects	NO	YES
p-value (Pr>chi2) from test that coefficients pre- and post-regulation are equal on:		
Other share of land prime farmland x value of farmland per acre	0.022*	0.043
Other share of land farmland of statewide importance x value of farmland per acre	0.270	0.018*
Other share of land farmland of local importance x value of farmland per acre	0.002**	0.680
Other share of land unique farmland x value of farmland per acre	0.028*	0.635
p-value (Pr>F)	0.000	0.000
# Observations	47,250	47,250
# Wells	1,196	1,196

Notes: Regressions include all the regressors involving pre- and post-regulation interactions in the respective regressions in Table B.5, the additional controls reported in this Table, as well as own land use share interacted with value of farmland per acre both pre- and post-regulation. We instrument for groundwater extraction at a neighboring well with the average annual extraction limit imposed by the regulation on that well. Significance codes based on robust standard errors: *** p<0.001, ** p<0.01, * p<0.05.

Table B.9: First-Stage F-Statistics: Jurisdictional Boundary Analysis

First-stage F-statistic	(1)	(2)	(3)	(4)	(5)
Pre-regulation					
Extraction at wells within 1 mile (acre-feet):					
Owned by same groundwater user, in the same basin	74.6	46.8	62.0	200.8	117.3
Owned by same groundwater user, in different basin	64.5	42.4	51.5	66.1	50.3
Owned by other groundwater users, in the same basin	143.4	85.4		743.3	416.1
Owned by other groundwater users, in the same basin, same regulation group			93		
Owned by other groundwater users, in the same basin, different regulation group			91.1		
Owned by other groundwater users, in different basin	109.0	90.6	90.0	179.6	114.5
Extraction at wells near political border, within 1 mile (acre-feet):					
Owned by same groundwater user, in the same basin		52.4			49.2
Owned by same groundwater user, in different basin		27.8			28.4
Owned by other groundwater users, in the same basin		135.3			119.6
Owned by other groundwater users, in different basin		103.2			104.1
Post-regulation					
Extraction at wells within 1 mile (acre-feet):					
Owned by same groundwater user, in the same basin	117.6	110.0	96.6	266.6	175.7
Owned by same groundwater user, in different basin	67.5	37.8	65.2	67.2	40.6
Owned by other groundwater users, in the same basin	144.3	88.6	459.2	266.6	
Owned by other groundwater users, in the same basin, same regulation group			84.5		
Owned by other groundwater users, in the same basin, different regulation group			38.5		
Owned by other groundwater users, in different basin	99.4	58.4	84.9	156.5	83.5
Extraction at wells near political border, within 1 mile (acre-feet):					
Owned by same groundwater user, in the same basin		67.2			65.3
Owned by same groundwater user, in different basin		42.6			40.0
Owned by other groundwater users, in the same basin		73.0			74.4
Owned by other groundwater users, in different basin		53.7			53.1
Pre-regulation Group Interaction Dummies	YES	YES	YES	YES	YES
Post-regulation Group Interaction Dummies	YES	YES	YES	YES	YES
Well fixed effects	YES	YES	YES	YES	YES
Basin-year effects	YES	YES	YES	YES	YES
# Observations	5,460	5,460	5,460	23,747	23,747
# Wells	250	250	250	1,067	1,067
Sample	Riverside	Riverside	Riverside	All	All

Note: We instrument for groundwater extraction at a neighboring well with the average annual extraction limit imposed by the regulation on that well.

Table B.10: IV Fixed Effects Spatial Regression Results: Jurisdictional Boundary Analysis

Dependent variable is groundwater extraction (acre-feet)	(1)	(2)	(3)	(4)	(5)
Pre-regulation dummy X extraction (acre-feet) at other wells:					
Within 1 mile:					
Same owner, same basin	0.0195	0.0418	0.0236	-0.00846	-0.0121
Same owner, different basin	0.240***	0.148	0.230***	0.0158	0.219**
Other owner, same basin	0.00934	0.0405		-0.00329	-0.00180
Other owner, same basin, same regulation group			-0.000509		
Other owner, same basin, different regulation group			0.0245		
Other owner, different basin	-0.0279	0.0172	-0.0213	0.0425	0.0233
Near political border, within 1 mile:					
Same owner, same basin		-0.101			-0.0607
Same owner, different basin		0.0942			0.00989
Other owner, same basin		-0.136**			-0.110**
Other owner, different basin		-0.0923			-0.106
Post-regulation dummy X extraction (acre-feet) at other wells:					
Within 1 mile:					
Same owner, same basin	0.0692***	0.113**	0.0687***	-0.0273***	-0.0320***
Same owner, different basin	0.128**	0.237	0.0131**	0.0385	0.192*
Other owner, same basin	-0.0174	0.0359		-0.0184**	-0.0160*
Other owner, same basin, same regulation group			-0.0251		
Other owner, same basin, different regulation group			0.000159		
Other owner, different basin	0.00447	0.0159	0.00768	0.0398	0.0452
Near political border, within 1 mile:					
Same owner, same basin		-0.0678			0.0598*
Same owner, different basin		-0.174			-0.144
Other owner, same basin		-0.131**			-0.102**
Other owner, different basin		-0.0737			-0.126
Pre-regulation Group Interaction Dummies	YES	YES	YES	YES	YES
Post-regulation Group Interaction Dummies	YES	YES	YES	YES	YES
Well fixed effects	YES	YES	YES	YES	YES
Basin-year effects	YES	YES	YES	YES	YES
p-value (Pr>chi2) from test that coefficients pre- and post-regulation are equal on:					
Extraction at other wells within 1 mile (acre-feet):					
Same owner, same basin	0.08	0.14	0.13	0.00***	0.00***
Same owner, different basin	0.11	0.65	0.20	0.62	0.66
Other owner, same basin	0.03*	0.8		0.00***	0.00***
Other owner, same basin, same regulation group			0.18		
Other owner, same basin, different regulation group			0.03*		
Other owner, different basin	0.02*	0.99	0.06	0.82	0.33
Extraction at other wells near political border, within 1 mile (acre-feet):					
Same owner, same basin		0.55			0.002**
Same owner, different basin		0.18			0.07
Other owner, same basin		0.78			0.52
Other owner, different basin		0.82			0.5
p-value (Pr>F)	0.000	0.000	0.000	0.000	0.000
# Observations	5,460	5,460	5,460	23,747	23,747
# Wells	250	250	250	1,067	1,067
Sample	Riverside	Riverside	Riverside	All	All

Notes: We instrument for groundwater extraction at a neighboring well with the average annual extraction limit imposed by the regulation on that well. Significance codes based on robust standard errors: *** p<0.001, ** p<0.01, * p<0.05.

Table B.11: First-Stage F-Statistics: Jurisdictional Boundary Analysis, Riverside Basin

	Dependent variable is groundwater extraction (acre-feet)							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pre-regulation dummy X extraction (acre-feet) at other wells:								
Within 1 mile:								
Same owner, same basin	81.6	73.2	46.4	41.9	48.5	42.6	91.4	101.3
Same owner, different basin	48.5	36.4	31.4	23.3	16.2	12.2	32.4	36.7
Other owner, same basin	98.5		160.3		97.8		85.5	49.1
Other owner, same basin, same regulation group		80.3		100.1		59.1		
Other owner, same basin, different regulation group		52.9	92.4		56.8			
Other owner, different basin	115.6	94.1	30.5	78.1	114.4	77.1	122.3	189.1
Post-regulation dummy X extraction (acre-feet) at other wells:								
Within 1 mile:								
Same owner, same basin	122.9	101.9	55.8	44.2	22.1	19 122.2	293.2	
Same owner, different basin	54.9	57.8	27.2	30.4	31.2	29.7	124.0	121.7
Other owner, same basin	82.3		100.2		78.4		85.7	43.1
Other owner, same basin, same regulation group		53.9		48.2		56.2		
Other owner, same basin, different regulation group		25.5		39.1		25.3		
Other owner, different basin	77.4	66.2	88.1	75.9	60.5	52.4	123.0	112.2
Pre-regulation Group Interaction Dummies	YES	YES	YES	YES	YES	YES	NO	NO
Post-regulation Group Interaction Dummies	YES	YES	YES	YES	YES	YES	NO	NO
Well fixed effects	YES	YES	YES	YES	YES	YES	YES	YES
Basin-year effects	YES	YES	YES	YES	YES	YES	YES	YES
# Observations	2,216	2,216	2,545	2,545	1,287	1,287	2,915	929
# Wells	95	95	122	122	56	56	128	39
Riverside, Riverside North, or Riverside South	Riverside	Riverside	R. North	R. North	R. North	R. North	R. South	R. South
Border Wells or All Wells	Border	Border	All	All	Border	Border	All	Border

Notes: We instrument for groundwater extraction at a neighboring well with the average annual extraction limit imposed by the regulation on that well. Border wells are wells within 1 mile from the administrative boundary separating Riverside North from Riverside South. Riverside South only includes a single regulation group, so regulation group interaction dummies cannot be included when the sample is from Riverside South only.

Table B.12: IV Fixed Effects Spatial Regression Results: Jurisdictional Boundary Analysis, Riverside Basin

	Dependent variable is groundwater extraction (acre-feet)							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pre-regulation dummy X extraction (acre-feet) at other wells:								
Within 1 mile:								
Same owner, same basin	-0.00518	-0.00245	0.00667	0.0644	-0.330	-0.239	0.0377	0.0427
Same owner, different basin	0.311***	0.307***	0.290*	0.221	-1.260	-1.536	0.262***	0.378***
Other owner, same basin	-0.0581*		0.00132		-0.152*		0.0692*	-0.147
Other owner, same basin, same regulation group		-0.123**		-0.0270		-0.461		
Other owner, same basin, different regulation group		-0.0356		0.0126		-0.204		
Other owner, different basin	-0.105*	-0.0909	0.0666	0.127*	0.0249	-0.0140	-0.183*	-0.0095
Post-regulation dummy X extraction (acre-feet) at other wells:								
Within 1 mile:								
Same owner, same basin	0.102***	0.103***	0.0508	0.0439	-0.849***	-0.588*	0.0809***	0.148***
Same owner, different basin	0.121	0.130*	0.127	0.165	-0.175	-0.0931	0.167*	0.250**
Other owner, same basin	-0.0186		-0.0525*		-0.0838**		0.0480*	0.0186
Other owner, same basin, same regulation group		-0.0661**		-0.0935*		-0.278***		
Other owner, same basin, different regulation group		0.0274		-0.00968		-0.0432		
Other owner, different basin	-0.0507	-0.0498	0.0832	0.104*	0.0103	-0.0330	-0.156	-0.0590
Pre-regulation Group Interaction Dummies	YES	YES	YES	YES	YES	YES	NO	NO
Post-regulation Group Interaction Dummies	YES	YES	YES	YES	YES	YES	NO	NO
Well fixed effects	YES	YES	YES	YES	YES	YES	YES	YES
Basin-year effects	YES	YES	YES	YES	YES	YES	YES	YES
p-value (Pr > chi2) from test that coefficients pre- and post-regulation are equal on:								
Extraction at other wells within 1 mile (acre-feet):								
Same owner, same basin	0.009**	0.015*	0.545	0.855	0.009**	0.015*	0.236	0.323
Same owner, different basin	0.005**	0.012*	0.368	0.884	0.005**	0.012*	0.233	0.132
Other owner, same basin	0.014*		0.012*		0.014*		0.344	0.399
Other owner, same basin, same regulation group		0.094		0.340		0.094		
Other owner, same basin, different regulation group		0.002**		0.158		0.002**		
Other owner, different basin	0.015*	0.095	0.397	0.383	0.015*	0.095	0.334	0.692
p-value (Pr>F)	0.000	0.0000	0.0000	0.0000	0.0116	0.4020	0.0000	0.0000
# Observations	2,216	2,216	2,545	2,545	1,287	1,287	2,915	929
# Wells	95	95	122	122	56	56	128	39
Riverside, Riverside North, or Riverside South	Riverside	Riverside	R. North	R. North	R. North	R. North	R. South	R. South
Border Wells or All Wells	Border	Border	All	All	Border	Border	All	Border

Notes: We instrument for groundwater extraction at a neighboring well with the average annual extraction limit imposed by the regulation on that well. Border wells are wells that are within 1 mile from the administrative boundary separating Riverside North from Riverside South. Riverside South only includes a single regulation group, so regulation group interaction dummies cannot be included when the sample is from Riverside South only. Significance codes based on robust standard errors: *** $p<0.001$, ** $p<0.01$, * $p<0.05$.

Table B.13: IV Fixed Effects Spatial Regression Results: Jurisdictional Boundary Analysis, Riverside Basin, Regulatory variables

Dependent variable is groundwater extraction (acre-feet)	(1)	(2)	(3)	(4)
Pre-regulation dummy X extraction (acre-feet) at other wells:				
Within 1 mile:				
Same regulatory group, same basin	0.0233	0.195	0.152	-0.257
Same regulatory group, different basin	0.0180		0.225	
Other nearby extraction	0.328	-0.0193	-3.395	-0.154*
Near monitoring site dummy	0.00270	0.00375	-0.00534	0.00553
Pre-regulation dummy X :				
Near monitoring site dummy	-151.4	-114.2	811.4	450.8*
Post-regulation dummy X extraction (acre-feet) at other wells:				
Within 1 mile:				
Same regulatory group, same basin	0.0394**	0.00721	0.0156	-0.0652*
Same regulatory group, different basin	0.00860		0.0419	
Other nearby extraction	0.347	-0.0617	-6.982	-0.0331**
Near monitoring site dummy	0.00393	0.0147	0.0303	0.00497
Post-regulation dummy X :				
Share of group extraction limit used in prior 3 years	1,924		-177.0	
Depth to groundwater (ft) at monitoring site divided by distance (m) to monitoring site		-2,927**		8,033
Pre-regulation Group Interaction Dummies	YES	YES	YES	YES
Post-regulation Group Interaction Dummies	YES	YES	YES	YES
Well fixed effects	YES	YES	YES	YES
Basin-year effects	YES	YES	YES	YES
p-value (Pr > chi2) from test that coefficients pre- and post-regulation are equal on:				
Extraction at other wells within 1 mile (acre-feet):				
Same regulatory group, same basin	0.26	0.001***	0.86	0.12
Same regulatory group, different basin	0.63	-	0.56	-
Other nearby extraction	0.89	0.02*	0.67	0.03*
Near monitoring site dummy	0.96	0.63	0.68	0.96
p-value (Pr>F)	0.00000727	0.00823	0.0113	9.69E-08
# Observations	3,811	1,494	1,330	849
# Wells	185	61	60	35
Regulation	Group Quantity	Stock Monitoring	Group Quantity	Stock Monitoring
Basin	Riverside	Riverside	Riverside	Riverside
Border Wells or All Wells	All Wells	All Wells	Border	Border

Notes: We instrument for groundwater extraction at a neighboring well with the average annual extraction limit imposed by the regulation on that well. For pre-regulation wells that were eventually regulated using monitored depth to groundwater at monitoring sites, we use counts of wells under the regulation at time t as an instrument in place of monitored depth. Border wells are wells that are within 1 mile from the administrative boundary separating Riverside North from Riverside South. Riverside South only includes a single regulation group, so regulation group interaction dummies cannot be included when the sample is from Riverside South only. Significance codes based on robust standard errors: *** $p<0.001$, ** $p<0.01$, * $p<0.05$.