NBER WORKING PAPER SERIES

# DO PROPERTY RIGHTS ALLEVIATE THE PROBLEM OF THE COMMONS? EVIDENCE FROM CALIFORNIA GROUNDWATER RIGHTS

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Working Paper 26268
http://www.nber.org/papers/w26268

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
September 2019

We acknowledge helpful comments from Max Auffhammer, Spencer Banzhaf, Lint Barrage, Youssef Benzarti, Chris Costello, Robert Heilmayr, Josh Hill, Matt Kahn, Bryan Leonard, Gary Libecap, Heather Royer, Randall Rucker, Walter Thurman, Randy Walsh, Paige Weber, participants at the NBER EEE Summer Institute, and at other seminars and conferences. We thank Vincent Thivierge for excellent research assistance. This research was funded by a grant through the UC Office of the President: MR-15-328650, Legal and Economic Data and Analysis of Environmental Markets and supported in part by PERC and EDF. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

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NBER Working Paper No. 26268
September 2019
JEL No. D23,P14,P48,Q15,Q25

## ABSTRACT

Property rights are widely prescribed for addressing the tragedy of the commons, yet causal evidence of their effectiveness remains elusive. This paper combines theory and empirics to produce a causal estimate of the net benefit of using property rights to manage groundwater. We develop a model of dynamic groundwater extraction to demonstrate how a spatial regression discontinuity design exploiting an incomplete property rights setting can recover a lower bound on the value of property rights. We apply this estimator to a major aquifer in water-stressed southern California, finding groundwater property rights led to substantial net benefits, as capitalized in land values. Heterogeneity analyses suggest that gains arise in part from the tradeability of property rights, enabling more efficient water use across sectors.

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# 1 Introduction

For over a century, scholars have recognized that common-pool resources, if left unmanaged, become inefficiently overextracted (Coman, 1911; Gordon, 1954; Hardin, 1968; Ostrom, 1990). Coase (1960) proposes a solution to this "tragedy of the commons:" the assignment of property rights. In theory, property rights can counter overextraction and improve welfare by introducing incentives for more efficient resource use. These appealing predictions have led property rights to be recommended for nearly every common-pool resource, from fisheries, forests, water, to the global climate (Stavins, 2011; Anderson and Libecap, 2014).

The effectiveness of property rights, however, is predicated on several stylized theoretical assumptions. Coase (1960) was the first to acknowledge that one key assumption, sufficiently low transaction costs, may be unrealistic in some settings. In the ensuing six decades, a large theoretical literature has systematically explored what happens when other crucial assumptions - such as complete property rights and complete information - are violated.[1] Given how pervasive these theoretical violations are in practice, it becomes an empirical question whether property rights are effective under real-world conditions, and if so, why. Indeed, Coase advocated for careful empirical analysis in his original article:

> "Satisfactory views on policy can only come from a patient study of... the problem of harmful effects... This... has to come from a detailed investigation of the actual results of handling the problem in different ways." Coase (1960, p.18-19)

This paper provides the first quasi-experimental estimate of the net benefit of using property rights to manage a common-pool resource.[2] We focus on groundwater for two reasons. First, it is a critical and increasingly scarce natural resource. Groundwater provides 50% of potable and 40% of irrigation water globally (Giordano, 2009; Aeschbach-Hertig and Gleeson, 2012). It is also widely overextracted, with one-third of the world's largest aquifers facing declining water levels today (Richey et al., 2015), and many aquifers showing signs of inefficient use (Bierkens et al., 2019). Second, incomplete groundwater property rights provide a unique opportunity for conducting causal inference. We combine a model of dynamic groundwater extraction with a potential outcomes framework to show that when property rights are incomplete, a spatial regression discontinuity (RD) design applied across

[1] See, for example, implications for the Coase theorem in the presence of imperfect competition (Hahn, 1984), incomplete information (Farrell, 1987), transaction costs (Stavins, 1995), endogenous contracting (Jackson and Wilkie, 2005), and when participation is voluntary (Ellingsen and Paltseva, 2016).

[2] Previous quasi-experimental research focuses on the impact of property right on extraction effort, generally finding reduced effort (Hsueh, 2017; Costello and Grainger, 2018; Isaksen and Richter, 2018; Drysdale and Hendricks, 2018) and on resource levels (Iwanowsky, 2019). As we will discuss, observing lower extraction or higher resource levels need not imply positive net benefits following the introduction of property rights.

the property rights boundary recovers a lower bound on the net benefit of property rights. We find substantial net benefits from groundwater property rights when applying this estimator to a major aquifer in southern California, one of the most water-stressed regions of the United States.

To date, efforts to produce causal evidence on the effectiveness of property rights have been hindered by two main empirical obstacles. First, property rights for common-pool resources remain rare. For example, only 8% of aquifers in California are managed by property rights, despite groundwater providing half of the state's water supply. Additionally, in cases where property rights are adopted, the managed resource is often in a critical state of overextraction (Shertzer and Prager, 2006; Mangin et al., 2018). As a result, simple comparisons between resources governed by property rights and under open access may be confounded by differences in unobserved resource characteristics.

To make progress on causal inference, this paper leans heavily on renewable resource theory to develop an identification strategy. Our estimand of interest is the average difference in land prices between open access and property right regimes for parcels receiving groundwater property rights. As in any potential outcomes framework, this difference can not be directly estimated as one does not jointly observe land prices under both regimes. Instead, we turn to a setting in which property rights are assigned to a spatial subset of land parcels overlying an aquifer. This incomplete property rights setting allows us to compare parcels under property rights and open access within the same regime.

We develop a model of dynamic groundwater extraction to first demonstrate that our estimand of interest is ambiguously signed when property rights are spatially incomplete. We then show how a spatial RD design comparing land values on either side of the property rights boundary addresses endogeneity concerns as groundwater characteristics are likely to vary continuously across the boundary. However, that same identifying assumption implies that an RD estimate deviates from our estimand by removing differences in water table heights, a key consequence of property rights. We turn to our model to sign this bias. Theory shows that a spatial RD estimate serves as a lower bound on the local average net benefit of an incomplete property right regime, and possibly also as a lower bound for the population average net benefit.

We apply our spatial RD estimator to a major aquifer in southern California. The Mojave Desert is the driest desert in North America, and yet, is where water-intensive crops are produced. Its verdant irrigated farms surrounded by a barren desert has long been a poster child for inefficient water use. This stark contrast occurs because underneath the Mojave Desert lies one of California's largest aquifers, which has historically been extracted under open access conditions. Agricultural irrigation has resulted in severe groundwater depletion: by the 1980s, two-fifths of the aquifer's total storage had been exhausted (Donohew, 2012; Mojave Water Agency, 2004). To stabilize aquifer water levels, a court process in the mid-1990s known as "adjudication" introduced groundwater property rights with two key features: (i) individual limits on groundwater pumping to stabilize the groundwater level, and (ii) individual tradeable water rights within those limits. Importantly, the spatial extent of the property rights regime - which is jointly determined by the boundaries of a preexisting regulatory institution and a surface geographical feature - did not include all overlying users of the hydraulically-connected aquifer. This incomplete property rights setting enables our spatial RD estimator.

Using parcel-level data, we estimate that the land values on the property rights side of the boundary are, on average, 280% higher than on the open access side. We confirm that relevant covariates vary continuously across the boundary. We also demonstrate that our RD estimate is robust to alternative statistical modeling assumptions, bandwidth choices, how the property rights boundary is defined, and other potential empirical concerns. Reassuringly, we do not detect an RD effect when using placebo property right boundaries falsely set within the property rights and open access areas.

Since our RD estimate omits the benefit of a higher water table, it may be puzzling why land values differ so much across the boundary. One explanation is that groundwater property rights are tradeable, which provides landowners an additional potential benefit of being able to sell water rights at market value. For the Mojave aquifer, higher water values likely come from urban users, particularly in the more urban southern areas of the aquifer. Indeed, heterogeneity analysis reveals that parcels in the southern part of the aquifer exhibit higher RD estimates, while northernmost parcels show negative RD estimates. This suggests that tradeable groundwater property rights may be leading to more efficient water use, away from water-intensive agriculture towards meeting growing urban demand.

Accounting for these heterogeneous effects and further assuming that unobserved characteristics are not systematically correlated with distance to the boundary, we calculate that groundwater property rights led to a lower-bound total net benefit of $477 million (in 2015 dollars) across all adjudicated parcels, or a 53% increase in total land value. This net benefit is more than an order of magnitude larger than the initial administrative cost of setting up the property rights system.

There is a timely need for causal evidence on whether property rights can effectively manage groundwater resources. Demographic shifts together with changing environmental conditions due to anthropogenic climate change predict increased water scarcity in many parts of the world in the coming decades (Vörösmarty et al., 2000; Covich, 2009; McDonald et al., 2011; Prudhomme et al., 2014; Elliott et al., 2014; Ferguson et al., 2018). For California in particular, a recent prolonged drought has led groundwater tables to fall dramatically across the state, raising concerns about long-term water availability (California Dept. of Water Res., 2015). To address this, California recently passed the Sustainable Groundwater Management Act (SGMA), an unprecedented law requiring users of overextracted aquifers to collectively formulate and adopt stringent management plans. Tradeable property rights are widely considered a key policy instrument under SGMA (Aladjem and Sunding, 2015; Babbitt and Brozovic, 2017; Green Nylen and Doremus, 2017). This paper demonstrates that net benefits from groundwater property rights can be substantial, which may inform future adoption of property rights.

The remainder of the paper is structured as follows: Section 2 provides background on the Mojave aquifer and its system of incomplete property rights. Section 3 introduces a dynamic model of groundwater extraction under open access and incomplete property right regimes. This theory informs our empirical strategy in Section 4. Section 5 details data sources. Section 6 presents our main results, robustness checks, heterogeneity analyses, and quantifies the total net benefit of groundwater rights in the Mojave. Section 7 concludes.

# 2 Background

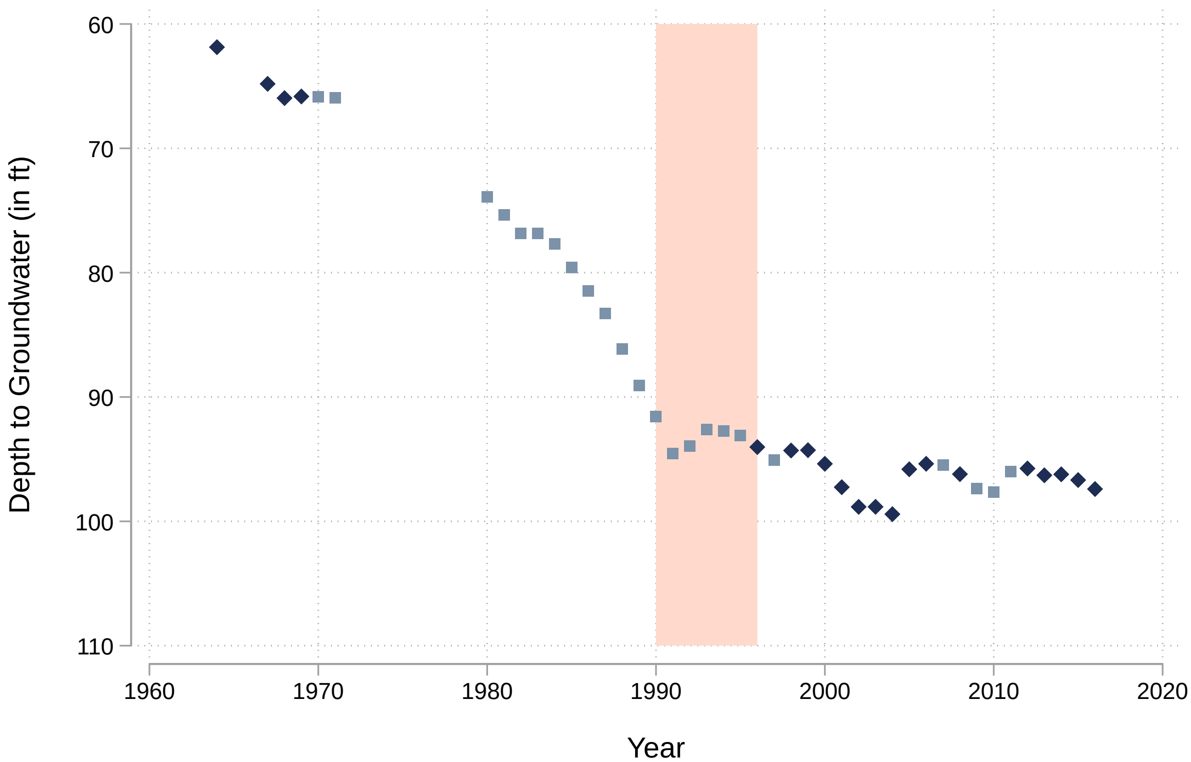
The Mojave Desert, located north of Los Angeles in southern California, is the driest desert in North America, receiving on average less than two inches of rainfall annually. Yet, farmers in the Mojave Desert have historically produced alfalfa, pistachios, and stone fruits, all highly water-intensive crops. This arises in part because beneath this desert lies one of California's ten largest groundwater resources, which has historically been extracted under de facto open access conditions.[3]

In recent decades, open access pumping has led to a dramatic drop in the aquifer's water table. Figure 1 plots the average depth from surface to the water table across monitoring wells in the Mojave Desert: between 1964 and 1990, the water table fell by 30 feet. After a failed attempt in the 1960s, a lawsuit in 1990 prompted negotiations to address the groundwater problem in the Mojave Desert. By 1996, an agreement was reached between most users and adopted by the court to implement a new property rights-based system that would stabilize water table levels. This system is commonly referred to as "adjudication."

Adjudication had two components. First, landowners receive individual annual groundwater pumping rights defined as a proportion of the annual total allowable pumping across the aquifer. Each landowner's proportion is based on her average share of total pumping

[3] California law requires groundwater use be "reasonable and beneficial." However, this criterion has historically allowed unrestricted irrigation in arid regions and thus has not limited groundwater extraction.

**Figure 1:** Depth to groundwater before and after property rights




Notes: Vertical axis shows average distance (in feet) to water table across monitoring wells in the Mojave Desert. Horizontal axis indicates years. Dark blue diamonds indicate years where there is data for all monitoring wells. Light blue diamonds indicate years where missing data from one or more monitoring wells is linearly interpolated. Orange-shaded area marks the period from 1990 when the initial adjudication lawsuit was filed to 1996 when the final adjudication court ruling was issued. Data from USGS well completion reports.

during 1986-1990, the period prior to adjudication. To stabilize water table levels, total annual pumping across the aquifer ramps down over time. Second, landowners can buy or sell "paper" groundwater rights, either via annual leases or permanent transactions. This is a paper right in the sense that landowners can not transfer physical water, but are permitted to sell pumping rights to any other user overlying the groundwater resource. The resulting water market enables landowners to capitalize on any allocative efficiency gains arising from the sale of rights to other users. This is an important change from open access, where landowners do not own pumping rights and thus can only pump water for use on their own land.

Despite these advantages, several features of the Mojave adjudication system deviate from a textbook optimal policy. First, it is unclear whether simply stabilizing the water level at its pre-adjudication level corresponds to an optimal water table height. Next, in addition to the prohibition on physical water transfers, limits are also placed on water right trading across space and time. Landowners can only trade groundwater rights within subareas of the groundwater resource such that each subarea essentially operates its own water market. Likewise, water rights can only be banked one year ahead and cannot be borrowed from the future, which limits intertemporal smoothing of water consumption.

Perhaps the most interesting feature of the Mojave adjudication that deviates from an ideal property rights system is that rights were not assigned over the entire groundwater resource under the Mojave Desert. Figure 2 maps the spatial boundary of the property rights regime (shown by purple and red lines) and the subsurface extent of the entire hydraulically-connected Mojave groundwater system (in blue shading), which we henceforth refer to as the Mojave aquifer for short.[4] Observe that the spatial footprint of the property rights and Mojave aquifer areas do not perfectly overlap: some areas overlying the aquifer are managed by property rights (i.e., blue areas within the purple and red box) while other areas overlying the aquifer remain under open access (i.e., blue areas outside the purple and red box).

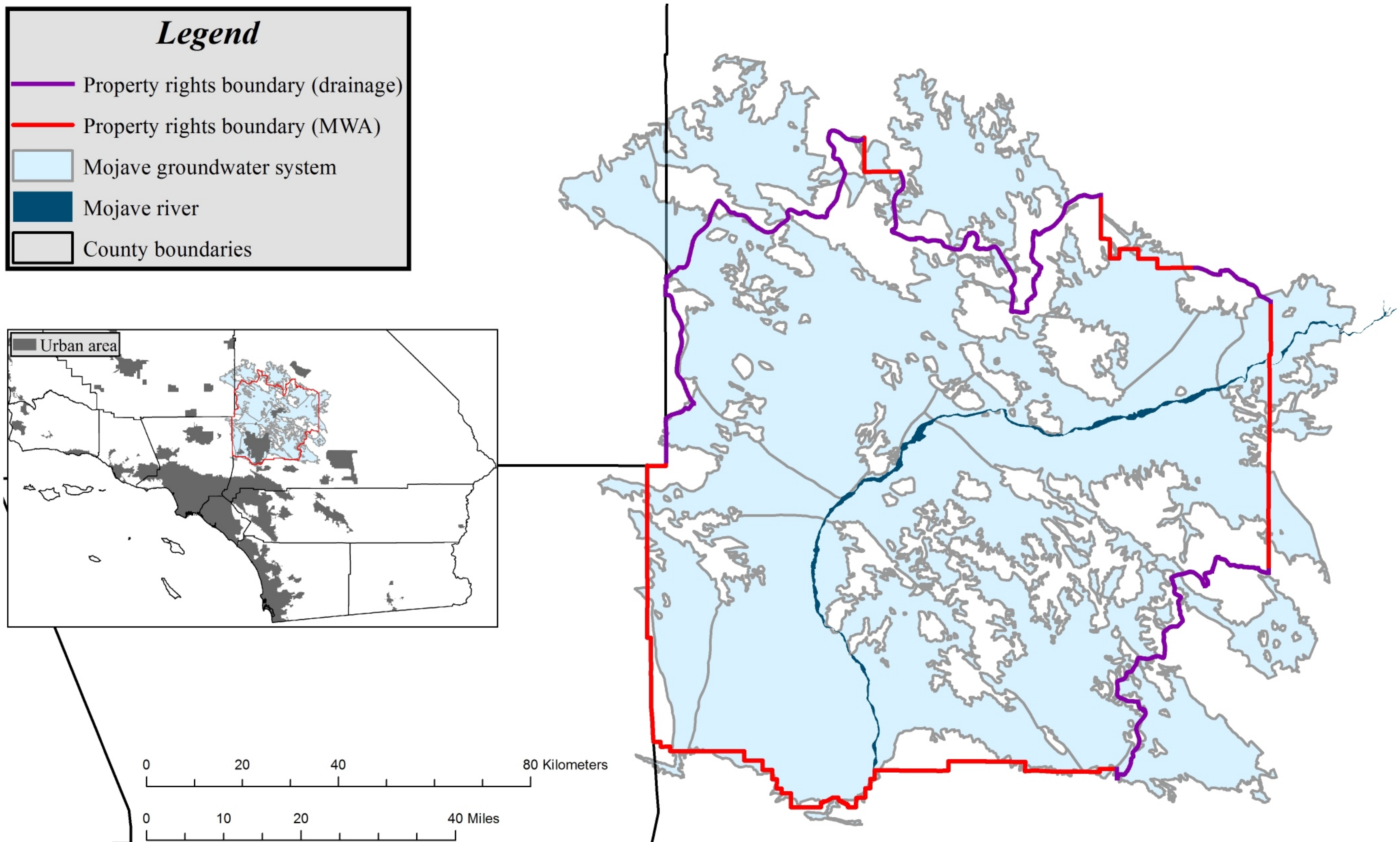
How the property rights boundary was drawn is also noteworthy. Specifically, it is the spatial intersection of two regions: the physical drainage area of the Mojave River (shown by purple line segments) and the jurisdictional area of the Mojave Water Agency (shown by red line segments), a pre-existing regulatory agency assigned to enforce the property rights regime.[5] The spatial extent of both regions are likely unrelated to groundwater characteristics and thus provides a plausibly exogenous property rights boundary.

Incomplete property rights, together with how the property rights boundary was drawn, suggests an opportunity to apply a spatial RD design. Before we do so, it is instructive to explore what existing data indicates regarding the net benefit of groundwater property rights in the Mojave. Figure 1 shows that groundwater levels indeed stabilized after 1996. However, stabilized water levels alone do not imply net benefits for landowners receiving property rights. In particular, it does not capture the costs of adjudication which includes pumping restrictions and transaction costs. Trends in agricultural activity are also inconclusive. Figure B.1 shows that agricultural revenue in the Mojave Desert declines after 1996. However, agricultural revenue does not capture possible gains from the reallocation of water to other sectors (e.g., urban water use), and thus is also inconclusive on whether property

[4] The key in defining the spatial extent of the relevant groundwater resource is hydraulic connectivity such that extraction in one location affects the water table level in another location. The blue area in Figure 2 shows all hydraulically-connected groundwater resources in the study area. This is a "groundwater system" because it technically includes separate resources as defined by California's Department of Water Resources. Conversations with Mojave Water Agency representatives confirm that these resources are hydraulically connected.

[5] The part of the property rights boundary defined by the Mojave Water Agency is largely determined by census tracts and was established before the adjudication regime. A robustness check examines whether these two boundary definitions exhibit different RD estimates.

**Figure 2:** Property rights and groundwater in the Mojave Desert




Notes: Blue shaded area shows the spatial extent of the hydraulically-connected Mojave groundwater system. Purple (red) line segments track the property rights area as defined by the spatial extent of the Mojave River drainage basin (Mojave Water Agency). Map inset shows the Mojave aquifer relative to urban areas, as defined by the Federal Highway Administration, in the broader southern California region.

rights benefited landowners.

Instead, one can follow the Ricardian tradition and examine land prices. This is possible because California Law ties groundwater to the overlying parcel, such that land prices reflect the discounted present value of rental streams from both land and water assets.[6] Under open access, land prices capture the value of unrestricted groundwater pumping for own use. Under adjudication, land prices reflect the cost of restricted groundwater pumping, as well as the benefits of a higher water table level and the potential gains from selling pumping rights. We now turn to a theoretical model of dynamic groundwater extraction to formalize what drives these land prices and how they relate to our empirical strategy.

## 3 Theory

This section develops a theory of dynamic groundwater extraction for the Mojave aquifer. Recognizing that the Mojave adjudication regime may deviate in practice from an optimal policy, we explicitly avoid characterizing optimality and instead consider a model that closely mirrors the policy's objective to stabilize water levels.[7] In particular, to replicate observed falling groundwater water levels prior to adjudication, as shown in Figure 1, we begin with all land parcels over the aquifer extracting groundwater under open access but without having yet reached a steady state. We then model land prices under two regimes for the period after adjudication is introduced. In the first (unrealized) regime, we model land price dynamics had open access conditions continued for all parcels over the aquifer. In the second (realized) regime, we model land price dynamics following the introduction of a spatially-incomplete property rights system.

Our theory generates several predictions that are used for interpreting our spatial RD estimator, presented in Section 4. First, we show that the difference in land prices between the two regimes, our estimand of interest, is of ambiguous sign. Intuitively, this is because relative to open access, property rights impose the cost of restricted pumping but also lead to benefits from a higher water table and the ability to sell water rights. Next, we demonstrate that in an incomplete property rights regime, a spatial RD estimator comparing parcels under property rights and open access at the property rights boundary produces a lower bound for the estimand at the boundary. This is because a spatial RD estimator, by design, omits differences in water table height, thus excluding the benefit of a higher water table due to property rights. Finally, because water table levels are lower at the boundary than

[6] Land prices, however, would not capture the one-time sunk costs of setting up the property rights regime.

[7] An optimal policy will always do at least as well as open access. Our theory leaves open the question of whether property rights increases net benefits.

in the interior of the property rights area, the RD estimator is also a lower bound on the estimand in the interior.

## 3.1 Setup

There are $N$ identical landowners, each of whom occupies $1/N$ of the area overlying the aquifer. Instantaneous profits are given by $\pi(w, h)$ where $w$ is the pumping rate and $h$ is the water table height, measured as the vertical distance from the bottom of the aquifer to the water level. $\pi(w, h)$ is assumed to be concave and singled-peaked in $w$, increasing in $h$, and $\pi_{wh} > 0$ since raising the water table height reduces the cost of pumping, making the marginal unit of water more profitable. The initial height of the water table is $h_0$ and the instantaneous rate of change in the water table height is $\dot{h}(t)$, where $t$ is time. After the initial period, dynamics of $h$ differ depending on whether the aquifer is under full open access or incomplete property rights, as we discuss below.

## 3.2 Full open access

Under full open access, profit-maximizing landowners ignore any effects of their pumping on the water table,[8] solving at each instant in time:

$$\max_{w} \pi(w, h) \tag{1}$$

The first-order condition $\frac{\partial \pi}{\partial w} = 0$ defines $w^a(h)$, the pumping rate as a function of the height of the water table (the 'a' indicates full open access). Using Cramer's rule, $\frac{dw^a}{dh} = -\frac{\pi_{wh}}{\pi_{ww}} > 0$, by the concavity of the profit identity, $\pi_{ww} < 0$, and $\pi_{wh} > 0$. Pumping rates under open access increase with the height of the water table.

**Transition and steady state**. Under open access, all users pump at the same rate and so the water table height is the same for all landowners. It evolves according to:

$$\dot{h}(t) = R - Nw^a(h(t)) \tag{2}$$

where $R$ is natural recharge and $Nw^a(h(t))$ is aggregate pumping.[9] Consistent with Figure 1, we assume that the aquifer is out of steady state initially and that aggregate pumping

[8] Alternatively, we could portray open access as uncoordinated spatial ownership (Kaffine and Costello, 2011), where each user has exclusive access to the water beneath their property, but pumping by other landowners gives rise to a stock externality. Our open access model is a limiting case in which a unit of water left by a landowner is completely captured by other users.

[9] The volume of the aquifer is normalized to one so that volumetric variables, $R$ and $w$, are conformable with $h$.

$Nw^a(h_0)$ exceeds recharge. By equation (2), this results in a declining water table. However, the drop in the water table height causes the open-access pumping rate to fall, by Cramer's rule. Assuming that exhaustion of the resource is unprofitable[10], a steady-state will be reached where pumping is equal to recharge. The steady-state is defined as $\bar{h}^a$ such that $\dot{h}^a = R - N\bar{w}^a = 0$, where $\bar{w}^a = w^a(\bar{h}^a) = R/N$.

The dynamics of the full open access system are illustrated in panel (a) of Figure 3. For a given value of $h$, the pumping rate is $w^a(h)$. Thus, any $w \neq w^a(h)$ moves immediately to the $\dot{w} = 0$ locus defined by $w^a(h)$. From there, the dynamics of the system are governed by equation 2. The blue line in Figure 3 shows the transition to the steady state from the initial height of $h_0 > \bar{h}^a$. When $h < \bar{h}^a$, the pumping rate and the water table height increase until the steady state is reached. In summary, under the full open access regime, we have $h_0 \geq h^a(t) \geq \bar{h}^a$ and $w^a(h_0) \geq w^a(h^a(t)) \geq \bar{w}^a$ for $t \geq 0$.

**Land price**. Under perfect competition, the price of a land parcel is equal to the present discounted value of the infinite stream of profits generated from the land. Thus, the full open access land price is given by:

$$V^a = \int_0^\infty \pi(w^a(s), h^a(s))e^{-\delta s} ds \tag{3}$$

where $\delta$ is the discount rate and the time interval covers both the transition period and the steady state.

## 3.3 Incomplete property rights

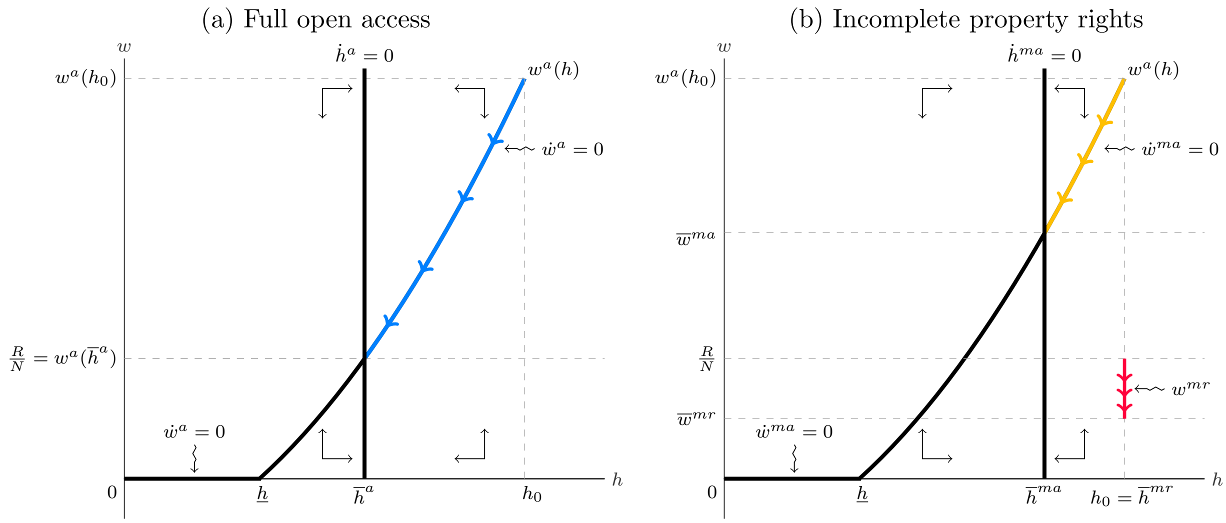
Property rights are introduced to stabilize the water table at $h_0$, preventing the draw down of the aquifer that occurs under open access. If all $N$ landowners were under the property rights regime, the regulator would simply assign individual pumping rights equal to $R/N$. If users pump their full allocation, then by equation (2), the water table remains at its initial level $h_0$. In the steady state, the same volume of water is pumped as under the open access regime, but because $h_0 > \bar{h}^a$, profits are higher than under open access (Gisser and Sanchez, 1980). The steady state is more complicated when property rights are incompletely assigned over the aquifer because users can pump at different rates.[11]

We examine this incomplete property rights setting by modeling the two components of the Mojave adjudication regime: a restriction on pumping to stabilize water levels and tradeable property rights to pump groundwater. First, we characterize how pumping restrictions

[10] Formally, there exists an $\underline{\mathrm{h}} > 0$ such that $w^a(\underline{\mathrm{h}}) = 0$.

[11] See Costello, Quérou and Tomini (2015) for a comparison of open access, incomplete property rights, and complete property rights regimes.

**Figure 3:** Phase plane diagrams of full open access and incomplete rights regimes




NOTES: Figure illustrate the transition to the steady state for the full open access and incomplete rights regimes starting from an initial water table height $h_0$. The directionals in each isosector apply to the open access users and are described in the text. The blue line in panel (a) is the transition path to the steady state at $\bar{h}^a$ and $w^a(\bar{h}^a)$ for open access users under the full open access regime. Under the incomplete property rights regime shown in panel (b), a representative open access parcel follows the orange line to the steady state at $h = \bar{h}^{ma}$ and $w = \bar{w}^{ma}$. A representative parcel with property rights follows the red line with a constant stabilization target of $\bar{h}^{mr}$ and an exogenous pumping rate (determined by the regulator) that reaches a steady state at $w = \bar{w}^{mr}$.

allow for stabilization of the water table. We then show how the market value of tradeable pumping rights is capitalized into land prices.

Under incomplete rights, only a share of the $N$ landowners hold property rights, with the rest of the landowners remaining under open access. Define $\alpha \in [0, 1]$ as the share of open access landowners. We assume that all landowners under the property rights regime face the same pumping restriction $w^{mr}$, whereas open access users are unconstrained ('m' denotes the incomplete, or mixed, regime and 'r' indicates users with rights). To simplify the analysis, we focus on two representative users, one within the property rights area with water table $h^{mr}$ and the other in the open access area with water table $h^{ma}$. The dynamics of the water table are described by a variant of equation (2):

$$\dot{h}^{ma} = \alpha R + \theta(h^{mr} - h^{ma}) - \alpha N w^a(h^{ma}) \tag{4}$$

$$\dot{h}^{mr} = (1 - \alpha)R + \theta(h^{ma} - h^{mr}) - (1 - \alpha)N w^{mr} \tag{5}$$

where it is assumed that recharge occurs uniformly throughout the aquifer and that the maximum allowable pumping occurs in the property rights area.[12] Due to gravity, differences in the water table height produce a flow of water, dictated by $\theta \in [0, 1]$, from one area to another.

**Stabilization and transition**. We assume that the goal of property rights is to stabilize the aquifer within the rights area at $\bar{h}^{mr} = h_0$ by imposing the pumping limit $w^{mr}(t)$. That is, the pumping limit is set in each period to achieve:

$$\dot{h}^{mr} = (1 - \alpha)R + \theta(h^{ma}(t) - \bar{h}^{mr}) - (1 - \alpha)Nw^{mr}(t) = 0 \tag{6}$$

Although the water table is stabilized in the rights area, it continues to be drawn down in the open access area. Consider $\dot{h}^{ma}$ at $t = 0$:

$$\dot{h}^{ma} = \alpha R + \theta(\bar{h}^{mr} - h^{ma}) - \alpha Nw^{a}(h^{ma}) = \alpha R - \alpha Nw^{a}(h_0) \tag{7}$$

where $\bar{h}^{mr} = h^{ma} = h_0$. As under full open access, open access users under incomplete rights pump more than recharge at $h_0$ and $\dot{h}^{ma} < 0$. The pumping rate by open access users depends only on the water table height according to $w^{ma} = w^{a}(h^{ma})$, as in the full open access case. The dynamics of the incomplete rights system is illustrated in panel (b) of Figure 3, where the orange line depicts the transition to the steady state for open access users.[13] Although the same trajectory is followed as under full open access, there is a positive flow of water to the open access area ($\bar{h}^{mr} - h^{ma} > 0$ for $t > 0$), which slows the decline in $h^{ma}$ relative to the full open access case (we prove this result in this next section).

In order to keep $\bar{h}^{mr}$ at $h_0$, $w^{mr}(t)$ must fall over time by equation 6. Solving for $w^{mr}(t)$ in equation 6 and taking the time derivative yields $\dot{w}^{mr} = \frac{\theta}{(1-\alpha)N}\dot{h}^{ma} < 0$. The transition path for the pumping rate in the rights area is depicted by the red line in panel (b) of Figure 3. At $t = 0$, $w^{mr} = R/N$, which is established from equation 6 and the fact that $\bar{h}^{mr} = h^{ma}$ at $t = 0$. The pumping limit $w^{mr}(t)$ declines until steady states are reach in both areas, which we solve for next.

**Steady states**. Setting $\dot{h}^{ma} = 0$ in equation 4 and substituting $\bar{h}^{mr}$, we define the following relationship between steady-state water table heights:

$$\bar{h}^{mr} = \bar{h}^{ma} + \frac{\alpha}{\theta}(Nw^{a}(\bar{h}^{ma}) - R) \tag{8}$$

The assumption in footnote 13 implies that for any stabilization target for the property rights

[12] We suppress time arguments except when it is necessary to clarify a variable's dependence on time.

[13] An additional assumption is needed to guarantee that a unique value of $h^{ma}$ solves $\dot{h}^{ma} = \alpha R + \theta(\bar{h}^{mr} - h^{ma}) - \alpha Nw^{a}(h^{ma}) = 0$, as shown in panel (b): $\frac{d^2 w^{a}(h)}{dh^2} \geq 0$, which holds if $\pi_{www}\pi_{wh} - \pi_{whh}\pi_{ww} \geq 0$.

area $\bar{h}^{mr}$, there is a unique steady-state water table $\bar{h}^{ma}$ and pumping rate $\bar{w}^{ma} = w^a(\bar{h}^{ma})$ in the open access area. We denote this mapping $q : \bar{h}^{mr} \to \bar{h}^{ma}$.

The steady state for the property rights area is found by substituting $\bar{h}^{mr}$ in equation (8) into equation (5) and setting $\dot{h}^{mr} = 0$, yielding:

$$R - \alpha N w^a(\bar{h}^{ma}) - (1-\alpha)N\bar{w}^{mr} = 0 \tag{9}$$

Substituting $\bar{h}^{ma} = q(\bar{h}^{mr})$ and rearranging equation (9), we obtain:

$$\bar{w}^{mr}(\bar{h}^{mr}) = \frac{R - \alpha N w^a(q(\bar{h}^{mr}))}{(1-\alpha)N} \tag{10}$$

For a given stabilization target $\bar{h}^{mr}$, equation (10) gives the steady-state pumping limit $\bar{w}^{mr} = \bar{w}^{mr}(\bar{h}^{mr})$ that needs to be imposed on landowners within the property rights area. The steady states are depicted in panel (b) of Figure 3.[14] In summary, under the incomplete property rights regime, we have $h_0 \geq h^{ma}(t)$, $w^a(h_0) \geq w^a(h^{ma}(t))$, and $w^{mr}(0) \geq w^{mr}(t)$ for $t \geq 0$.

**Land price**. Tradeable property rights allow right holders to sell water to other agricultural users or to meet non-agricultural demand such as that coming from nearby expanding urban areas. We represent this outside option with a salvage value $F(t)$, where it is assumed $F_t > 0$.[15] The profit-maximizing landowner will solve:

$$\max_{t^*} \int_0^{t^*} \pi(w^{mr}(s), \bar{h}^{mr})e^{-\delta s}ds + F(t^*)e^{-\delta t^*} \tag{11}$$

where $t^*$ is the time at which water rights are sold, which may occur before or after the steady state $w^{mr}(t) = \bar{w}^{mr}$ is reached. In equation 11, landowners pump up to the limit $w^{mr}(t)$ in every period because $\frac{\partial \pi}{\partial w} > 0$ at every $w^{mr}(t)$.[16] Assuming an interior solution,[17] the first-order condition for the optimal time to sell water rights is:

$$\pi(w^{mr}(t^*), \bar{h}^{mr}) + F_t(t^*) - \delta F(t^*) = 0 \tag{12}$$

Water rights are optimally sold when the annual return to using water in agriculture equals the annualized salvage value net of the instantaneous rate of increase in this value (i.e.,

[14] It can be shown that $\bar{w}^{ma} \geq \bar{w}^a \geq \bar{w}^{mr}$ and $\bar{h}^{mr} \geq \bar{h}^{ma} \geq \bar{h}^a$.

[15] The salvage value includes the residual value of land without water.

[16] This follows from $\frac{\partial \pi(w^a(h_0), h_0)}{\partial w} = 0$, $w^a(h_0) > w^{mr}(t)$ for all $t$, $\bar{h}^{mr} = h_0$, and the properties of $\pi$.

[17] An interior solution is consistent with the Mojave setting where permanent transfers of water rights have been rare.

$\delta F(t^*) - F_t(t^*))$. Under incomplete property rights, the land price is:

$$V^{mr} = \int_0^{t^*} \pi(w^{mr}(s), \bar{h}^{mr}) e^{-\delta s} ds + F(t^*) e^{-\delta t^*} \tag{13}$$

The land price for landowners in the open access area is:

$$V^{ma} = \int_0^{\infty} \pi(w^{ma}(s), h^{ma}(s)) e^{-\delta s} ds \tag{14}$$

We made the simplifying assumption that there are single water table heights in the two areas. In reality, there is a declining gradient in the water table as one moves from the property rights to the open access area. At the boundary of the two areas, the water table height is the same for parcels under the rights and open access regimes. That is, denoting water table height at the boundary as $h^b(t)$, $\bar{h}^{mr} \geq h^b(t) \geq h^{ma}(t)$ for $t \geq 0$. This property has important implications for our RD estimator, as discussed below.

## 3.4 Comparing across regimes

We now turn to several land value comparisons across the full open access and incomplete property right regimes that will facilitate interpretation of an RD estimate in Section 4.

**Proposition 1** *If (i)* $\bar{h}^{mr} \geq h^a(t)$*, (ii)* $\bar{h}^{mr} \geq h^{ma}(t)$*, (iii)* $h^{ma}(t) \geq h^a(t)$*, and (iv)* $w^a(h_0) \geq w^{ma}(t) \geq w^a(t) \geq w^{mr}(t)$ *for* $t \geq 0$*, then*

*(a)* $V^{mr} - V^a \gtreqless 0$ *(treatment effect has ambiguous sign)*

*(b)* $V^{mr} - V^{ma} \gtreqless 0$ *(estimated effect has ambiguous sign)*

*(c)* $(V^{mr}(h^b) - V^a) - (V^{mr}(h^b) - V^{ma}(h^b)) \geq 0$ *(estimated effect at the boundary is a lower bound for treatment effect at the boundary)*

*(d)* $(V^{mr} - V^a) - (V^{mr}(h^b) - V^a) \geq 0$ *(treatment effect at the boundary is a lower bound for treatment effect in the interior)*

*(e)* $\frac{d}{dt}(V^{mr}(h^b) - V^{ma}(h^b)) \gtreqless 0$ *(the change over time in the estimated effect at the boundary has ambiguous sign)*

Proof. We establish conditions (i)-(iv) here and prove Proposition 1(a) -1(e) in Appendix A. It was shown in Sections 3.2 and 3.3 that $h_0 \geq h^a(t)$ and $h_0 \geq h^{ma}(t)$ for $t \geq 0$, respectively. Conditions (i) and (ii) follow from the definition $\bar{h}^{mr} = h_0$. To prove condition (iii), we show that $\dot{h}^a \leq \dot{h}^{ma}$ at any $h_0 \geq h \geq \bar{h}^a$. Condition (iii) then follows from $h^a(0) =$

$h^{ma}(0) = h_0$. As shown in Section 3.2, $w^a(\bar{h}^a) = R/N$. For any $h \geq \bar{h}^a$, $w^a(h) \geq R/N$ by $\frac{dw^a}{dh} > 0$. Using equations 2 and 4, we write:

$$\dot{h}^{ma} - \dot{h}^a = \theta(\bar{h}^{mr} - h) + (1 - \alpha)(Nw^a(h) - R) \tag{15}$$

This difference is positive from $\bar{h}^{mr} = h_0$ and $w^a(h) \geq R/N$, which establishes condition (iii). It follows immediately from conditions (i)-(iii) and $\frac{dw^a}{dh} > 0$ that $w^a(h_0) \geq w^{ma}(t) \geq w^a(t)$ for $t \geq 0$. It remains to show that $w^a(t) \geq w^{mr}(t)$ for $t \geq 0$. In Section 3.3, we showed that $w^{mr}(0) = R/N$ and $\dot{w}^{mr} \leq 0$, which implies $w^{mr}(t) \leq R/N$ for $t \geq 0$. We showed earlier that $w^a(t) \geq R/N$ for $t \geq 0$ and so condition (iv) is established.

# 4 Empirical strategy

This section draws on the theoretical results from Section 3 to inform our empirical strategy. We first introduce our estimand of interest. We then propose a spatial RD estimator that exploits the incomplete nature of property rights over the Mojave aquifer. Theoretical predictions from Section 3 inform the relationship between the spatial RD estimate and the estimand, what drives the RD estimate, and how the RD estimate varies over time.

## 4.1 Causal estimand

We are interested in whether the Mojave aquifer's incomplete property rights regime led to net benefits for landowners that receive property rights relative to a full open access counterfactual. For the population of parcels that received property rights, indexed by $i = 1, ..., N$, this is the difference in potential outcomes $V_i^{mr}$ (see equation (13)) and $V_i^a$ (see equation (3)). Our estimand of interest is the population average treatment effect:

$$\beta = \underbrace{\mathop{\mathbb{E}}_i[V_i^{mr} - V_i^a]}_{\lesseqqgtr 0} \tag{16}$$

$\beta$ is the average net benefit of property rights to adjudicated landowners relative to the full open access counterfactual. By Proposition 1(a), $\beta$ is of unknown sign. This is because relative to a full open access regime, parcels with property rights benefit from a higher water table and the ability to sell rights, but also bear the cost of restricted pumping. Unfortunately, $\beta$ cannot be directly estimated since $V_i^{mr}$ and $V_i^o$ are potential outcomes under counterfactual states and thus are not simultaneously observed (Holland, 1986).

### 4.2 Spatial regression discontinuity estimator

Instead, we consider a spatial RD estimator that exploits the incomplete property rights boundary of the Mojave adjudication regime. Define $d_i$ as parcel $i$'s distance to the property right boundary of the property rights regime. $d_i$ is normalized so that a parcel is under property rights when $d_i \geq 0$ (i.e., blue area inside the red and purple-lined box in Figure 2) and under open access when $d_i < 0$ (i.e., blue area outside the red and purple-lined box in Figure 2). Our spatial RD estimator is:

$$\begin{aligned} \hat{\beta}^{RD} &= \underset{d_i \downarrow 0}{\mathbb{E}}\left[V_i^{mr}\right] - \underset{d_i \uparrow 0}{\mathbb{E}}\left[V_i^{ma}\right] \\ &= \underbrace{\underset{i:d_i=0}{\mathbb{E}}\left[V_i^{mr} - V_i^{ma}\right]}_{\lesseqgtr 0} \end{aligned} \tag{17}$$

where the first equality defines our spatial RD estimator at the property rights boundary. The second equality uses the RD identifying assumption that expected land price under open access is continuous at the boundary, $d_i = 0$.[18] In particular, it implies that the water table height $h_i(d_i)$ and other unobserved characteristics are continuous at $d_i = 0$. While $\hat{\beta}^{RD}$ removes the benefit of a water table, the remaining opposing influences of gains from rights trading and losses from pumping restrictions imply that $\hat{\beta}^{RD}$ remains of unknown sign, as indicated by Proposition 1(b).

How does $\hat{\beta}^{RD}$ relate to $\beta$? There are both internal and external validity considerations. Turning first to internal validity, let us denote the local $\beta$ for parcels at the boundary as $\beta_{i:d_i=0}$. The difference between $\beta_{i:d_i=0}$ and $\hat{\beta}^{RD}$ is:

$$\beta_{i:d_i=0} - \hat{\beta}^{RD} = \underbrace{\underset{i:d_i=0}{\mathbb{E}}\left[(V_i^{mr} - V_i^{a}) - (V_i^{mr} - V_i^{ma})\right]}_{\geq 0}$$

where is weakly positive by Proposition 1(c). The RD estimator serves as a lower bound for the treatment effect at the boundary because it omits the benefit of a higher water table. This lower bound can also be interpreted from the perspective of spillover effects. As our theory shows, in an incomplete property rights regime, water from the property rights area spills into the open access area, raising land prices for remaining open access parcels. Because this spillover benefit would not occur under full open access, the RD estimator produces a

[18] Specifically, following Hahn, Todd and Klaauw (2001), the identifying assumption is

$$\mathbb{E}\left[V_i^{ma}\right] \text{ is continuous in } d_i \text{ at } d_i = 0$$

lower value than our estimand.

The external validity of our RD estimate depends on the spatial structure of other land parcel characteristics. Water levels increase as one moves into the property rights area away from the boundary. If other land parcel characteristics are uncorrelated with distance to the property rights boundary, then by Proposition 1(d), the treatment effect at the boundary serves as a further lower bound for the treatment effect in the interior of the property rights area. Thus, this orthogonality assumption, together with Propositions 1(c) and 1(d) jointly imply that the spatial RD estimate is a lower bound for the population average net benefit, $\hat{\beta}^{RD} < \beta$.

Our theory also highlights what drives the RD estimate. Specifically, we can write $\hat{\beta}^{RD}$ as the difference between equations (13) and (14) at the boundary:

$$\hat{\beta}^{RD} = \mathop{\mathbb{E}}_{i:d_i=0}\left[\underbrace{\int_0^{t^*}[\pi(w^{mr}(s), h(s, d_i = 0)) - \pi(w^{ma}(s), h(s, d_i = 0))]e^{-\delta s}ds}_{\leq 0 \text{ restriction cost}} \right.$$
$$\left. + \underbrace{F(t^*)e^{-\delta t^*} - \int_{t^*}^{\infty}\pi(w^{ma}(s), h(s, d_i = 0))e^{-\delta s}ds}_{\lesseqgtr 0 \text{ potential trading benefit}}\right]$$

$\hat{\beta}^{RD}$ is positive when the potential gains from selling pumping rights offset the cost of restricted pumping, and depends on the value of water for own use relative to its market value across the aquifer. When the value of own water use is high, so too is the cost of pumping restrictions under property rights relative to open access, resulting in a lower $\hat{\beta}^{RD}$. Alternatively, when the value of own water use is low, the gains from selling water rights to other users increase, which drives up $\hat{\beta}^{RD}$.

Finally, Section 3 defines land prices at the start of the program, when $t = 0$ or in 1996. $\hat{\beta}^{RD}$ using such land prices examines whether landowners received a positive stream of discounted net benefits when property rights was first introduced. Additionally, one may also be empirically interested in whether continuation of the policy since 1996 has been economically justified. Our theory is agnostic on this matter: Proposition 1(e) shows that the time derivative of the estimate effect at the boundary is of ambiguous sign. To test this, one can also examine land prices observed in later periods to estimate both an average RD effect over time, as well as separate RD effects for different periods since 1996.

# 5 Data

We collect data on assessed land value, parcel size, location, and most recent transaction year (known also as base year) from the San Bernardino County Assessor for 2015. We use assessed land values because California law requires assessors to include the value of water rights attached to a land parcel.[19] [20] This contrasts with publicly-recorded land sales which are not required to include water rights when such rights are jointly transferred with a land parcel, and thus may omit the value of water rights. We impose two sample restrictions. First, we restrict our sample to land parcels that were most recently transacted after 1996, the period after property rights were introduced. Second, we remove urban land parcels as they do not hold water rights.

Additional covariates include a parcel's average slope and aspect (compass direction), constructed from a USGS digital elevation map,[21] and whether a parcel is within one mile of a groundwater well, constructed using well completion reports from the USGS.[22]

# 6 Results

This section presents our main result, robustness checks, heterogeneity analyses, and quantifies the total net benefit of groundwater rights.

## 6.1 Specification

To estimate our RD coefficient, $\hat{\beta}^{RD}$, from Section 4.2, we follow Hahn, Todd and Klaauw (2001) and model log land value for parcel $i$ using a local polynomial regression

$$lnV_i = \beta^{RD} R_i + f(d_i) + \theta' \mathbb{X}_i + \epsilon_i, \tag{18}$$

where as in Section 4.2, $d_i$ is normalized distance to the boundary of the property rights regime. $R_i = \mathbf{1}\{d_i \geq 0\}$ is an indicator variable equaling 1 when parcel $i$ is in the property rights regime and 0 otherwise. $f(d_i)$ is a flexible local polynomial function that is fully

[19] See Sections 501 and 542 of the California Assessor's Handbook. Available here: http://www.boe.ca.gov/proptaxes/ahcont.htm. Personal communication with the San Bernardino County Assessor and Recorder's Office further confirms that assessors account for the value of water rights by looking to market information and not via a prescribed formula.

[20] California's Proposition 13 caps the rate of increase in assessed value during the period after a property sale. In Section 6.5, we discuss Proposition 13 in more detail and explore its implications for our results.

[21] Available here: https://viewer.nationalmap.gov/basic/

[22] Available here: https://data.ca.gov/dataset/well-completion-reports.

interacted with $R_i$, allowing for different parameters on either side of the boundary. For example, under a linear specification $f(d_i) = \alpha_1 + \alpha_2 d_i + \alpha_3 d_i R_i$.

In some models, we include a vector of covariates, $\mathbb{X}_i$, which contains a land parcel's average slope, average aspect, size, most recent transaction year, and a dummy for whether the parcel is within one mile of a groundwater well. For our baseline specification, standard errors are clustered at the zip code level to allow for arbitrary forms of heteroscedasticity and spatial autocorrelation across land parcels within the same zip code. To address the bias-precision trade-off inherent in RD designs, our baseline model uses a mean squared error (MSE) optimal RD bandwidth that is common across both sides of the threshold following Calonico, Cattaneo and Titiunik (2014) and Calonico et al. (2019). Observations within the bandwidth are uniformly weighted in our baseline model. Robustness checks will consider alternative error structures and bandwidth selection algorithms.

## 6.2 Covariate smoothness

To assess the validity of our RD estimator, we begin by examining whether relevant covariates exhibit discontinuities at the property rights boundary. Specifically, we estimate equation (18) modeling each covariate in $\mathbb{X}_i$ as a separate dependent variable. Each model uses a local linear function for $f(d_i)$ and excludes other covariates as regressors. Table 1 shows $\hat{\beta}^{RD}$ for each covariate, displayed across columns.

**Table 1:** Examining covariate smoothness

| | (1)<br>slope | (2)<br>aspect | (3)<br>near well? | (4)<br>size | (5)<br>transaction year |
|---|---|---|---|---|---|
| $\hat{\beta}^{RD}$ | 1.575<br>(1.271) | 11.291<br>(36.255) | -0.048<br>(0.104) | 9.660<br>(7.340) | -1.117<br>(0.872) |
| Observations | 3288 | 3288 | 3288 | 3288 | 3288 |

NOTES: Estimates of $\beta^{RD}$ from equation (18) with each covariate as outcome. Specification includes a local linear model for $f(d_i)$ and excludes $\mathbb{X}_i$. Estimating bandwidth from benchmark log land value model in column 1 of Table 2. Observations uniformly weighted within the bandwidth. Covariates indicated across columns rows. Average slope in column 1 is measured in degrees relative to level surface. Average aspect in column 2 is measured in compass direction between 0 and 360. Column 3 examines a dummy variable equaling one if a parcel is within 1 mile of a well. Column 4 examines parcel size in acres. Column 5 examines the most recent year in which the parcel was transacted. Standard errors clustered at the zip code level. *** p<0.01, ** p<0.05, * p<0.1.

In some places, the property rights boundary is defined according to the surface water drainage area of the Mojave River. Because this typically corresponds to a local elevation peak, surface topological features may vary systematically across the boundary. For example, the slope of the land may be asymmetric across the boundary, which would affect the marginal agricultural value of water. The aspect of the land, or its compass direction, may also vary systematically at the boundary, affecting sunlight exposure and thus the marginal agricultural value of water.[23] Columns 1 and 2 do not detect a discontinuity in parcel slope and aspect at the boundary. Using another proxy measure for the agricultural value of water, column 3 shows that the presence of a groundwater well within one mile of a parcel also does not differ across the boundary.

We further examine two covariates that may affect the interpretation of our RD results. If groundwater property rights led to consolidation or division of land parcels, there may be a discontinuity in land parcel size across the boundary. Column 4 finds that parcel size, measured in acres, does not jump at the boundary. Parcels under property rights may also be sold more or less recently. If so, this would complicate whether we can detect time-varying treatment effects, discussed further below. Column 5 does not detect a boundary discontinuity in a parcel's most recent transaction year.

## 6.3 RD estimate

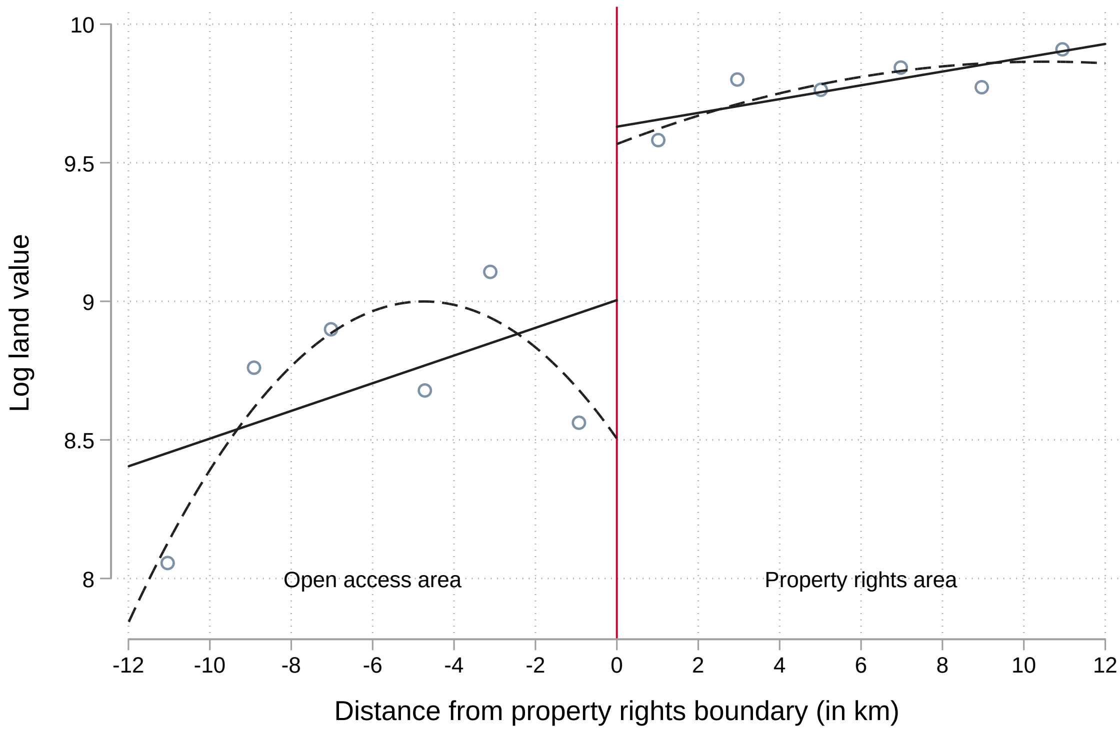
We first present our main RD result graphically. Figure 4 plots log land value, our main outcome of interest, against distance to the property rights boundary, $d_i$. Log land value is shown as local averages within 2 km-wide bins (circles) as well as separate linear (solid line) and quadratic (dashed line) fits over the unbinned data on each side of the discontinuity. Two features of Figure 4 are worth noting. First, there is a clear jump in land values at the discontinuity.[24] Second, we find that land values are generally increasing from left to right in Figure 4. This is consistent with our theoretical prediction that water table levels rise as one moves from the open access area into the interior of the property rights area.

We now turn to estimates of $\beta^{RD}$ from equation (18), shown in Table 2. Columns 1 and 3 model $f(d_i)$ using a local linear model while columns 2 and 4 use a local quadratic model. Columns 1 and 2 exclude covariates while columns 3 and 4 include covariates. We detect a positive and statistically significant RD effect across all columns. Translating these coefficients on binary treatment into percentage effects, we estimate a 190% to 280% increase in land value due to groundwater property rights at the boundary.

[23] We thank Jeff Vincent for this insight.

[24] A density continuity test based on Cattaneo, Jansson and Ma (2018) did not detect a discontinuity in the density of the distance variable at the RD threshold. We note that sorting around the threshold is of lesser concern with land parcels, particularly if there is no discontinuity in parcel size, as shown in column 4 of Table 1.

**Figure 4:** Graphical RD effect




NOTES: Vertical axes shows log land value. Horizontal axes shows normalized distance in kilometers, $d_i$, to property rights boundary with $d_i \geq 0$ indicating property rights area and $d_i < 0$ indicating open access area. Circles indicate average log land values within a 2 km-wide bin. Solid (dashed) line shows linear (quadratic) fit over unbinned data separately on each side of the boundary.

**Table 2:** Main RD results

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | Outcome is log land value | | | |
| $\hat{\beta}^{RD}$ | 1.327** | 1.328** | 1.256*** | 1.071** |
| | (0.519) | (0.583) | (0.452) | (0.447) |
| Percentage effect (%) | 277 | 277 | 251 | 192 |
| Polynomial order | 1 | 2 | 1 | 2 |
| Covariates | No | No | Yes | Yes |
| Bandwidth | 2.894 | 4.971 | 3.060 | 4.872 |
| Observations | 3288 | 5664 | 3513 | 5564 |

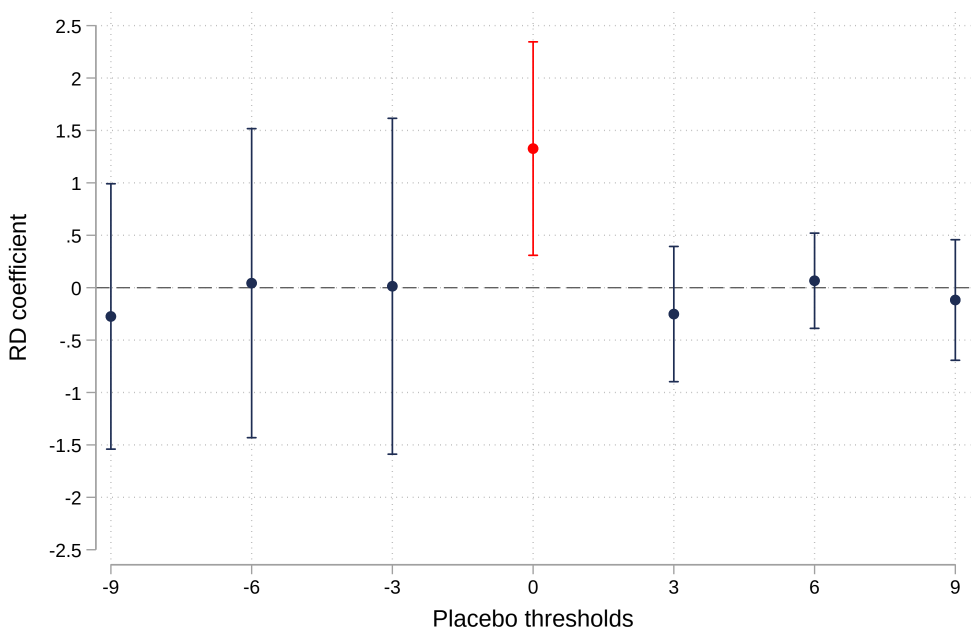
NOTES: Estimates of $\beta^{RD}$ from equation (18) with log land value as outcome. Columns 1 and 2 exclude covariates; columns 3 and 4 include covariates. Columns 1 and 3 use a local linear model for $f(d_i)$; columns 2 and 4 use a local quadratic model for $f(d_i)$. Estimating sample based on a common MSE-optimal bandwidth across both sides of the threshold (Calonico, Cattaneo and Titiunik, 2014). Observations uniformly weighted within the bandwidth. Percentage effects are $100(e^{\hat{\beta}^{RD}} - 1)$. Standard errors clustered at the zip code level. *** p<0.01, ** p<0.05, * p<0.1.

### 6.4 Additional robustness checks

We present several robustness checks. Throughout, the baseline model is shown in column 1 of Table 2.

Figure 5 and Table C.1 show RD estimates from equation (18) with the boundary threshold set to placebo distance values. We do not find discontinuities in land values when the boundary is falsely set within either the property rights or open access areas up to 9 kilometers away from the true boundary. Figure 6 and Table C.2 present additional estimates using bandwidths smaller than one-half and larger than twice that of the baseline MSE-optimal bandwidth. Our RD result is not sensitive to these different bandwidth sizes.

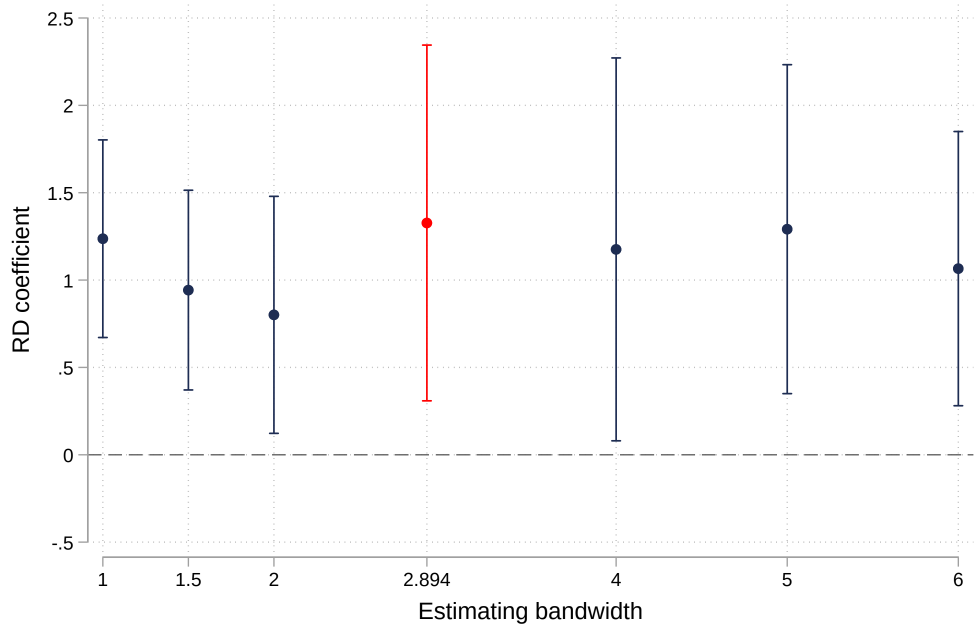
**Figure 5:** Robustness: placebo boundaries




NOTES: Estimates of $\beta^{RD}$ from equation (18) with placebo boundaries. Red indicates baseline estimate from column 1 of Table 2 using the true property rights boundary. 95% confidence intervals shown.

We also conduct several checks suggested by the recent RD literature. In Table C.3, we re-estimate the RD coefficient allowing the MSE-optimal bandwidth to differ on both sides of the discontinuity and consider bandwidths that are coverage error-rate (CER) optimal (Calonico, Cattaneo and Farrell, 2019). We also alternatively weight observations using a triangular, rather than a uniform, kernel. Our estimates do not change much with these modeling choices. Table C.4 considers alternative variance estimators. We show that our RD result is insensitive to whether variance estimation is robust to zip code-level clustering, nearest neighbor matching, or both.

**Figure 6:** Robustness: alternative bandwidths




NOTES: Estimates of $\beta^{RD}$ from equation (18) with different estimating bandwidths. Red indicates baseline model from column 1 of Table 2 using a MSE-optimal bandwidth. 95% confidence intervals shown.

## 6.5 Heterogeneity

We now turn to heterogeneity analyses, both across time and space.

Our main RD estimate pools together land parcels that were most recently transacted within the 1996-2015 period. How these transaction dates affect the interpretation of our main RD result requires a brief discussion of California's Proposition 13. Property taxes in California are based on assessed land values. Since 1978, Proposition 13 has limited property tax increases by placing a 2% cap on the annual appreciation of assessed land value for the period after a property sale. Strong housing demand in southern California over recent decades means that this 2% limit has regularly constrained increases in assessed value.[25] Under such circumstances, the 2015 assessed land values of a previously transacted parcel would not capture its 2015 market value but rather its price at the time of last sale, with a 2% annual adjustment. This, together with column 5 of Table 1 showing no boundary discontinuity in the most recent sales year, suggest that our main RD estimate likely reflects the average treatment effect of groundwater property rights across the 1996-2015 period, rather than the treatment effect for only 2015. A natural question then is whether the

[25] Using assessed land values in 2000, we calculate that between 2000 and 2015, Proposition 13's 2% annual limit was binding for 80% of land parcels in our sample that were last sold before 2000.

net benefit of groundwater property rights has evolved since adjudication was completed in 1996. Since Proposition 1(e) shows that the time derivative of discounted net benefits is ambiguously signed, we turn to empirical tests shown in Table 3.

**Table 3:** Heterogeneity across time

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | Outcome is log land value | | | | | |
| $\hat{\beta}^{RD}$ | 1.327** | 1.440** | 1.449*** | 1.233* | 1.489 | 1.517** |
| | (0.519) | (0.668) | (0.498) | (0.748) | (0.977) | (0.597) |
| Transaction year | 1997-2015 | 1997-2003 | 2004-2009 | 2010-2015 | 2015 | 2015 |
| Bandwidth | 2.894 | 2.894 | 2.894 | 2.894 | 2.894 | 3.176 |
| Observations | 3288 | 722 | 1441 | 1125 | 192 | 220 |

NOTES: Estimates of $\beta^{RD}$ from equation (18) with log land value as outcome. All models use a local linear model for $f(d_i)$, include covariates, restrict sample based on a common MSE-optimal bandwidth across both sides of the threshold (Calonico, Cattaneo and Titiunik, 2014), and uniformly weight observations. Column 1 replicates baseline model in column 1 of Table 2. Columns 2-4 estimate baseline model using the baseline bandwidth for the subsample of parcels most recently transacted in 1997-2013, 2004-2009, and 2010-2015, respectively. Column 5 estimates the baseline model using the baseline bandwidth for the subsample of parcels most recently transacted in 2015. Column 6 estimates baseline model for the subsample of parcels most recently transacted in 2015, but uses a MSE-optimal bandwidth for that subsample. *** p<0.01, ** p<0.05, * p<0.1.

Column 1 of Table 3 reproduces our benchmark RD estimate, pooling 1997-2015 transaction years. Columns 2-4 estimate our baseline model using the same bandwidth as in column 1, but for separate subsamples of parcels that were most recently transacted during the 1997-2013, 2004-2009, and 2010-2015 periods, respectively. Remarkably, the discounted net benefit of groundwater property rights has changed very little since 1996. That our estimates remain positive across time suggests that the continuation of this policy since 1996 has been economically justified.

Regardless of whether or not Proposition 13's 2% limit binds, the assessed value of a parcel not transacted that year will necessarily be a noisy measure of its actual market value. To isolate parcels whose assessed values more closely reflects their market values, columns 5 and 6 of Table 3 estimate our baseline model for the subsample of parcels that were transacted in 2015, the same year as our assessed land value data. For consistency with other results, column 5 uses the distance bandwidth used for our baseline sample, while column 6 employs a distance bandwidth that is MSE-optimal for the subsample of 2015-transacted parcels. We find again that these subsamples produce RD effects that are similar to our baseline result.

Section 4.2 shows that besides serving as a lower bound for the population average treatment effect, our spatial RD estimate also captures the incentive to participate in a property rights regime. Our theory postulates that the strength of this incentive depends on the market value of water (i.e., "salvage value"). When this outside value is higher than one's own value of water, tradeable property rights allow landowners to gain by selling water rights to other users in the aquifer. For groundwater in the Mojave, this higher-value use is likely strongest in the more urban southern part of the aquifer which is part of the expanding urban periphery of Los Angeles (see inset map in Figure 2).

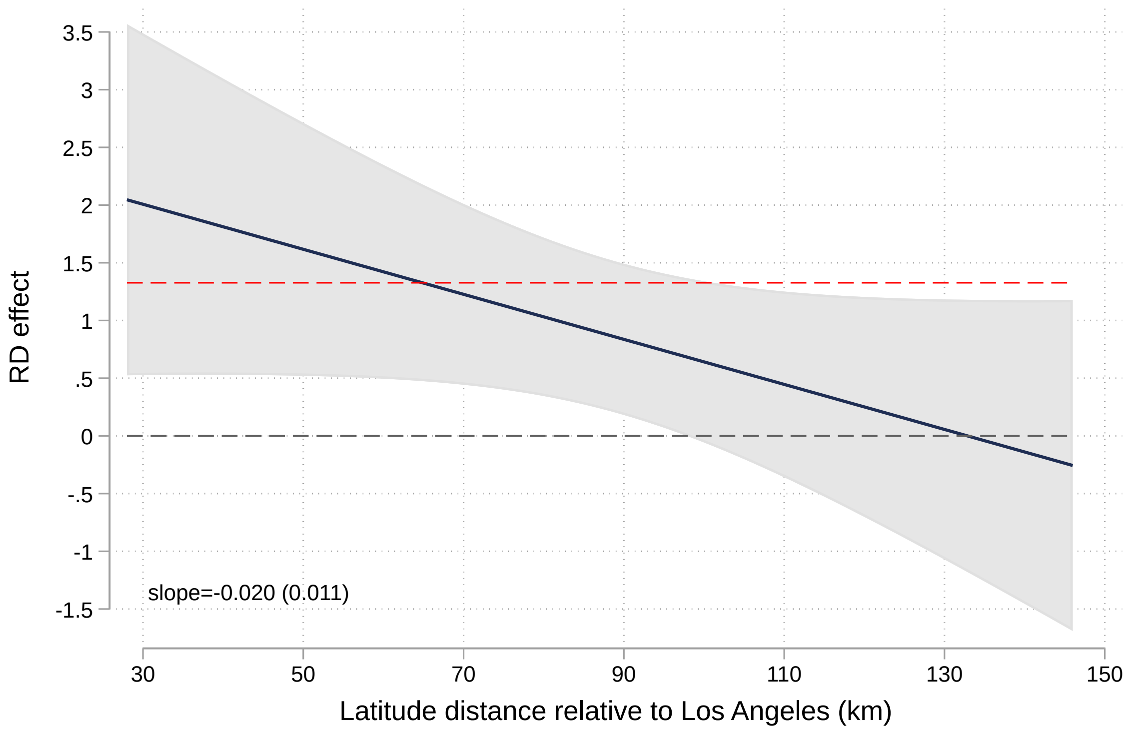
**Table 4:** Heterogeneity across space

| | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| | Outcome is log land value | | | | |
| $\hat{\beta}^{RD}$ | 1.327** | 1.984** | 0.334 | 1.219*** | 0.017 |
| | (0.519) | (0.845) | (0.464) | (0.401) | (0.841) |
| Area | All | South | North | South | North |
| Boundary definition | All | All | All | River basin | River basin |
| Bandwidth | 2.894 | 2.894 | 2.894 | 2.894 | 2.894 |
| Observations | 3288 | 2412 | 876 | 166 | 535 |

Notes: Estimates of $\beta^{RD}$ from equation (18) with log land value as outcome. All models use a local linear model for $f(d_i)$, include covariates, restrict sample based on a common MSE-optimal bandwidth across both sides of the threshold (Calonico, Cattaneo and Titiunik, 2014), and uniformly weight observations. Column 1 replicates baseline model in column 1 of Table 2. Columns 2 and 3 restrict the sample to land parcels in southern and northern subareas, respectively. Columns 4 and 5 further restrict the southern and northern subarea sample, respectively, by including only parcels whose nearest property rights boundary is defined by the Mojave River drainage basin. Standard errors clustered at the zip code level. *** p<0.01, ** p<0.05, * p<0.1.

To test whether potential urban water demand creates larger benefits from property rights, Table 4 examines heterogeneity in the RD coefficient for southern and northern subareas of the aquifer. Column 1 replicates our baseline results. Column 2 restricts the sample to parcels in the southern subareas, while only northern subarea parcels are considered in column 3. The RD coefficient in the southern subareas of the aquifer is almost six times larger than in the northern subareas. As an alternative way to model this heterogeneity, we interact $R_i$ and $f(d_i)$ from our baseline model of equation (18) with a parcel's latitude, relative to the centroid of the City of Los Angeles. Figure 7 plots how $\hat{\beta}^{RD}$ varies as one moves northward across the aquifer, showing a statistically significant decline of 0.02 per kilometer. For sample parcels that are farthest north, the RD effect becomes negative. Larger RD effects for southern parcels is consistent with our theoretical prediction that landowners benefit from tradeable property rights by having the option to sell rights to higher-value urban use.

**Figure 7:** Heterogeneity: south to north




NOTES: Plot shows heterogeneity in $\hat{\beta}^{RD}$ as a function of a parcel's latitude, relative to the centroid of Los Angeles. Point estimate and standard error on slope shown. Horizontal red dashed line shows baseline uninteracted RD effect from column 1 of Table 2. 95% confidence intervals shown.

Next, the RD effect may be heterogeneous depending on how the boundary is defined. In column 4 of Table 4, we further restrict the sample of southern subarea parcels to those whose nearest property right boundary is defined by the spatial extent of the Mojave River drainage basin (shown by purple line segments in Figure 2) and not the Mojave Water Agency (shown by red line segments in Figure 2). We find a similar RD effect as that shown in column 2. Likewise, column 5 shows that the RD effect for northern subareas are similar across the two boundary definitions. Thus, it does not appear that our RD effect differs systematically by how the property rights boundary is defined.[26]

[26] Figure 2 shows that property rights boundary segments defined by the Mojave River drainage basin (shown by purple line segments) are better represented in the northern parts of the property rights area. Thus, an RD estimate using all parcels near the Mojave River drainage basin boundary would have more northern subarea parcels and would not be comparable to an RD estimate using all parcels near the Mojave Water Agency boundary. Table 4 addresses this by examining whether RD estimates differ by boundary definition separately for northern and southern subsamples. Alternatively, we also follow Gerardino, Litschig and Pomeranz (2017) by running an RD subsample test that weights all parcels by their latitude and do not find RD estimates that differ by boundary definition.

### 6.6 Total net benefit of property rights

Lastly, we quantify the total net benefit of groundwater property rights across all adjudicated parcels in the Mojave aquifer.

Section 4.2 notes that our RD estimate is a lower bound on the local average treatment effect for adjudicated parcels at the boundary. Additionally, if one assumes that unobserved characteristics are uncorrelated with distance to the boundary, our RD estimate further serves as a lower bound for the population average treatment effect of all adjudicated parcels. This orthogonality assumption, together with the south-north heterogeneity in the RD coefficient enables a lower bound calculation for the total net benefit of property rights across adjudicated parcels.

To that end, we multiply the heterogeneous RD effect separately for parcels in southern (i.e., column 2 of Table 4) and northern (i.e., column 3 of Table 4) subareas with each parcel's land value. We then sum this product across all non-urban land parcels in the property rights area.[27] This results in a lower bound total net benefit of groundwater property rights of $477 million (in 2015 dollars), or a 53% increase in total land value.[28] By contrast, the initial administrative cost of setting up the adjudication system is estimated at $40 million (in 2015 dollars) (Figueroa, 2001).

## 7 Conclusion

Property rights are widely advocated as a solution to the tragedy of the commons, but causal empirical evidence on their effectiveness in practice has been lacking. This paper applies a spatial regression discontinuity design to quantify the net benefit of using property rights to manage a common-pool resource. We find that the introduction of tradeable groundwater property rights for a major aquifer in southern California led to substantial gains, as captured by higher land values. Using a model of dynamic groundwater extraction, we show that our RD estimate corresponds to a lower bound on the net benefit of property rights. Additional analyses suggest that a key component of these benefits is the tradeability of property rights, which enable more efficient allocation of water away from water-intensive agriculture to urban residential use.

Our findings can inform efforts to address overextraction of other common-pool resources, such as fisheries, forests, and the global climate. For groundwater in particular, California

[27] We exclude urban land parcels because they do not hold groundwater rights.

[28] Observe that by Proposition 1(c), this value is yet another lower bound for the total net benefit of groundwater property rights for all parcels overlying the aquifer, both those with property rights and under open access.

recently passed the Sustainable Groundwater Management Act, an unprecedented policy requiring users of overextracted aquifers to adopt management plans to achieve sustainable use. While it remains contentious which management tools should be employed, this paper's findings suggest that tradeable property rights can help stabilize groundwater levels, increase land value, and induce more efficient water use. Users and regulators alike may reference these benefits in future efforts to establish property rights for groundwater and common-pool resources more generally.

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# Appendix – For Online Publication

## A Theory appendix

This section derives Proposition 1.

**Proposition 1(a): $V^{mr} - V^a \gtreqless 0$**

Using equations (3) and (13), define

$$V^{mr} - V^a = \int_0^{t^*} \pi(w^{mr}(s), \bar{h}^{mr}) e^{-\delta s} ds + F(t^*) e^{-\delta t^*} - \int_0^{\infty} \pi(w^a(s), h^a(s)) e^{-\delta s} ds$$

which we now examine separately for each period.

**Before rights are sold: $t \in [0, t^*]$** The difference in discounted profit before $t^*$ is

$$\begin{aligned} \int_0^{t^*} \left[\pi(w^{mr}(s), \bar{h}^{mr}) - \pi(w^a(s), h^a(s))\right] e^{-\delta s} ds = \int_0^{t^*} \Bigg[ & \underbrace{\pi(w^{mr}(s), \bar{h}^{mr}) - \pi(w^a(s), \bar{h}^{mr})}_{\leq 0} \\ & + \underbrace{\pi(w^a(s), \bar{h}^{mr}) - \pi(w^a(s), h^a(s))}_{\geq 0} \Bigg] e^{-\delta s} ds \\ & \gtreqless 0 \end{aligned} \tag{A.1}$$

where the first bracketed term in equation (A.1) is weakly negative because for $\bar{h}^{mr}$, $\pi(w, \bar{h}^{mr})$ is optimal at $w^a(h_0)$ and $w^a(h_0) \geq w^a(t) \geq w^{mr}(t)$ for $t \geq 0$. The second bracketed term in equation (A.1) is weakly positive because $\bar{h}^{mr} \geq h^a(t)$ for $t \geq 0$ and $\pi_h > 0$.

**After rights are sold: $t \in [t^*, \infty]$** The difference in discounted profit after $t^*$ is

$$\begin{aligned} F(t^*) e^{-\delta t^*} - \int_{t^*}^{\infty} \pi(w^a(s), h^a(s)) e^{-\delta s} ds = & \underbrace{F(t^*) e^{-\delta t^*} - \int_{t^*}^{\infty} \pi(w^{mr}(s), \bar{h}^{mr}(s)) e^{-\delta s} ds}_{\geq 0} \\ & + \int_{t^*}^{\infty} \Bigg[ \underbrace{\pi(w^{mr}(s), \bar{h}^{mr}(s)) - \pi(w^a(s), h^a(s))}_{\gtreqless 0} \Bigg] e^{-\delta s} ds \\ & \gtreqless 0 \end{aligned} \tag{A.2}$$

where the first bracketed term in equation (A.2) is weakly positive because $t^*$ solves the optimization problem in equation (11). The second bracketed term in equation (A.2) is ambiguously signed by equation (A.1).

$V^{mr} - V^a \gtreqless 0$ follows from summing the terms in equations (A.1) and (A.2).

**Proposition 1(b): $\boldsymbol{V^{mr} - V^{ma} \gtreqless 0}$**

Using equations (13) and (14), define

$$V^{mr} - V^{ma} = \int_0^{t^*} \pi(w^{mr}(s), \bar{h}^{mr})e^{-\delta s}ds + F(t^*)e^{-\delta t^*} - \int_0^{\infty} \pi(w^{ma}(s), h^{ma}(s))e^{-\delta s}ds$$

which we now examine separately for each period.

**Before rights are sold: $\boldsymbol{t \in [0, t^*]}$** The difference in discounted profit before $t^*$ is

$$\begin{aligned}\int_0^{t^*} \left[\pi(w^{mr}(s), \bar{h}^{mr}) - \pi(w^{ma}(s), h^{ma}(s))\right] e^{-\delta s}ds &= \int_0^{t^*} \Bigg[\underbrace{\pi(w^{mr}(s), \bar{h}^{mr}) - \pi(w^{ma}(s), \bar{h}^{mr})}_{\leq 0} \\ &\quad + \underbrace{\pi(w^{ma}(s), \bar{h}^{mr}) - \pi(w^{ma}(s), h^{ma}(s))}_{\geq 0}\Bigg] e^{-\delta s}ds \\ &\gtreqless 0\end{aligned} \tag{A.3}$$

where the first bracketed term in equation (A.3) is weakly negative because for $\bar{h}^{mr}$, $\pi(w, \bar{h}^{mr})$ is optimal at $w^a(h_0)$ and $w^a(h_0) \geq w^{ma}(t) \geq w^{mr}(t)$ $t \geq 0$. The second bracketed term in equation (A.1) is weakly positive because $\bar{h}^{mr} \geq h^{ma}(t)$ for $t \geq 0$ and $\pi_h > 0$.

**After rights are sold: $\boldsymbol{t \in [t^*, \infty]}$** The difference in discounted profit after $t^*$ is

$$\begin{aligned}F(t^*)e^{-\delta t^*} - \int_{t^*}^{\infty} \pi(w^{ma}(s), h^{ma}(s))e^{-\delta s}ds &= \underbrace{F(t^*)e^{-\delta t^*} - \int_{t^*}^{\infty} \pi(w^{mr}(s), \bar{h}^{mr}(s))e^{-\delta s}ds}_{\geq 0} \\ &\quad + \int_{t^*}^{\infty} \Bigg[\underbrace{\pi(w^{mr}(s), \bar{h}^{mr}(s)) - \pi(w^{ma}(s), h^{ma}(s))}_{\gtreqless 0}\Bigg] e^{-\delta s}ds \\ &\gtreqless 0\end{aligned} \tag{A.4}$$

where the first bracketed term in equation (A.4) is weakly positive because $t^*$ solves the maximization problem in equation (11). The second bracketed term in equation (A.4) is ambiguously signed by equation (A.3).

$V^{mr} - V^{ma} \gtreqless 0$ follows from summing the terms in equations (A.3) and (A.4).

**Proposition 1(c): $(V^{mr}(h^b) - V^a) - (V^{mr}(h^b) - V^{ma}(h^b) \geq 0$**

Using equations (3) and (14), define

$$
\begin{aligned}
(V^{mr}(h^b) - V^a) - (V^{mr}(h^b) - V^{ma}(h^b) &= V^{ma}(h^b) - V^a \\
&= \int_0^\infty \left[\pi(w^{ma}(s), h^b(s)) - \pi(w^a(s), h^a(s))\right] e^{-\delta s} ds \\
&= \int_0^\infty \Bigg[\underbrace{\pi(w^{ma}(s), h^b(s)) - \pi(w^a(s), h^b(s))}_{\geq 0} \\
&+ \underbrace{\pi(w^a(s), h^b(s)) - \pi(w^a(s), h^a(s))}_{\geq 0}\Bigg] e^{-\delta s} ds \qquad \text{(A.5)} \\
&\geq 0
\end{aligned}
$$

where the first bracketed term in equation (A.5) is weakly positive because for $h^b(t)$, $\pi(w, h^b(t))$ is maximized at $w^{ma}(t)$ for $t \geq 0$. The second bracketed term in equation (A.5) is weakly positive because $h^b(t) \geq h^a(t)$ since $h^{ma}(t) \geq h^a(t)$ and $h^b(t) \geq h^{ma}(t)$for $t \geq 0$ and $\pi_h > 0$.

**Proposition 1(d): $(V^{mr} - V^a) - (V^{mr}(h^b) - V^a) \geq 0$**

Using equation (13), define

$$
\begin{aligned}
(V^{mr} - V^a) - (V^{mr}(h^b) - V^a) &= V^{mr} - V^{mr}(h^b) \\
&= \int_0^{t^*} [\underbrace{\pi(w^{mr}(s), \bar{h}^{mr}) - \pi(w^{mr}(s), h^b(s))}_{\geq 0}] e^{-\delta s} ds \qquad \text{(A.6)} \\
&\geq 0
\end{aligned}
$$

where the bracketed term in equation A.6 is weakly positive because $\bar{h}^{mr} \geq h^b(t)$ for $t \geq 0$ and $\pi_h > 0$.

**Proposition 1(e): $\frac{d}{dt}(V^{mr}(h^b) - V^{ma}(h^b)) \gtreqless 0$**

Using equations (13) and (14), the estimated effect at the boundary at any time $t$ is

$$V^{mr}(h^b) - V^{ma}(h^b) = \int_t^{t^*} \pi(w^{mr}(s), h^b(s))e^{-\delta(s-t)}ds + F(t^*)e^{-\delta(t^*-t)} - \int_t^{\infty} \pi(w^{ma}(s), h^b(s))e^{-\delta(s-t)}ds$$

Using Liebnitz's Rule, we obtain

$$\frac{d}{dt}(V^{mr}(h^b) - V^{ma}(h^b)) = \delta[V^{mr}(h^b) - V^{ma}(h^b)] + [\underbrace{\pi(w^{ma}(t), h^b(t)) - \pi(w^{mr}(t), h^b(t))}_{\geq 0}]$$

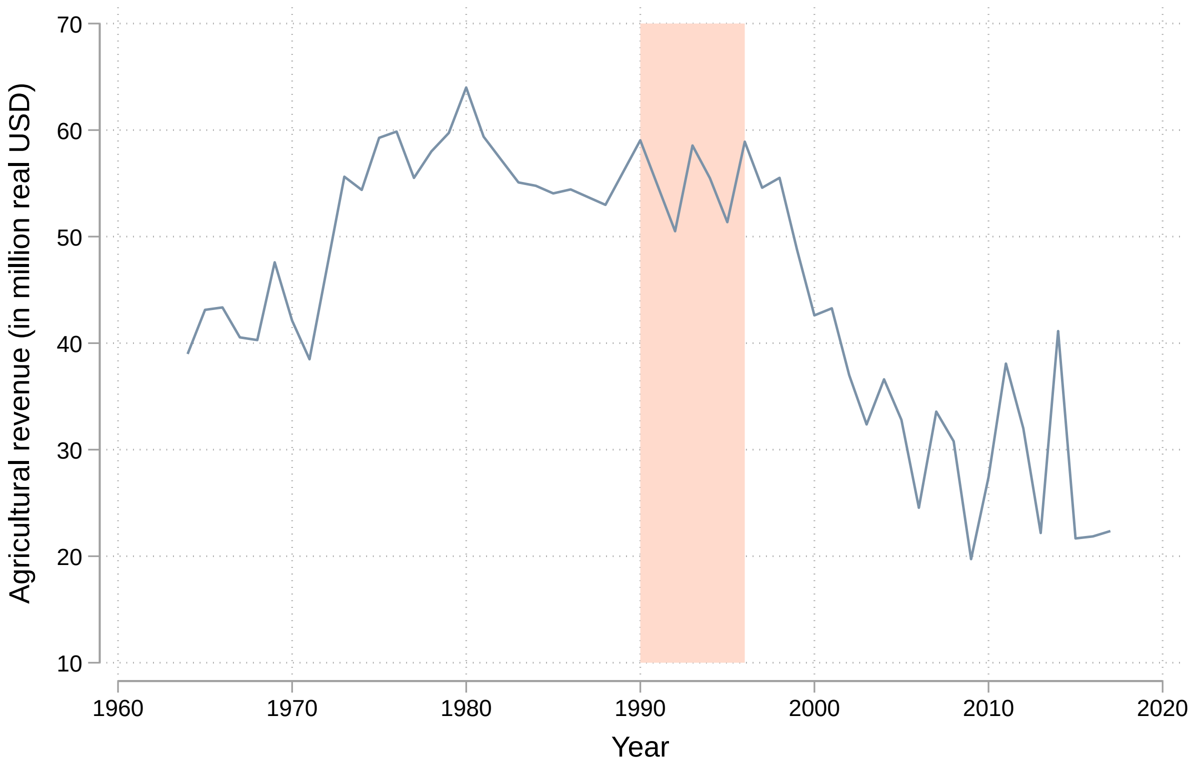
The second bracketed term is weakly positive because for $h^b(t)$, $\pi(w, h^b(t))$ is maximized at $w^{ma}(t)$ for $t \geq 0$. The first bracketed term is

$$V^{mr}(h^b) - V^{ma}(h^b) = \int_t^{t^*} [\underbrace{\pi(w^{mr}(s), h^b(s)) - \pi(w^{ma}(s), h^b(s))}_{\leq 0}]e^{-\delta(s-t)}ds + \underbrace{F(t^*)e^{-\delta(t^*-t)} - \int_{t^*}^{\infty} \pi(w^{ma}(s), h^b(s))e^{-\delta(s-t)}ds}_{\gtreqless 0}$$

The second term is ambiguously signed since our model imposes no constraints on the value of $F(t^*)$. Thus, $\frac{d}{dt}(V^{mr}(h^b) - V^{ma}(h^b)) \gtreqless 0$.

# B Appendix Figures

**Figure B.1:** Agricultural revenue before and after property rights




NOTES: Plot shows agricultural revenue (in real million USD) for the Mojave Desert from 1960-2017. Data takes the sum of revenue from the North and South Desert regions of San Bernardino county, obtained from the San Bernardino county Annual Crop Reports. Orange-shaded area marks the period from 1990 when the initial adjudication lawsuit was filed to 1996 when the final adjudication court ruling was issued.

# C Appendix Tables

**Table C.1:** Robustness: placebo boundaries

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| | Outcome is log land value | | | | | | |
| $\hat{\beta}^{RD}$ | -0.274 | 0.043 | 0.014 | 1.327** | -0.252 | 0.066 | -0.117 |
| | (0.646) | (0.752) | (0.817) | (0.519) | (0.329) | (0.232) | (0.293) |
| RD threshold | -9 | -6 | -3 | 0 | 3 | 6 | 9 |
| Bandwidth | 2.009 | 2.221 | 6.318 | 2.894 | 4.092 | 3.210 | 3.673 |
| Observations | 197 | 387 | 4382 | 3288 | 7077 | 6388 | 6851 |

NOTES: Estimates of $\beta^{RD}$ from equation (18) with log land value as outcome. All models use a local linear model for $f(d_i)$, include covariates, restrict sample based on a common MSE-optimal bandwidth across both sides of the threshold (Calonico, Cattaneo and Titiunik, 2014), and uniformly weight observations. RD thresholds, in distance to true property rights boundary, vary by column. Column 4 replicates baseline model in column 1 of Table 2 with true boundary threshold. Standard errors clustered at the zip code level. *** p<0.01, ** p<0.05, * p<0.1.

**Table C.2:** Robustness: alternative bandwidths

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| | Outcome is log land value | | | | | | |
| $\hat{\beta}^{RD}$ | 1.327** | 1.237*** | 0.943*** | 0.801** | 1.176** | 1.291*** | 1.066*** |
| | (0.519) | (0.289) | (0.292) | (0.346) | (0.559) | (0.480) | (0.400) |
| Bandwidth | 2.894 | 1.000 | 1.500 | 2.000 | 4.000 | 5.000 | 6.000 |
| Observations | 3288 | 1079 | 1601 | 2151 | 4609 | 5684 | 6653 |

NOTES: Estimates of $\beta^{RD}$ from equation (18) with log land value as outcome. All models use a local linear model for $f(d_i)$, include covariates, and uniformly weights observations. Column 1 replicates baseline model in column 1 of Table 2 with sample restriction based on a common MSE-optimal bandwidth across both sides of the threshold (Calonico, Cattaneo and Titiunik, 2014). Column 2-7 use narrower and wider bandwidths, imposing the same value for both the main and bias bandwidths. Standard errors clustered at the zip code level. *** p<0.01, ** p<0.05, * p<0.1.

**Table C.3:** Robustness: optimal bandwidth selector

| | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| | Outcome is log land value | | | | |
| $\hat{\beta}^{RD}$ | 1.327** | 1.234** | 0.977* | 1.176** | 1.181** |
| | (0.519) | (0.537) | (0.542) | (0.501) | (0.495) |
| Optimal bandwidth selector | MSE-1 | MSE-2 | CER-1 | CER-2 | MSE-1 |
| Kernel | uniform | uniform | uniform | uniform | triangular |
| Bandwidth | 2.894 | 2.559/5.038 | 2.423 | 2.142/4.218 | 3.355 |
| Observations | 3288 | 5153 | 2611 | 4317 | 3864 |

Notes: Estimates of $\beta^{RD}$ from equation (18) with log land value as outcome. All models use a local linear model for $f(d_i)$, and include covariates. Columns 1-4 uniformly weights observations. Column 1 replicates baseline model in column 1 of Table 2 with sample restriction based on a common MSE-optimal bandwidth across both sides of the threshold (Calonico, Cattaneo and Titiunik, 2014) Column 2 allows the MSE-optimal bandwidth to differ on both sides. Column 3 uses a common coverage error-rate (CER) optimal bandwidth (Calonico, Cattaneo and Farrell, 2019). Column 4 allows the CER-optimal bandwidth to differ on both sides. Column 5 uses a common MSE-optimal bandwidth but weights observations using a triangular kernel. Standard errors clustered at the zip code level. *** p<0.01, ** p<0.05, * p<0.1.

**Table C.4:** Robustness: alternative variance estimators

| | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| | Outcome is log land value | | | | |
| $\hat{\beta}^{RD}$ | 1.327** | 1.098*** | 1.013*** | 1.017*** | 1.259*** |
| | (0.519) | (0.159) | (0.160) | (0.161) | (0.428) |
| Standard error | zipcode cluster | 50 NN | 100 NN | 200 NN | 200 NN/ zipcode cluster |
| Bandwidth | 2.894 | 2.644 | 2.574 | 2.568 | 3.456 |
| Observations | 3288 | 2902 | 2822 | 2815 | 3978 |

Notes: Estimates of $\beta^{RD}$ from equation (18) with log land value as outcome. All models use a local linear model for $f(d_i)$, include covariates, restrict sample based on a common MSE-optimal bandwidth across both sides of the threshold (Calonico, Cattaneo and Titiunik, 2014), and uniformly weights observations. Column 1 replicates column 1 of Table 2 using standard errors clustered at the zip code level. Columns 2, 3, and 4 use a nearest neighbor variance estimator with 50, 100 and 200 minimum nearest neighbors (NN). Column 5 uses a zip code cluster-robust, nearest neighbor variance estimator with 200 minimum nearest neighbors. *** p<0.01, ** p<0.05, * p<0.1.