The Economic Value of Secure Water: Landowner Returns to Defining Groundwater Property Rights

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Abstract:

Groundwater is a prime example of a common-pool resource subject to over-extraction and rent dissipation under open access. To avoid this, users can assign groundwater rights: a cap is set on the volume of groundwater that can be pumped annually, and rights are allocated among users. Although this process restricts pumping, it also improves long-term resource availability, grants a fungible asset that can be traded, and reduces uncertainty for urban developers. We investigate the effect on land values by exploiting a plausibly exogenous discontinuity in the definition of rights in the Mojave groundwater basin in California. Because both the long-term stream of agricultural rents and the value of tradable permits are capitalized into land value, spatial regression discontinuity designs identify the difference between the value of interior parcels with water rights and those of free riders on the exterior, who can drain from the regulated area with no restrictions. Results suggest that the value of rights outweighs gains realized by free riders and that property rights increase land value substantially. Nonetheless, we also find evidence that resource characteristics, urban growth, and proximity to free riders affect the magnitude of returns.

JEL Codes: D02, K11, Q25, Q15

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I. Introduction

Common-pool resources are subject to excessive exploitation and rent dissipation in the absence of well-defined economic property rights (Gordon, 1954; Hardin, 1968; Ostrom, 1994). In the absence of transaction costs, fully defined rights allow users to bargain among one another to reach an efficient allocation of resource use (Coase, 1960); the resource is used in its most efficient production processes, and if too many rights have been allocated, they can be purchased and retired. This can improve outcomes in a variety of resource settings, including increasing harvested value from fisheries, reducing pumping costs in groundwater aquifers, and improving forestry yields. Nonetheless, in many cases new institutions are not adopted because some users do not perceive a benefit, which suggests the need for better understanding of when returns are likely to be positive and economically meaningful.

Although the establishment of property rights holds promise for alleviating resource depletion and rent dissipation that result from the tragedy of the commons, few investigations have rigorously documented the economic value of gains from property rights (exceptions are from fisheries: see, for example, Grafton et al., 2000). Water is a critical resource for humanity, and groundwater in particular regularly suffers from poor institutions and is mispriced. Our work helps to further understanding of the impact of tradable property rights on the value of natural resources by looking at a complementary input (land) to assess the impact of property rights to groundwater. Where water is a critical input for agricultural production and urban development, do land prices change when property rights are assigned to users of a common pool of groundwater?

Identifying the true effect of water institutions on land value is difficult because there are so few examples of their adoption and endogeneity concerns complicate inference in direct cross-sectional comparisons. In California, some groundwater basins have been adjudicated, meaning that tradable volumetric pumping rights[3] have been established and allocated to individual users. We look to the Mojave Basin in southern California, which completed adjudication proceedings in 1996 and where groundwater represents a major constraint on agricultural and development activity. Our empirical approach exploits plausibly exogenous variation in the boundary of the adjudicated area—and thus the extent of the adjudication rules—to identify part of the effect of groundwater adjudication on land values.

Theory suggests two pathways for groundwater adjudication to affect land values: First, the definition of tradable property rights results in a wealth effect for users holding rights, and the present discounted value of future agricultural rents increases because the water table stabilizes. Second, free riders along the fringe can drain groundwater from within the regulated area and thereby enjoy an agricultural rent premium. Because we compare parcels overlying the aquifer across the adjudication boundary, we identify the difference between these two effects.

The spatial regression discontinuity we implement subtracts this second effect from the first; whether the outcome is positive or negative is theoretically ambiguous and depends on resource characteristics and the marginal value of water. This coefficient represents a lower bound on the effect of groundwater property rights. Results suggest that the net effect is positive and, in some cases, results in a near doubling of land value within the adjudicated area. Furthermore, evidence suggests a potential role for variable exposure to the risk of drainage by free riders: the effect of adjudication increases for parcels farther from the boundary, although this result is poorly identified. Finally, heterogeneous treatment effects across adjudicated

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[3] These rights are defined as a share of a "safe yield" cap that can be pumped from the basin in each year and are measured in acre-feet/year. Depending on the adjudication, the total safe yield may vary interannually, but it is generally set at the amount of pumping that will stabilize water levels in the long term.

subareas, between which trades are prohibited, suggest a role for resource commonality and urban demand in determining the magnitude of economic gains.

This work contributes to the literature on common-pool resource management by documenting a portion of the returns to collective action to restrict open-access extraction rates. These estimates are the first to address the returns to groundwater property rights, and moreover the first to use parcel-level data to examine the returns to groundwater management more broadly. Aside from demonstrating that expected returns can be economically meaningful when groundwater is a constraining factor for agriculture and development, these results illustrate how gains for cooperators depend on resource characteristics and demand growth, providing guidance for where agreement on institutions should be easy to reach.

Furthermore, our work has implications for California's Sustainable Groundwater Management Act (2014). This legislation requires basin users to ensure sustainable use of groundwater resources; for many basins, this will require adjudication, which is a costly process (Ayres et al., 2017). Oftentimes, complications that inhibit agreement on management arise from uncertainty about how reduced groundwater withdrawals will affect future agricultural production and land value. As the first estimate of the effect of groundwater adjudication on agricultural land values, this research can help reduce uncertainty about the expected returns to landowners and promote more sustainable groundwater management through markets.

II. Background

A. Motivation

Sound management of common-pool resources, such as shared timber stocks, fisheries, and groundwater aquifers, is critical for economic development and the welfare of resource-dependent populations. Where property rights are poorly defined, and especially under open-access conditions, incentives for efficient resource use and investment are threatened because any resource value not extracted can be captured by other users. This results in a race to extract and rent dissipation; however, institutions that better define economic property rights can address the problem (Gordon, 1954; Hardin, 1968; Ostrom, 1994). The definition of legal property is one avenue to resolve the problem because it allows users to restrict aggregate use and reallocate it through trading (Coase, 1960). Users themselves often initiate the formation of rights. In defining property rights, users attempt to increase the value of the resource by restricting aggregate extraction, enriching themselves in the process because they remain residual claimants to the resource.

The economic literature has long stressed the importance of residual claimants in the management of natural resources, but empirical estimation of the benefits of adopting legal property rights are few, especially in the case of groundwater. One example comes from fisheries: Grafton et al. (2000) demonstrate that rationalizing the British Columbia halibut fishery led to increased efficiency and greater resource rents, in particular due to the ability to market higher-quality fishery products. This result suggests gains for rights holders and the fishery overall despite restricted resource access; tradable property rights to harvest certain numbers of fish outperformed both open access and a costly regulatory approach. In this paper, we ask a similar question of groundwater.

Groundwater is a critical resource worldwide and supplies approximately 30% of total freshwater to almost half of the world’s population (Giordano, 2009; Aesbach-Hertig and Gleeson, 2012). It is commonly exploited under open access conditions, which often result in excessive pumping. Groundwater is especially important in California, where it regularly supplies more than half of all water consumption in drought years. Basins are depleted during those times, and pumping costs rise in response. Additionally, future water supplies are threatened when this drawdown continues without sufficient recharge in wet years. Rapid extraction also can lead to permanent losses in storage potential as subsurface geologic strata compact, with severe cases in Mexico City, Bangkok, Shanghai, and California's Central Valley (Konikow and Kendy, 2005). Meanwhile, seawater intrusion as a result of excessive pumping harms water quality, rendering it unfit for human consumption and agriculture. Intrusion has been documented in coastal areas from Oman to California (Zekri, 2008; Barlow and Reichard, 2010).

In California, the basic legal doctrine governing groundwater restricts the number of potential groundwater users and requires that groundwater use be "reasonable and beneficial." However, this restriction has been interpreted to include low-value agricultural uses, such as growing alfalfa in the desert. The result is *de facto* open access for landowners. Resource users have several options for restricting groundwater use, which vary in stringency. We focus in this paper on the most stringent and most difficult to implement: groundwater rights adjudication.

Adjudicating groundwater rights places a restriction on pumping, which constrains land owners' productive capacity; however, doing so ensures long-term resource availability for those still able to produce, grants a fungible asset that can be traded, and reduces uncertainty for residential developers. While the restriction may reduce agricultural rents initially, improvements in resource health make future resource access more certain. As expectations about resource access improve, the time horizon of rent generation increases. Previous work suggests resource access is reflected in land prices (Hornbeck and Keskin, 2014; Edwards, 2016).

B. Literature Review

Economists' understanding of groundwater resource management has evolved significantly over the past decades. Gisser and Sanchez (1980) present an early dynamic model of groundwater exploitation in a simple "bathtub" aquifer with homogeneous users. The main theoretical result is that marginal benefits of groundwater pumping should be equated with the sum of marginal extraction costs and the shadow value of leaving water in the aquifer for use in future periods. A sole owner follows this extraction path, while competitive extractors under open-access conditions ignore all or part of the shadow value of water because they are not the residual claimants to any water left in ground. This results in over-extraction under open-access conditions. However, under Gisser and Sanchez's model assumptions, the magnitude of this inefficiency is unlikely to be economically meaningful, leaving little room for groundwater management initiatives – this has been termed the "Gisser-Sanchez Effect" (GSE).

This result does not match reality on the ground. While many open-access groundwater aquifers remain in good health because exploitation is low, many are also overexploited, exhibiting falling water tables, increasing pumping costs, subsidence, seawater intrusion, and other negative effects. Aquifer drawdown may be efficient, especially during drought when surface water supplies are scarce, but these cases suggest that the costs of open access are not trivial. Indeed, agents in California and elsewhere have engaged in collective action to limit withdrawals, suggesting that potential gains exist.

Koundouri (2004) provides a useful overview of the conditions required for the GSE: that the aquifer is arbitrarily large, demand is linear, demand growth is not present, and quality or other externalities do not exist. These conditions do not usually hold. When the aquifer is small, wells are close enough that cross-well interference is an issue, demand growth is present, demand is nonlinear, or collateral impacts of drawdown are severe (such as with seawater intrusion or subsidence), the losses of open access may be large and of significant economic importance (Brozovic et al., 2010; Brill and Burness, 1994; Worthington et al., 1985; Zekri, 2008; Barlow and Reichard, 2010). These costs can be attenuated through adjudication of property rights, as a cap is set on total extractions and users subject to substantial collateral impacts of drawdown can contract with other users to reduce these impacts. Important for our work is that the total value of the resource increases as aggregate pumping is reduced from open-access levels; because water is a critical production input, this has implications for the value of agricultural land (Hornbeck and Keskin, 2014; Edwards, 2016).

This is not the first paper to use a spatial regression discontinuity design (RD) to estimate the effect of institutions on land value. Grout et al. (2011) use a spatial RD to demonstrate that land values are affected by urban development boundaries in Portland, Oregon. More recently, Turner et al. (2014) identify own-lot, spillover, and scarcity effects of land use regulation using sophisticated spatial RD designs that estimate different effects at different distances from the boundary. These studies investigate the effect of institutions on the regulated item itself: land. In contrast, we follow the literature suggesting that institutions that alter the ability to access groundwater have implications for land values and use land prices as an indicator of the value of increased groundwater reliability. Because groundwater levels do not change discontinuously at the border, we do not identify the total effect of adjudication but rather the effect of being in a regulated area (which we describe in the next section). Nonetheless, the fundamental approach and assumptions of our empirical strategy are similar to those in the literature.

III. Conceptual Model

We present a model of how land prices are expected to vary across our discontinuity threshold. Following Cappozza and Helsley (1989, 1990) we assume the land price for any undeveloped parcel capitalizes the present value of expected land rents. This rent is made up of two components: the agricultural rent potential of the land and the value of future rent increases due to urban growth, should the parcel eventually be developed. To these we add the wealth derived from allocated pumping permits. However, because the discontinuity is located quite far from urban areas and development pressure is unlikely to change discontinuously at the boundary, we focus here on the effects of groundwater adjudication on agricultural rent generation and ignore effects on the likelihood of development. Nonetheless, development pressure may still play a role in the market price of groundwater pumping rights.

In our case, groundwater adjudication defines volumetric pumping rights (as shares of a total safe yield) based on historical use, allocates them to groundwater users within the adjudicated area, and allows for a trading market. Groundwater rights are then ramped down until the basin is brought into balance, i.e., long-term groundwater levels are stabilized. Any user overlying the aquifer but outside of the adjudicated area that can drill a well is effectively unrestricted in pumping, as before adjudication.

An extension is made to the groundwater pumping model presented by Edwards (2016). We first illustrate how adjudication results in relatively higher agricultural rents for a free rider outside the adjudicated area and then show that the allocation of free pumping permits to adjudicated groundwater users increases firm value. Finally, we describe what is identified by the spatial regression discontinuity treatment effect. To begin, a groundwater user i maximizes his or her utility at point in time t, $\pi(w_i(t), h_i(t))$, from pumping groundwater subject to an equation of motion describing recharge and the movement of groundwater. Water pumped is represented by $w_i(t)$ and the contemporaneous water table height is $h_i(t)$. The dynamic optimization problem is:

$$\begin{gathered} V_i^0 = \max_{w_i} \int_0^\infty \pi(w_i(t), h_i(t)) e^{-\delta t} \, dt \\ s.t \quad \dot{h} = r - w_i(t) - \theta(h_i(t) - h_{-i}(t)) \end{gathered} \tag{1}$$

Throughout time, net benefits of water use are discounted by a rate δ. Meanwhile, local water table elevation, $h_i(t)$, gains local recharge, r, and loses water extracted by the user as well as the water that flows away from or toward i. $h_{-i}(t)$ represents the average water level of surrounding parcels. If $h_{-i}(t) > h_i(t)$, i is a net recipient of water and inflow increases local water table elevation. We assume a constant local recharge rate, r, because along the adjudication boundary recharge is unlikely to vary. The subterranean flow of water is regulated by $\theta = \frac{k}{d}$, where k represents hydraulic conductivity and d the distance between parcels. The optimal steady-state pumping pathway under open access is determined by the following condition:

$$\frac{\partial \pi}{\partial w_i} = \frac{1}{\delta}\left(\frac{\partial \pi}{\partial h_i} - \frac{\partial \pi_i}{\partial w_i} \cdot \theta\right). \tag{2}$$

The first coefficient is the inverse of the discount rate, making this a perpetuity value. The pumper extracts groundwater until the marginal benefit of doing so equals the discounted cost of lower water tables in the future attenuated by the value of additional water that flows towards (or doesn't flow away from) user i, which is regulated by θ. In cases where overdraft is a concern, $\sum_{i=1}^{n} w_i > n * r$ such that water tables falls in aggregate until increasing pumping costs force all users to reduce pumping such that $\sum_{i=1}^{n} w_i = n * r$ and the basin is in balance.

This may occur when the aquifer storage is depleted.[4] This results in a constant water table at h^* and zero marginal profits because the resource is overutilized.

Now suppose that all users agree to adjudicate and restrict pumping. They define annual pumping rights, A_{it}, and restrict those rights such that in each period $\sum_{i=1}^{n} A_i = n * r$ and water levels stabilize. However, stabilization is achieved at a higher water table level than results under open access, $\bar{h} > h^*$. When this higher water table is maintained, marginal gains of each unit of pumping in equilibrium are higher than under open access, so positive rents accrue to resource users. Although resource users lose out in the short term because less water can be pumped, higher water levels in the long term ensure a stream of profits greater than those realized under open access. For adjudication to enhance welfare, discount rates must be low enough that the long-term benefits outweigh short-term costs. We now illustrate the difference in benefits across the adjudication boundary.

In the case that users overlie the aquifer but are not subject to adjudication restrictions, such as free riders on the fringe of the resource, their rents increase following adjudication more than those of adjudicated parties. To see this, consider that a free rider faces an exogenous neighboring water table height of $\bar{h}$:[5]

$$\begin{aligned} V_i^{FR} &= \max_{w_i(t)} \int_0^\infty \pi(w_i(t), h_i(t)) e^{-\delta t}\, dt \\ s.t \quad \dot{h} &= r - w_i(t) - \theta\big(h_i(t) - \bar{h}_{-i}(t)\big). \end{aligned} \tag{3}$$

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[4] We assume for now that all users are homogeneous so that pumping is reduced for all and no users exit or stop pumping altogether.

[5] We assume for simplicity the free rider does not affect aggregate water levels within the adjudication (i.e., $\frac{\partial h_{-i}}{\partial h_i} = 0$); relaxing this assumption requires the interior users to restrict pumping even more to make up for drainage out of the adjudicated area.

Because $\bar{h} > h^*$, the free rider can drain water more easily from within the adjudicated area compared to under open access conditions, effectively increasing recharge. This increased drainage from neighbors results in a higher rate of profitable steady-state pumping. The free rider does not face a constraint on pumping and can siphon off water left in the ground within the adjudicated area, increasing private net benefits. The excess rents that can be earned by a free rider in steady state are derived from this increased inflow, which scales with $\theta = \frac{k}{d}$. In contrast, the adjudicated users are restricted. Define the number of permits purchased by any user in time t as the amount of pumping in excess of allocated rights, $z_i(t) = w_i(t) - A_i(t)$. An additional restriction must be imposed that some finite amount of basin overdraft, D, is permitted as rights are ramped down (proportionally) to their long-term levels, $\bar{A}_i$, at some time t^{Eq} to bring the basin into balance. We have:

$$V_i^{AD} = \max_{w_i(t)} \int_0^\infty [\pi\big(w_i(t), h_i(t)\big) - \gamma(w_i(t) - A_i(t))]e^{-\delta t}\, dt$$

$$s.t \qquad \dot{h} = r - w_i(t) - \theta(h_i(t) - h_{-i}(t)), \tag{4}$$

$$\int_0^{t^{Eq}} \sum_{i=1}^{n} w_i(t) - r\, dt = D.$$

If balance is imposed immediately, $D = 0$ and $A_i(t) = \bar{A}_i\ \forall\ t$. For users subject to adjudication, pumping can exceed initial allocation for the unit price of a volumetric pumping right, γ. These users exploit groundwater according to the following rule:

$$\frac{\partial \pi}{\partial w_i} = \frac{1}{\delta}\left[\frac{\partial \pi}{\partial h_i} + \theta(\gamma - \frac{\partial \pi}{\partial w_i})\right] + \gamma. \tag{5}$$

The amount of steady-state pumping for an adjudicated user decreases with γ because pumping takes on a new opportunity cost: that of selling permits.[6] If $\gamma > \frac{\partial \pi}{\partial w_i}$, the pumper is better off restricting pumping in order to sell the permit. All held permits in excess of pumping in each period become part of the firm's value function, assuming optimal pumping $w_i^*(t)$:

$$V_i^{AD} = \int_0^\infty [\pi\big(w_i^*(t), h_i(t)\big) + \gamma(A_i(t) - w_i^*(t))]e^{-\delta t}\, dt. \tag{6}$$

Whether adjudicated parcels will be worth more than unadjudicated parcels on the fringe of the resource depends on the relative magnitude of two effects described here. First, a small number of unadjudicated users will be able to generate higher agricultural rents in steady state because they can siphon off water effectively from the adjudicated area, increasing the amount of water that can be pumped at profit. The interior group restricts pumping for its own benefit, but unrestricted free riders benefit more. On the other hand, interior users are granted pumping allowances that are tradable. When the returns to water use elsewhere are sufficiently large, users with adjudicated rights can trade them away at profit (free riders do not have this opportunity). In cases where permit prices grow over time due to increasing demand, such as the expansion of developed urban areas, or a user is granted more permits than needed to satisfy private agricultural demands, this wealth effect can be quite large.

Thus, stipulating to an adjudication decision increases land value relative to free riders when the capitalized present value of groundwater pumping permits exceeds the agricultural rent premium enjoyed by free riders. A spatial regression discontinuity empirical approach based on the adjudication boundary will subtract the average value of untreated parcels at the boundary

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[6] A higher right-hand side implies lower pumping due to the concavity of the profit function with respect to pumping.

from that of treated parcels. The following expression represents the theoretical interpretation of what is identified empirically in the following sections:

$$V_i^{AD} - V_i^{FR} =$$

$$\int_0^\infty \pi^{AD}(w_i^*(t), h_i(t))\, e^{-\delta t} dt - \int_0^\infty \pi^{FR}(w_i'(t), h_i(t)) e^{-\delta t} dt$$
$$+ \int_0^\infty \gamma(A_i(t) - w_i^*(t))\, e^{-\delta t} dt. \tag{7}$$

The first term is the discounted value of agricultural production for an adjudicated user, while the second is that for a free rider, subject to optimal pumping choices, $w_i^*(t)$ and $w_i'(t)$, respectively. The final term represents the discounted value of any pumping rights sold, or purchased in excess of initial endowment. Three main hypotheses result. First, as mentioned above, since the level of steady-state pumping and profits should be higher for free riders, the overall sign of the expression will be positive if the final term dominates the difference between the first two, which is negative. Second, the magnitude of the effect should decrease as the bandwidth is restricted because parcels nearer the border are at greater risk of drainage by free riders. This results because θ is decreasing in distance between pumpers. Finally, where demand for permits grows quickly (such as in areas with growing urban areas) or hydraulic conductivity is low, the effect should be larger. Demand growth causes γ to increase over time, and lower hydraulic conductivity, k, causes θ to decline, allowing interior users to more easily capture the gains from defining property rights.

IV. Data and Empirical Setting

Our study area is the Mojave River Groundwater Basin, located in southern California just north of San Bernardino. Approximately 95% of the water resources in this area originate from the Mojave River; the river experiences surface flow only rarely, during large storm events. Most water for human uses is acquired through pumping groundwater, which is recharged by precipitation and the eventual percolation of river flow. As a result, groundwater is a critical resource for both agriculture and urban development (drinking water). Although over-extraction has led to ground subsidence and drying and cracking of the land surface, restricting pumping mainly returns resource benefits by reducing pumping costs and ensuring long-term access. The study area is detailed in the map on page 15 (Figure 1).

The Mojave River groundwater basin was adjudicated between 1990 and 1996 after a failed earlier attempt to reach agreement in the 1960s. Volumetric pumping rights were defined as a proportion of an aggregate annual pumping yield. Each user's proportion equals his or her proportion of total pumping, on average, in the five years preceding adjudication. This total yield was initially set at historical levels, and the rights are designed to be ramped down until basin balance is achieved (i.e., water tables are stabilized in the long run). Rights are tradable; however, the adjudicated area is split into five primary subareas, and rights can only be traded within the subarea in which they were allocated. These subareas will play a role in our structuring our empirical analysis because differing permit demand across subareas may explain heterogeneous treatment effects.[7]

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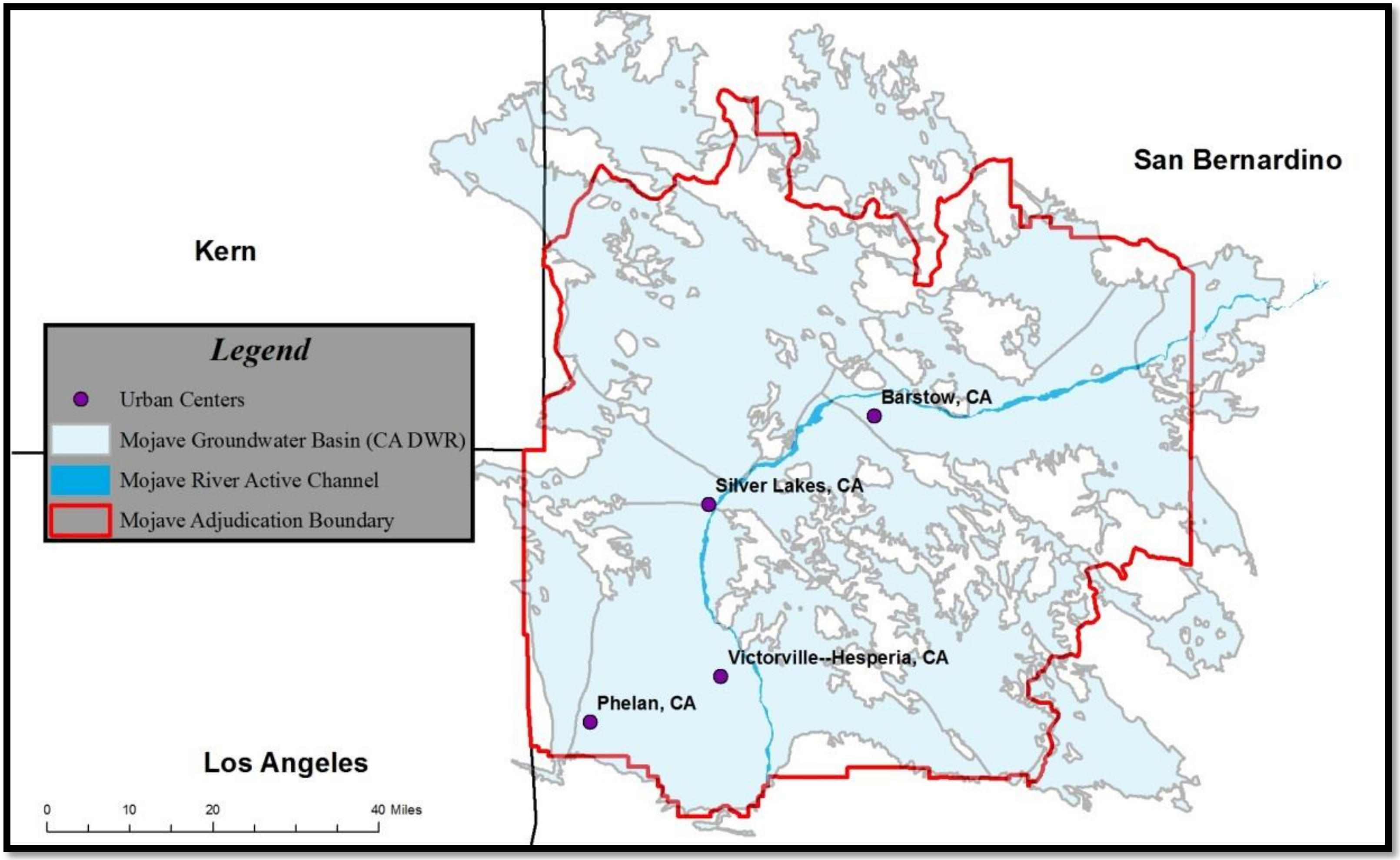
[7] Subarea boundaries were drawn to reflect physical (hydrogeologic) features. Although the entire aquifer is connected, some areas share higher hydraulic conductivity than others and were lumped together into a subarea.

Figure 1: Map of Study Area



Caption: The Mojave River groundwater basin in southern California. The Mojave River flows from mountains in the south through the desert to the northeast. Victorville, Hesperia, and Barstow are the largest and most quickly growing urban areas. We restrict ourselves to sections of the boundary found in San Bernardino County to avoid the confounding influence of boundaries with Kern and Los Angeles counties.

Leasing of groundwater pumping rights is widespread in the Mojave, while sales of permanent rights are rarer. The average lease price is ~$250/acre-foot, while sale prices vary substantially between subareas, from $2,000/acre-foot to $4,000/acre-foot (Donohew, 2005). While the leasing demand is made up of agricultural and urban users, permanent sales often involve agricultural users selling rights in perpetuity to growing urban areas.[8] This is spurred in large part by growing urban demand; for example, between 2000 and 2010 the population of Victorville almost doubled (~64,000 inhabitants vs. ~115,000 inhabitants).[9] Hesperia and Barstow have also grown substantially. Rapid urban growth suggests the wealth effect may be substantial.

We have collected data on assessed land values for agricultural and vacant land parcels in San Bernardino County. Assessed land values are constructed on the basis of local land sales and updated annually to keep pace with inflation and market conditions. The assessor explicitly considers access to groundwater resources, especially for agricultural or vacant land parcels. An important note is that the assessment procedure for land does not explicitly account for adjudication. No additional term is added to the assessor's land value prediction model to account for adjudication, so our estimation does not simply recover a parameter from the assessor's model.[10] Because the assessor's model uses only local comparable sales prices, we estimate differences that result from different parcel sales prices on either side of the boundary. Although a pumping right can be severed from the land, severance does not occur until a permanent transfer is undertaken; before that, the value of adjudicated pumping rights is included in the parcel value. Furthermore, if a water right is transferred to another parcel, the assessor uses the market transaction price to value the water right before including it in the assessed value of

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[8] Personal communication with Tony Winkel, Senior Hydrologist, Mojave Water Agency. 8 February 2017.
[9] U.S. Census figures.
[10] Personal communication with San Bernardino County Assessor and Recorder's Office. 20 July 2017.

the new land parcel.[11] Only if a severed right is sold to a municipal water agency is its value no longer reflected in the land values on the assessor roll. Incidentally, water right value may also be missing from our analysis if a right is severed and transferred to another parcel that is notwithin the buffer we choose for our regression discontinuity. In the global sample, all water rights still on the assessor roll should be included; for the 1-kilometer sample, there is a larger risk. Still, we are not especially concerned with the possibility of missing rights because permanent transfers are relatively rare: the average number of permanent pumping right sales in any year is less than one percent of the total cap, and most such transaction take place in the Alto subarea, which we omit from our analysis (Donohew, 2005).

Assessed land value data reflect market transaction prices, but they are nonetheless imputed and may not accurately reflect market value. Land value assessors update land values at the time of sale but thereafter model market prices using observed local transactions and taking relevant factors into account. Ma and Swinton (2012) investigate the usefulness of assessed land value data for hedonic studies of agricultural land using data from Michigan. In comparing assessed and transaction data, they focus on the contribution of local environmental amenities and find that assessor data does not do a good job of capturing those values in exurbanizing areas; however, their empirical results suggest that assessed values do a very good job of capturing the contribution of agricultural productive potential, which is the focus of our task. We follow other recent work in using assessed land value data as well; for example, Bigelow et al. (2017) find that assessed values in Oregon serve as a good proxy for true land value.

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[11] *Idem.*

Along with value, we also possess measures of parcel area, the base year of appraisal,[12] distance to an urban center, and distance to a local groundwater recharge site operated by the MWA. We calculate the distance to the adjudication boundary as the shortest straight-line distance from a parcel's centroid to the adjudication boundary.

We pare down the sample significantly. First, we remove all urban parcels. Second, we omit parcels in Kern and Los Angeles counties because the adjudication boundary overlies the county line exactly, which would confound inference. In addition, we omit parcels with missing data and those owned by government or government-associated entities. Finally, parcels not in the Centro, Baja, or Este Subareas of the adjudicated area are removed because the remaining areas contain numerous urban parcels, parcels on the urban fringe, and interior parcels with no nearby partner parcels on the exterior. The final sample of 26,617 observations is illustrated in Figure 2 on page 19.

In general, identifying the effect of groundwater adjudication on land value is difficult due to endogeneity concerns. A simple cross-sectional analysis across basins is problematic because treatment is not randomly assigned; basins with higher land values may be more likely to adjudicate to protect resource access, or other unobserved basin characteristics may affect both the likelihood of adjudication and the level of land values (for example, being near a coastline). Because we have parcel-level data on assessed land values, we are able to exploit discontinuity in the boundary of the adjudicated area to achieve identification. However, there are two major considerations.

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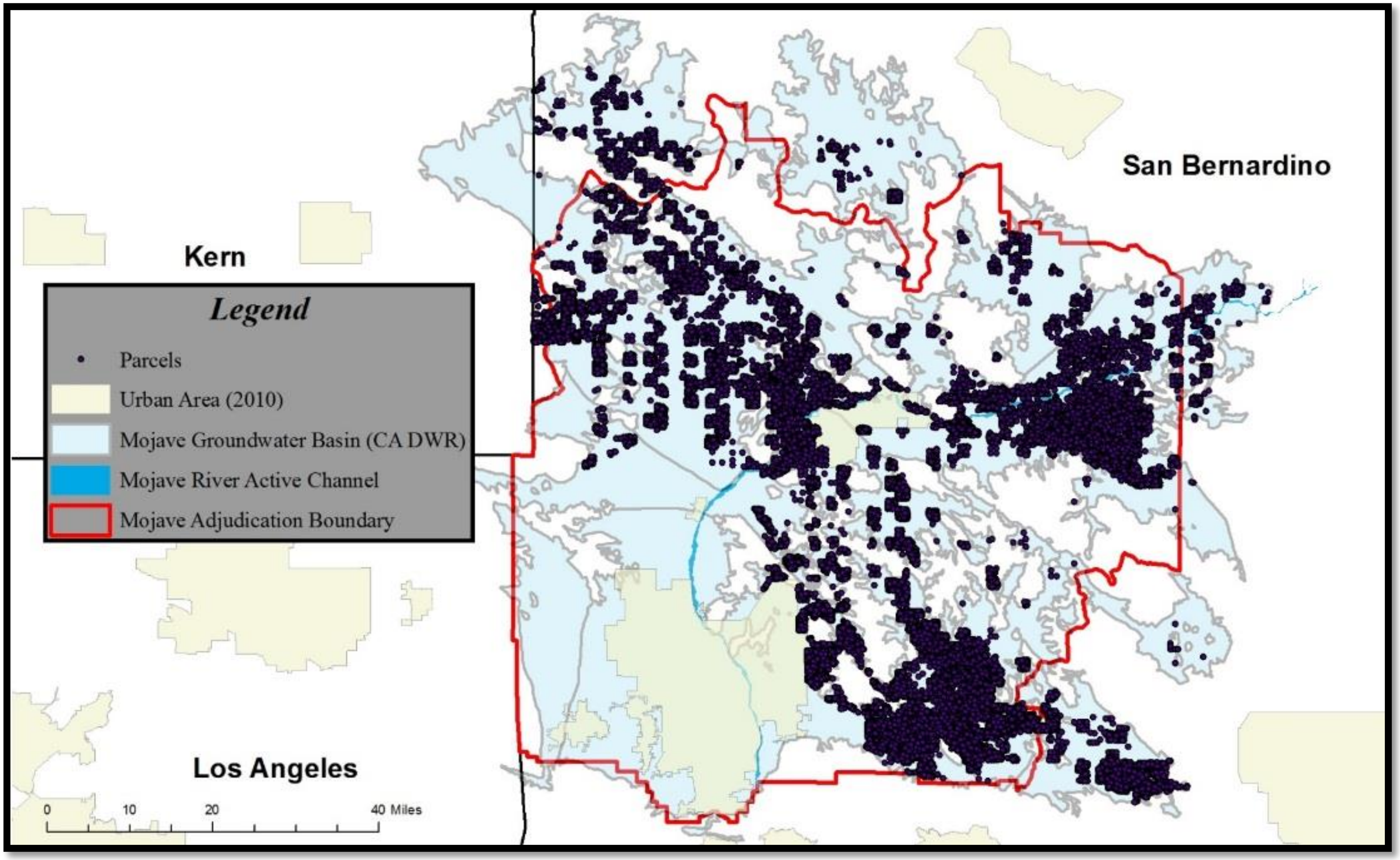
[12] The base year of appraisal or assessment matters because it represents the point in time at which the real value of the property was either observed in a market transaction or estimated on the basis of comparable nearby parcels by the assessor's office (in the event the parcel was not transacted but rather built upon or otherwise substantially altered). While the assessor has some leeway to change a parcel's assessed value aside from adjusting for inflation, California statutes do not allow the assessor to apply a rate of increase greater than 2% annually. Thus, base year of appraisal may be influential in explaining observed land values.

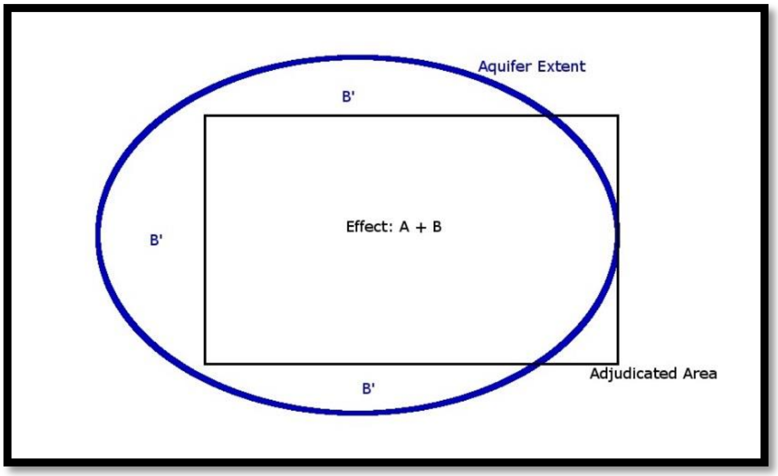
Figure 2: Study Sample



Caption: The sample presented here consists of 26,617 parcels. We remove any parcels located within urban areas as well as any not overlying the aquifer. We also only include parcels in the northwest (Centro), northeast (Baja), and southeast (Este) subareas. Parcel clustering suggests subarea boundaries.

If the boundary of the adjudicated area aligns with the boundary of the aquifer, identification is confounded by the effect of having groundwater access at all; we must find sections of the adjudication boundary that overlie the aquifer, separating unadjudicated (open access) parcels overlying the aquifer from adjudicated parcels overlying the aquifer. Second, because higher groundwater table levels spill over the boundary to unadjudicated parcels, we define two different resource endowment effects. Our identification strategy is summarized in Figure 3.

Figure 3: Identification Mechanics



Caption: Various effects of adjudication on land value.

In this diagram, A represents one effect of being adjudicated: the possession of a guaranteed right to pump groundwater that can be traded. The effects on agricultural productivity, reflected in land value, are denoted with the letter B. Higher water levels created by adjudication are enjoyed by all users, but free riders and cooperators exploit the resource endowment effect differently due to the lack of pumping restrictions outside the boundary. Therefore, B is defined as the effect for adjudicated parcels and $B' > B$ as the effect for parcels outside the boundary. Through our spatial RD we identify the difference in land value between parcels inside and outside the adjudication boundary: $(A + B) - B' = A + (B - B')$. A positive value will be recovered when the present value of allocated permits, A, exceeds the agricultural rent premium enjoyed by free riders, $(B' - B) = -(B - B')$, as described in Section III.

The assumptions required for identification of general regression discontinuity designs are summarized by Lee and Lemieux (2010). The most important in our case is that agents cannot sort themselves across the boundary (i.e., it is exogenous): if they cannot, then treatment randomization is ensured and observational units on either side of the discontinuity should be proper counterfactuals for one another. In this case, the average treatment effect is estimated. One way to assess whether this assumption holds is to test whether relevant covariates develop smoothly across the boundary.[13]

Our discontinuity of interest is the edge of the adjudication boundary. It was set as the intersection of the boundary of the surface water drainage area for the Mojave River and the boundaries of the Mojave Water Agency (MWA), the third-party watermaster appointed to enforce the judgement. Parcels in the analysis lie above the aquifer but are treated based on their location relative to the boundary defined above. Because the MWA was formed several decades prior to adjudication for different reasons, individual parcels could not sort themselves across the boundary at the time of adjudication, so we do not suspect manipulation of treatment status on the part of landowners. In particular, the boundaries of the MWA were drawn to include parcels that would finance State Water Project infrastructure, although the Project was not connected to this area until decades later; concerns over defining groundwater rights played no role in the formation of the boundary.

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[13] In contrast, a typical matching approach would simply test whether covariates are balanced – in this case, we can allow for imbalanced covariate means because so long as the difference at the boundary is smooth identification is not threatened. Another option is the McCrary test, which we report in the Results Appendix, D.

V. Results

We first present results using the entire sample and then present segment-specific estimates to uncover any spatial heterogeneity in the treatment effect. The dependent variable is log land value for each parcel. Our regression specification takes the following form, typical of other spatial RD designs:

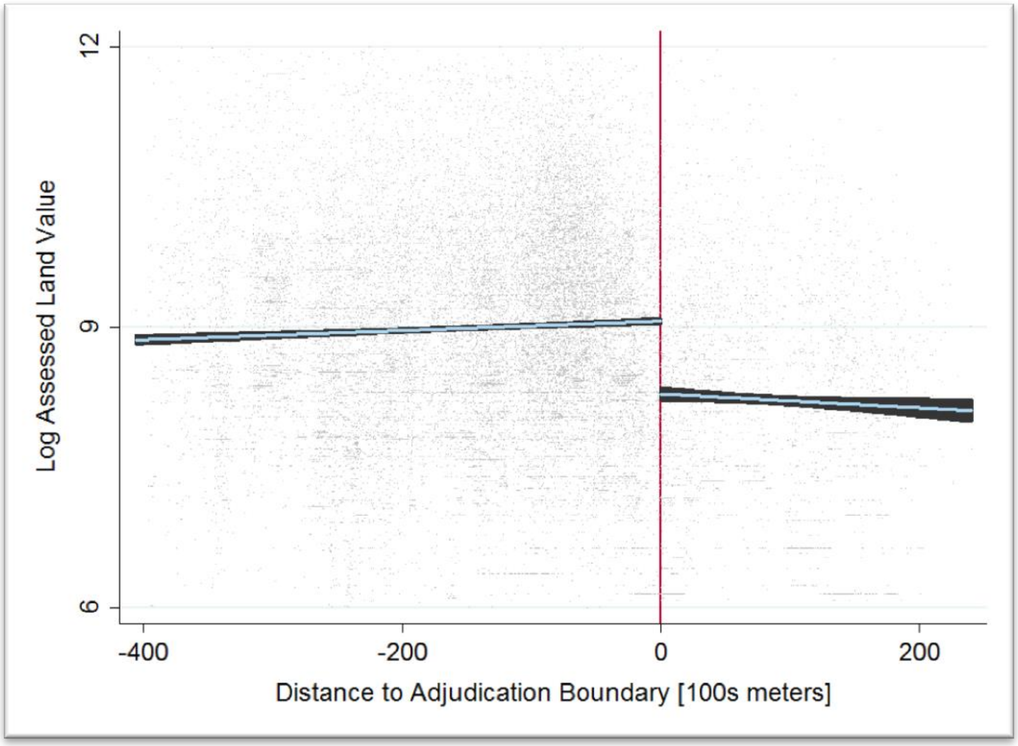
$$Ln(Value_i) = \beta_0 + \beta_1 Distance_i + \beta_2 Distance_i * Adj_i + \beta_3 Adj_i + \beta_4 X_i + \varepsilon_i, \qquad (7)$$

in which the treatment effect of interest is identified by β_3 and we allow land value to vary with the forcing variable, distance to the boundary, differently on either side. Including relevant covariates, X_i, can help to reduce variance in the identification of the treatment effect, control for any changes at the boundary (should they exist), and correct for imbalance across the treated and control samples (Lee and Lemieux, 2010), so we present selected specifications with parcel area, distance to nearest urban center, the base year of assessment, and distance to nearest recharge station. In all specifications, standard errors are corrected for potential heteroscedasticity and spatial autocorrelation using uniform kernels (code from Hsiang, 2010).

First, we illustrate the effect of adjudication semi-parametrically using linear functions in Figure 4. Distance values above zero correspond to parcels outside the adjudicated area. The gap in land values at the boundary is the effect of interest; the slopes of the lines on either side are not well identified and do not necessarily inform about the relationship with respect to distance. Further evidence will be given for this later. Confidence intervals suggest a significant jump across the adjudication boundary, which we test more rigorously using local linear regression, with results in Table 1 on page 24.

We use several different bandwidths in order to regulate the bias-precision tradeoff inherent in spatial RD design: as the bandwidth expands (i.e., more parcels are drawn into the analysis from a farther distance), more observations allow for the effect to be estimated with greater precision, but bias potentially increases as parcels farther away are included. Columns (1) and (2) have no bandwidth restriction, (3) and (4) use only parcels within 5 kilometers of the boundary, and (5) and (6) use 1 kilometer. Alternating columns include control covariates.

Figure 4: Relationship between Distance to Boundary and Log Land Value



Caption: Visual representation of log land value data, with boundary location in red.

The first row of Table 1 reports the treatment coefficient, and it is positive and statistically significant in nearly all cases. Its magnitude attenuates slightly as we shorten the RD bandwidth, but it remains significant and economically meaningful until column (6). Within one kilometer (and even five kilometers), the likelihood of spatially dependent bias is small. That the result is generally robust to bandwidth changes and the inclusion of covariates lends confidence to our interpretation that the adjudication boundary represents a relevant discontinuity.[14]

Table 1: Spatial RD Results – Linear, Assessed Value

	(1) Log LV	(2) Log LV	(3) Log LV	(4) Log LV	(5) Log LV	(6) Log LV
Adjudication Dummy	0.779***	0.772***	0.554**	0.402*	0.523***	0.252
	(0.157)	(0.132)	(0.275)	(0.242)	(0.167)	(0.194)
Boundary Distance	0.000742	-0.000892	-0.0120	-0.00728	0.0185	0.0101
	(0.00137)	(0.00122)	(0.00898)	(0.00697)	(0.0338)	(0.0299)
Distance*Adjudicated	-0.00124	-0.000687	0.0222**	0.0183**	0.0202	0.00882
	(0.00142)	(0.00126)	(0.0106)	(0.00860)	(0.0623)	(0.0507)
Covariate Controls						
Parcel Area		0.0119***		0.0118***		0.00885***
		(0.000574)		(0.00109)		(0.00163)
Base Year		-1.71e-05		-5.70e-05**		-7.69e-05*
		(1.19e-05)		(2.71e-05)		(4.57e-05)
Distance to Urban Center		-0.000125		-0.0000243		0.00219
		(0.000281)		(0.000548)		(0.00184)
Distance to Recharge Station		-0.00112***		-0.000905*		-0.00260**
		(0.000253)		(0.000469)		(0.00129)
Constant	8.286***	8.566***	7.934***	8.323***	8.013***	8.401***
	(0.150)	(0.206)	(0.249)	(0.346)	(0.253)	(0.973)
Observations	26,617	26,617	5,053	5,053	746	746
R-squared	0.0420	0.201	0.0598	0.2218	0.0901	0.2691
Bandwidth	Global	Global	5KM	5KM	1KM	1KM
Covariates	None	Yes	None	Yes	None	Yes

Standard errors in parentheses and corrected for heteroscedasticity and spatial autocorrelation, and significance as follows: *** p<0.01, ** p<0.05, * p<0.1. Bandwidths are global (1-2), 5 kilometers (3-4), and 1 kilometer (5-6).

Meanwhile, parcel area and distance to a recharge site are reliably significant, and the inclusion of covariates attenuates the magnitude and significance of the treatment effect in columns (4) and (6) in Table 1. This suggests that they may not develop smoothly across the boundary, which can be assessed using an identical spatial RD procedure but with these variables

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[14] Quadratic specifications generally support the linear results (see Appendix, A). Following Gelman et al. (2014), we do not include higher-order polynomial results here. In addition, we test whether the results are affected by restrictions on the selection of base appraisal years in Table 7, Appendix, C. They generally are, although a lower number of observations causes coefficient estimates at the 5-kilometer level to be insignificant.

as dependent variables. Results are presented in Table 2 for infinite and 5 kilometer bandwidths. If covariates develop smoothly across the adjudication border, the coefficient on the adjudication dummy should be insignificant in Table 2.

Table 2: Covariate Smoothness Tests

	(1) Parcel Area	(2) Base Year	(3) Urban Dist	(4) Recharge Dist	(5) Parcel Area	(6) Base Year	(7) Urban Dist	(8) Recharge Dist
Adjudication Dummy	-6.040 (3.675)	3.882 (38.16)	-36.97** (18.81)	-66.37*** (15.92)	10.42** (5.009)	-82.65 (67.60)	43.15 (31.57)	-28.16 (21.05)
Boundary Distance	0.0462 (0.0292)	0.0182 (0.318)	0.312** (0.132)	-1.007*** (0.0924)	-0.304 (0.229)	0.201 (1.848)	-1.245 (1.423)	1.276** (0.541)
Distance*Adjudicated	-0.0347 (0.0301)	-0.288 (0.335)	-0.896*** (0.137)	0.229** (0.106)	0.106 (0.254)	1.084 (2.218)	-1.018 (1.562)	-3.003*** (0.824)
Constant	19.05*** (3.552)	1,581*** (32.61)	378.8*** (17.34)	387.0*** (12.89)	8.188** (4.084)	1,588*** (50.83)	337.3*** (25.51)	427.3*** (11.04)
Observations	26,617	26,617	26,617	26,617	5,053	5,053	5,053	5,053
Bandwidth	Global	Global	Global	Global	5KM	5KM	5KM	5KM
Kernel	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform

Standard errors in parentheses and corrected for heteroscedasticity and spatial autocorrelation, and significance as follows: *** p<0.01, ** p<0.05, * p<0.1. Columns (1-4) use an infinite bandwidth, (5-8) a 5-km bandwidth.

The results indicate that in most cases relevant covariates do not differ significantly at the discontinuity (and thus identification is not threatened by their omission). However, the distance measures decrease discontinuously in columns (3) and (4), and parcel area increases significantly in the 5-kilometer sample (column (5)). That these results are not consistent across bandwidths lessens concern about endogenous selection across the boundary. Furthermore, that these particular covariates may vary across the boundary is not problematic if they are included in the regression specification; however, if some relevant covariates seemingly differ across the boundary, there may be concern that other, unobserved characteristics correlated with these variables also differ discontinuously. If these unobserved characteristics relate to land value, identification may be threatened.

To further asses the validity of our finding, a falsification test in space can be performed. To do so, we shrink the adjudicated region’s area to 80% of its original, creating a new discontinuity on the interior of the original. Anchoring the original southwest vertex shifts the adjudication boundary on the northeast, northwest, and southeast sections inward substantially (see Figures 1 and 2 for reference). We then perform the same regression using this arbitrary boundary and find no clear effect, substantiating our interpretation of the identified effect as a result of the true adjudication boundary. Results are in Table 3 below.

Table 3: Spatial RD - False Adjudication Boundary Test

	(1)	(2)	(3)	(4)	(5)	(6)
	Log LV	Log LV	Log LV	Log LV	Log LV	Log LV
False Adjudication Dummy	-0.0200	-0.00709	0.244*	0.187	0.111	0.155
	(0.0923)	(0.0829)	(0.129)	(0.118)	(0.109)	(0.101)
Boundary Distance	0.00248***	0.00205***	-0.0107***	-0.00831**	0.0156	0.0139
	(0.000510)	(0.000467)	(0.00344)	(0.00328)	(0.0185)	(0.0172)
Distance*Adjudicated	-0.0029***	-0.0029***	0.0162***	0.0108**	-0.0103	-0.0203
	(0.000696)	(0.000636)	(0.00480)	(0.00483)	(0.0332)	(0.0306)
Observations	26,617	26,617	10,283	10,283	3,357	3,357
R-squared	0.0204	0.1854	0.0144	0.1607	0.0089	0.1275
Bandwidth	Global	Global	5KM	5KM	1KM	1KM
Covariates	None	Yes	None	Yes	None	Yes

Standard errors in parentheses and corrected for heteroscedasticity and spatial autocorrelation, and significance as follows: *** p<0.01, ** p<0.05, * p<0.1. Bandwidths are global (1-2), 5 kilometers (3-4), and 1 kilometer (5-6).

One additional test of boundary exogeneity is the McCrary test, which involves computing parcel density distributions on either side of the boundary using the observed sample (for more, see McCrary, 2008). A discontinuous jump in density at the boundary suggests that agents are sorting themselves around the boundary, or in our case that the boundary was drawn to exclude certain parcels or parcels were subdivided in response to adjudication. A McCrary test at 1-kilometer bandwidth indicates no spatial sorting or endogeneity (see Appendix, D). Finally, we also address concerns that base appraisal year may affect our results if it varies across the boundary because properties appraised more recently are more likely to have an accurate assessed value. We run our spatial regressions discontinuity specifications using only parcels that have been appraised recently (since 1990 or 2000), and results are in Appendix, C. Although coefficients are no longer significant using a 5-kilometer bandwidth due to a lower number of observations, signs remain positive and the results are generally supportive.

Our theory predicts that the magnitude of the ATE should decrease as parcels become closer to the adjudication boundary. The agricultural potential of any land parcel depends on groundwater access, and groundwater levels are more likely to be affected by free riding from the exterior the closer they are to the boundary, *ceteris paribus*. In other words, only parcels within some distance of the boundary are exposed to drainage from free riders. One way to test this is to implement the regression discontinuity design while dropping a section of observations near the boundary that may be subject to drainage; if the estimated ATE is higher, this further supports the model prediction. We find exactly this, with results in Table 6 in the Appendix, B.

While there may be concern that using a large bandwidth and removing near-boundary parcels invites spatially dependent bias, these estimates control for distance to urban centers, distance to recharge stations, and spatially correlated error structures, so any bias would have to be unrelated to recharge availability and the development potential of land. Although the risk cannot be eliminated, it is minimal and we present this as supporting evidence for our theoretical prediction.

Table 4 below presents results for each of the three major segments of the adjudication boundary to assess whether the effect identified in Table 1 is spatially heterogeneous or being driven by one particular area of the Mojave groundwater basin. These segments correspond to management subareas within the adjudicated area that restrict trading spatially (a right cannot be traded outside of its subarea, so exchange prices vary across subareas).

Table 4: Assessed Values – Segment Effects

	Reference	Northeast (Baja)		Northwest (Centro)		Southeast (Este)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Log LV	Log LV	Log LV	Log LV	Log LV	Log LV	Log LV
Adjudication Dummy	0.554**	0.332	0.368	0.527***	0.388	1.542***	1.419***
	(0.275)	(0.254)	(0.465)	(0.191)	(0.260)	(0.281)	(0.441)
Boundary Distance	-0.0120	-0.000005	0.000034	-0.0000476*	0.000028	-0.000029	-0.000938***
	(0.00898)	(3.72e-05)	(0.000137)	(2.49e-05)	(8.67e-05)	(1.85e-05)	(0.000172)
Distance*Adjudicated	0.0222**	0.0000019	-0.000184	0.0000524**	-0.00001	0.0000257	0.00125***
	(0.0106)	(3.85e-05)	(0.000177)	(2.53e-05)	(0.000111)	(2.15e-05)	(0.000192)
Constant	7.934***	8.878***	8.969***	8.194***	8.318***	7.608***	6.310***
	(0.249)	(0.215)	(0.399)	(0.186)	(0.280)	(0.260)	(0.257)
Observations	5,053	5,401	572	11,953	2,575	9,263	1,906
R-squared	0.0598	0.0021	0.0251	0.017	0.0549	0.1198	0.2091
Bandwidth	5KM	Global	5KM	Global	5KM	Global	5KM
Covariates	None	None	None	None	None	None	None

Standard errors in parentheses and corrected for heteroscedasticity and spatial autocorrelation, and significance as follows: *** p<0.01, ** p<0.05, * p<0.1. Bandwidths are infinite (2,4,6) or 5 kilometers (1,3,5,7).

Column (1) provides the full sample 5-kilometer results for reference, while (2) and (3) correspond to the Baja subarea, (4) and (5) to the Centro subarea, and (6) and (7) to the Este subarea. For each segment, estimates using the infinite and 5-kilometer bandwidths are presented. In all segments, the estimated RD effect is positive, although we identify here statistically significant effects only in the northwest and southeast segments; this may be due to the relatively lower number of observations, especially within 5 kilometers, in the northeast segment.

The large, statistically significant effect in the Este subarea deserves attention. Two potential explanations exist: First, this boundary segment contains a section of the aquifer with relatively low hydraulic conductivity across the boundary,[15] so the returns to groundwater management may be more easily appropriable by users on the interior. Second, recall that our model predicts that the effect of being in the adjudicated area will be positive when the capitalized value of permits is large. The Este subarea contains a developing urban area, Lucerne Valley. Urban areas require guaranteed water access in perpetuity to fuel development; prior to adjudication, development was restricted because groundwater rights did not exist, but the definition of tradable property rights to the resource allows developers and water utilities to acquire rights to groundwater in perpetuity.[16] In doing so, developers bid up the price of groundwater pumping permits, increasing the present value of firms holding rights. This demand for permits drives up prices in the Este section and its corresponding trading subarea, leading to a much stronger positive effect of adjudication. The same is true of the Centro subarea; hydraulic conductivity is low along the boundary, and Barstow, California, is a rapidly growing urban area. In contrast, the Baja subarea has the highest conductivity of the three segments along the border (due to the fact that the Mojave River active channel flows across it; see Figure 1) and does not contain a growing urban area.

VI. Discussion

Our results document a strong positive effect of adjudication that is robust to several different bandwidth choices and the inclusion of a set of covariates related to land value. Indeed, results from column (1), Table 1, indicate that the average effect of groundwater adjudication is

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[15] Personal communication with Tony Winkel, Senior Hydrologist, Mojave Water Agency. 8 February 2017.

[16] Indeed, municipalities in our study area have been growing rapidly over the past few decades and have aggressively acquired water rights to fuel this growth.

to double vacant land values. Theory suggests that this effect is positive where the capitalized value of groundwater pumping permits exceeds the agricultural rent premium enjoyed by free riders outside the adjudicated area. We find evidence that this is the case. Furthermore, water scarcity is a major restriction on development and many municipalities, water utilities, and counties adopt resolutions that require proof of water access before land can be developed. San Bernardino County has such a requirement. Groundwater adjudication provides developers with certainty over access to groundwater resources in perpetuity, and their demand drives up market prices for permits and thus also the land value of those holding permits because those permit values are included in land value (either indirectly or directly, see Section IV).

The estimated magnitudes of these effects are quite large. Even a doubling of land value is enormous, and in some subareas we find effects that near a tripling of land value. These must be placed in context. In the Mojave, water is the major constraint on both agriculture and urban development, not land. As a result, institutional changes to the use of groundwater (the primary source of water in the region) can have massive effects on the productive and development potential of land, and thus its value. Consider that some groundwater pumping right bundles have traded for millions of dollars (compared to an average land sale price of between $10,000-20,000). Furthermore, evidence suggests that the Mojave aquifer would have suffered considerable additional drawdown, potentially rendering it unfit for most uses, in the absence of intervention. By the 1980s, it is was estimated that two-fifths of the aquifer's total storage capacity had already been extracted, and water tables fell 50-100 feet in the decades preceding adjudication (Donohew, 2005).

Aside from guiding our interpretation of the treatment effects we identify, our theory is supported in two additional instances. First, our analysis of separate segments of the adjudication boundary indicates that the Este subarea of our study area exhibits a much larger treatment effect than other areas. This may result from urban growth within the subarea, which increases expected future permit values and is reflected in land values through the capitalization of groundwater rights.[17] Indeed, urban areas in the sample region have been growing steadily since adjudication and have bought up groundwater pumping rights from marginal agricultural users to do so. Low hydraulic conductivity also increases the effect (as free riders outside of the adjudicated area are less able to drain water), and is a competing explanation for this result. In addition, we find that the estimated treatment effect is larger when observations are dropped from a small band around the discontinuity; this is consistent with lower returns due to exposure to risk of drainage by free riders.

Our main results are corroborated by a falsification test in space, where we find no substantial evidence of land value discontinuities across an arbitrary boundary above the aquifer. In addition, the reliably statistically significant effect of distance to a recharge site, even when controlling for distance to an urban center, further corroborates our story that groundwater access affects land value in this arid, groundwater-constrained area. Furthermore, these results are supported by anecdotal evidence from the study region. Cropping patterns have changed significantly since adjudication, as farmers who inherited reliable water rights have switched to higher-value yet more water-intensive crops such as almonds and pistachios. On the other hand, the benefits of free ridership are also clear: local wisdom suggests that anyone interested in entering agricultural production in the basin should consider buying land outside the adjudicated area in order to avoid pumping restrictions. Municipalities have also tried to avoid restrictions. The Phelan community services district in the southwestern corner of the study area recently

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[17] Note that this effect does not depend on a landowner's distance from an urban area because "paper" water can be traded over any distance, provided the buyer is within the same subarea of the adjudication.

drilled wells 50-100 feet outside the western boundary of the adjudication in order to access groundwater that is hydrologicaly connected to the main Mojave aquifer and thereby circumvent restrictions.[18]

VII. Conclusion

The results presented here document a positive, statistically significant, and economically meaningful effect of groundwater adjudication on agricultural and vacant land values. In some cases, the average treatment effect implies a doubling in land value. This large effect reflects the tight restriction that groundwater places on both urban and agricultural development in the Mojave. Furthermore, the results indicate that gains from trade are substantial when demand growth is present and a market approach to reallocation is adopted: markets allow efficient agricultural producers to continue growing crops despite pumping restrictions and urban areas to expand more rapidly and with more certainty, which results in high permit prices that are capitalized into land value. Finally, there is suggestive evidence for our model predictions regarding exposure to drainage risk from free riders and the role of hydraulic conductivity.

This work contributes to the literature on common-pool resource management by documenting the returns to collective action to restrict open-access extraction rates. While recent studies have either addressed the adaptation of users to new institutions (Smith et al., 2017) or the economic returns to less stringent management institutions (Edwards, 2016), this investigation is the first to assess the impact of tradable property rights to groundwater on land value using parcel-level data. This work also fits into a larger literature that documents the

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[18] Personal communication with Senior Hydrologist, Mojave Water Agency. 8 February 2017

margins along which economic gains accrue to common-pool resource users when management institutions are adopted, in this case in the value of a complementary production input.

In addition, insights gained from this project will help to streamline the implementation of California's Sustainable Groundwater Management Act of 2014. Numerous stakeholder organizations are currently embroiled in negotiations over how to manage groundwater aquifers to avoid "undesirable outcomes," as defined in this legislation. Historically, collective responses to groundwater overdraft have remained elusive in California due to high transaction costs in bargaining over management institutions (Ayres et al., 2017), but recent attempts have been made to simplify the adjudication process to reduce these costs.[19] Nonetheless, reaching agreement on pumping restrictions remains very difficult. This analysis demonstrates that private benefits accrue to landowners who collectively adopt pumping restrictions to address over-extraction. Users and regulators alike may hope that a promise of appropriable gains in resource values can help ease negotiating tensions and support sustainable groundwater management.

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[19] For example, California Assembly Bill 1390 (2015-16).

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IX. Results Appendix

A. Quadratic Specifications

Table 5 below presents regression discontinuity results for specifications including quadratic terms on the running variable, distance to the adjudication boundary.

Table 5: Quadratic Specifications – Assessed Values

	(1)	(2)	(3)	(4)	(5)	(6)
	Log LV	Log LV	Log LV	Log LV	Log LV	Log LV
Adjudication Dummy	0.835***	0.842***	0.827***	0.446*	0.297	0.169
	(0.226)	(0.193)	(0.301)	(0.269)	(0.286)	(0.326)
Boundary Distance	-0.00401	-0.00267	-0.0401	-0.0247	0.00843	-0.0332
	(0.00516)	(0.00425)	(0.0257)	(0.0215)	(0.0957)	(0.0770)
Distance*Adjudicated	0.00468	0.000596	0.0445	0.0447	0.185	0.151
	(0.00539)	(0.00441)	(0.0342)	(0.0314)	(0.138)	(0.110)
Distance^2	-2.59e-05	-9.45e-06	-0.000585	-0.000363	-0.00102	-0.00437
	(2.42e-05)	(1.98e-05)	(0.000520)	(0.000416)	(0.00858)	(0.00643)
Distance^2*Adjudicated	2.25e-05	1.08e-05	0.000695	0.000193	-0.0148	-0.00567
	(2.42e-05)	(1.99e-05)	(0.000580)	(0.000484)	(0.0175)	(0.0150)
Covariate Controls						
Parcel Area		0.0119***		0.0118***		0.00880***
		(0.000574)		(0.00109)		(0.00161)
Base Year		-1.69e-05		-5.46e-05**		-8.36e-05*
		(1.19e-05)		(2.76e-05)		(4.79e-05)
Distance to Urban Center		-0.000110		-4.43e-05		0.00222
		(0.000289)		(0.000537)		(0.00183)
Distance to Recharge Station		-0.00116***		-0.000962**		-0.00256**
		(0.000243)		(0.000455)		(0.00128)
Constant	8.162***	8.532***	7.718***	8.216***	7.997***	8.314***
	(0.213)	(0.236)	(0.287)	(0.364)	(0.257)	(0.975)
Observations	26,617	26,617	5,053	5,053	746	746
R-squared	0.043	0.2011	0.0622	0.2231	0.0944	0.2711
Bandwidth	Global	Global	5KM	5KM	1KM	1KM
Covariates	None	Yes	None	Yes	None	Yes

Standard errors in parentheses and corrected for heteroscedasticity and spatial autocorrelation, and significance as follows: *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Bandwidths are infinite (1,2), 5 kilometers (3,4), or one (5,6).

B. Results Omitting Parcels near Boundary

Table 6 below presents regression discontinuity results when omitting parcels near the boundary that are potentially subject to drainage by free riders. Columns (1) and (2) omit parcels within 10 kilometers of the boundary, (3) and (4) parcels with 5 kilometers, and (5) and (6) parcels within 1 kilometer.

Table 6: Results without Boundary Parcels – Assessed Values

	(1) Log LV	(2) Log LV	(3) Log LV	(4) Log LV	(5) Log LV	(6) Log LV
Adjudication Dummy	1.388***	1.041**	0.513**	0.686***	0.664***	0.732***
	(0.499)	(0.406)	(0.238)	(0.219)	(0.173)	(0.145)
Boundary Distance	-0.00289	-0.00421*	0.00424**	0.00159	0.00182	-0.000232
	(0.00309)	(0.00249)	(0.00173)	(0.00160)	(0.00144)	(0.00128)
Distance*Adjudicated	0.00239	0.00496*	-0.00566***	-0.00373**	-0.00241	-0.00144
	(0.00312)	(0.00255)	(0.00177)	(0.00165)	(0.00148)	(0.00131)
Covariate Controls						
Parcel Area		0.0118***		0.0119***		0.0120***
		(0.000713)		(0.000656)		(0.000597)
Base Year		-1.94e-05		-1.22e-05		-1.62e-05
		(1.57e-05)		(1.31e-05)		(1.21e-05)
Distance to Urban Center		0.00170***		-0.000202		-0.000189
		(0.000473)		(0.000318)		(0.000279)
Distance to Recharge Station		-0.000920**		-0.000750**		-0.00103***
		(0.000375)		(0.000294)		(0.000255)
Constant	7.650***	7.317***	8.755***	8.727***	8.421***	8.622***
	(0.489)	(0.457)	(0.231)	(0.305)	(0.165)	(0.218)
Observations	14,872	14,872	21,564	21,564	25,871	25,871
R-squared	0.980	0.984	0.982	0.985	0.982	0.985
Omitted Parcels	<10KM	<10KM	<5KM	<5KM	<1KM	<1KM
Covariates	None	Yes	None	Yes	None	Yes

Standard errors in parentheses and corrected for heteroscedasticity and spatial autocorrelation, and significance as follows: *** p<0.01, ** p<0.05, * p<0.1. Omitted parcels are within 10KM (1,2), 5KM (3,4,), and 1KM (5,6,).

C. Assessed Values – Restrictions by Base Appraisal Year

Below we present linear results at two different bandwidth choices for subsamples of our dataset that control for different base appraisal years. Results are in Table 7.

Table 7: Spatial RD – Assessed Value, Base Year Restrictions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Log LV	Log LV	Log LV	Log LV	Log LV	Log LV	Log LV	Log LV
Adjudication Dummy	0.837***	0.874***	0.254	0.175	0.786***	0.821***	0.378	0.297
	(0.207)	(0.215)	(0.285)	(0.234)	(0.191)	(0.180)	(0.275)	(0.242)
Boundary Distance	-0.000865	-0.00219	0.00447	0.0106	-0.000495	-0.00168	0.00146	0.00536
	(0.00146)	(0.00137)	(0.0127)	(0.0103)	(0.00136)	(0.00121)	(0.0119)	(0.00955)
Distance*Adjudicated	0.000211	0.000163	0.00545	-0.00239	-5.06e-05	-4.04e-05	0.00377	-0.00105
	(0.00151)	(0.00151)	(0.0135)	(0.0103)	(0.00142)	(0.00131)	(0.0133)	(0.0101)
Covariate Controls								
Parcel Area		0.0104***		0.0136***		0.0102***		0.0113***
		(0.000640)		(0.00193)		(0.000566)		(0.00129)
Base Year		-0.0369***		-0.0425***		-0.0125***		-0.000487
		(0.00433)		(0.00988)		(0.00279)		(0.00904)
Distance to Urban Center		-0.000762**		-0.000389		-0.000597*		-0.000752
		(0.000323)		(0.000558)		(0.000312)		(0.000660)
Distance to Recharge Station		-0.00073***		-0.000839*		-0.00070***		-0.000658
		(0.000277)		(0.000446)		(0.000272)		(0.000631)
Constant	8.523***	82.99***	8.586***	94.22***	8.550***	33.87***	8.532***	9.932
	(0.201)	(8.807)	(0.272)	(19.81)	(0.185)	(5.610)	(0.253)	(18.10)
Observations	11,546	11,546	2,203	2,203	13,817	13,817	2,602	2,602
R-squared	0.0329	0.2121	0.0739	0.2785	0.031	0.1971	0.0476	0.2202
Bandwidth	Global	Global	5KM	5KM	Global	Global	5KM	5KM
Base Years	After 2000	After 2000	After 2000	After 2000	After 1990	After 1990	After 1990	After 1990
Covariates	None	Yes	None	Yes	None	Yes	None	Yes

Standard errors in parentheses and corrected for heteroscedasticity and spatial autocorrelation, and significance as follows: *** p<0.01, ** p<0.05, * p<0.1. Bandwidths are infinite (1,2 and 5,6) or 5 kilometers (3,4 and 7,8).

D. McCrary Test

We present below in Figure 5 a plot of McCrary test outputs at one kilometer (adjudicated parcels are on the left). Density estimates are not statistically different across the border, which supports the boundary exogeneity assumption.

Figure 5: McCrary Test