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DO ENVIRONMENTAL MARKETS IMPROVE ON OPEN ACCESS?EVIDENCE FROM CALIFORNIA GROUNDWATER RIGHTS

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ABSTRACT

Environmental markets are widely prescribed as an alternative to open-access regimes for natural resources. We develop a model of dynamic groundwater extraction to demonstrate how a spatial regression discontinuity design that exploits a spatially-incomplete market for groundwater rights recovers a lower bound on the market's net benefit. We apply this estimator to a major aquifer in water-scarce southern California and find that a groundwater market generated substantial net benefits, as capitalized in land values. Heterogeneity analyses reveal that gains arise in part from rights trading, enabling more efficient water use across sectors. Additional findings suggest the market increased groundwater levels.

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1 Introduction

For almost two centuries, scholars have recognized that common-pool resources, if left under open-access conditions, tend to be used inefficiently (Lloyd, 1833; Coman, 1911; Gordon, 1954; Hardin, 1968; Ostrom, 1990). This issue is even more relevant today, with increasing concern over the status of natural resources such as fresh water, fisheries, and the global climate (Stavins, 2011).

In many settings, this "problem of the commons" arises because a market for property rights to the resource is missing (Coase, 1960). This insight underlies the modern framework for environmental markets - as suggested by Crocker (1966) and Dale (1968) and formalized by Montgomery (1972) - whereby a regulator sets a limit on total extraction, allocates extraction rights to users equaling this total, and oversees rights trading.[1] Today, some form of environmental market covers 30% of global fisheries (Costello et al., 2016), accounts for over $36 billion in global ecosystem service payments (Salzman et al., 2018), and governs over 10% of global greenhouse gas (GHG) emissions (World Bank Group, 2020).[2]

The effectiveness of environmental markets, however, is predicated on a number of theoretical assumptions. A large literature has explored how the presence of market power (Hahn, 1984; Malueg, 1990), inadequate enforcement (Malik, 1990), transaction costs (Stavins, 1995), and other features (see Cropper and Oates (1992)) may adversely affect environmental market performance. Given how pervasive these features are in practice,[3] it is an empirical question whether net benefits arise when an environmental market replaces an open-access regime, and if so, why.

Researchers face three empirical challenges when quantifying the net benefit of an environmental market. First, one must track all agents that are directly affected by the regulated environmental good. This may be difficult for goods such as air quality where the (possibly unobserved) set of beneficiaries is highly dispersed. Second, one needs a measure of the good's economic value, which in the case of a stock resource such as groundwater or fish must reflect both current and future values. Third, environmental markets are often adopted when a resource is in a critical state of overextraction (Shertzer and Prager, 2006; Costello, Gaines and Lynham, 2008; Worm et al., 2009; Mangin et al., 2018). As such, simple comparisons between resources governed by a market and under open-access conditions may

[1]This additional structure overcomes some practical impediments to Coase's original formulation. In particular, having a regulator set a total extraction limit and manage rights trading can avoid transactions costs that may limit Coasian bargaining.

[2]In fisheries, such policies are often called rights-based management or individualized tradeable quotas. For air pollution and greenhouse gas emissions, they are typically known as cap-and-trade.

[3]Recent surveys of implemented environmental markets can be found in Tietenberg (2003), Freeman and Kolstad (2006), Goulder (2013), and Schmalensee and Stavins (2017).

be confounded by differences in unobserved resource characteristics.

This paper studies a particular market for groundwater rights in southern California's Mojave Desert.[4] We select this setting for two reasons. First, groundwater is a critical and increasingly scarce natural resource. It provides 50% of potable and 40% of irrigation water globally (Giordano, 2009; Aeschbach-Hertig and Gleeson, 2012), yet one-third of the world's largest aquifers are facing declining water levels (Richey et al., 2015). Moreover, groundwater scarcity is expected to worsen under demographic trends and anthropogenic climate change (Vörösmarty et al., 2000; Covich, 2009; McDonald et al., 2011; Prudhomme et al., 2014; Elliott et al., 2014; Ferguson et al., 2018). Second, our setting addresses the aforementioned empirical challenges. Land parcels within a known area possess tradeable groundwater rights, the current and future values of which are capitalized in land values. Importantly, this market for groundwater rights does not cover the entire aquifer, allowing us to address endogeneity concerns by applying a spatial regression discontinuity (RD) design across the groundwater market boundary.

Our identification strategy leans heavily on renewable resource theory. The estimand of interest is the parcel-averaged difference in (potential) land prices between a groundwater market and a open-access regimes. As in any potential outcomes framework, this difference cannot be estimated because land prices are not observed under both regimes. However, when a groundwater market does not spatially cover the entire aquifer, an opportunity arises for comparing land prices of parcels subject to the groundwater market with that of parcels under open access, all within the same observed setting. We develop a model of dynamic groundwater extraction to demonstrate that our estimand is ambiguously signed when the market for groundwater rights is spatially incomplete. A spatial RD design comparing land prices on either side of the groundwater market boundary remove potential endogeneity concerns as groundwater characteristics are likely continuous across the boundary. However, that same identifying assumption also removes changes in the water table, a potentially important consequence of the groundwater market, such that an RD estimate deviates from the estimand. We turn to our model to sign this bias, showing that the RD estimate yields a weak lower bound on the local average net benefit of a spatially-incomplete groundwater market, as well as for the population average net benefit under further assumptions.

Our empirical setting is the Mojave Desert, the driest desert in North America and yet a region that produces water-intensive crops. Mojave's verdant, irrigated farms in the midst of a barren desert have long been a poster child for inefficient water use. This stark contrast arises because underneath the Mojave Desert lies one of California's largest aquifers, which

[4]Interest in California water use in economics dates back at least to the article by Katherine Coman in the inaugural issue of the *American Economic Review* in 1911, revisited recently by Libecap (2011).

has historically been extracted for agricultural use under open-access conditions. Agricultural irrigation led to severe groundwater depletion: between 1964 and 1990, the water table fell by 30 feet. Following failed attempts to limit pumping by creating a groundwater market in the 1960s and 1970s, a court process beginning in 1990 and finalized in 1996 created a system known as "adjudication" that imposes a total limit on groundwater pumping and allocates tradeable pumping rights to users within a particular spatial area. Importantly, this area - jointly determined by the boundaries of a pre-existing regulatory institution and a surface topographical feature - did not include all land parcels overlying the aquifer. This distinct spatial feature, together with a requirement that reported land values for agricultural parcels include the value of groundwater access, enables our RD estimator.[5]

We estimate that agricultural land values on the groundwater market side of the boundary are, on average, 250% higher than on the open access side. To validate the magnitude of this estimate, we show that it is less than an upper bound on the policy's net benefit: the total value of groundwater rights attached to adjudicated land parcels. We confirm that relevant covariates do not exhibit discontinuities at the boundary. We also demonstrate that our RD estimate is robust to alternative statistical modeling assumptions, bandwidth choices, potential error in land value assessments, how the boundary is defined, and other empirical concerns. Reassuringly, we do not detect RD effects using placebo boundaries falsely set within the groundwater market and open access areas. Using earlier land value data, we also fail to detect a statistically significant RD estimate during the 1970s and 1980s. Point estimates from that period are roughly one-third to one-half the size of estimates after the introduction of the groundwater market. We note that a zero effect is not necessarily expected if an earlier failed attempt at establishing a similar groundwater market continued to influence expectations about management.

One potential explanation for our large RD estimate is that groundwater trading provides agricultural landowners the opportunity to capitalize on water's market value. For the Mojave aquifer, higher water values likely come from municipalities, particularly in the southern, more urban, areas overlying the aquifer. Indeed, heterogeneity analysis reveals a substantially higher RD estimate in the southern part of the aquifer compared to the north. This suggests that the ability to trade groundwater rights enhances land values by reallocating water away from water-intensive agriculture and towards meeting growing urban demand.[6]

[5] Groundwater rights have also been introduced elsewhere in California, and in total twenty-six basins have well-defined rights. Twenty of those basins have rights defined volumetrically, and trading is allowed in 19 of those. These 19 systems represent 4% of California's aquifers. However, the spatially-incomplete nature of the Mojave groundwater market, combined with rights trading, is unique in California.

[6] While our RD design prohibits us from exactly isolating the gains from groundwater trading, a back-of-the-envelope calculation suggests that at most 59% of the net benefit can be attributed to trading.

Accounting for these heterogeneous effects and further assuming that unobserved characteristics are uncorrelated with distance to the boundary, we calculate that the groundwater market produced an aggregate net benefit of $440 million (in 2015 dollars) for agricultural parcels, or a 50% increase in aggregate land value.

Our RD approach has two primary drawbacks. First, by measuring effects at the groundwater market boundary, our estimate does not capture potential benefits from higher groundwater levels under adjudication relative to the open access counterfactual. Instead, we turn to three additional pieces of evidence, all of which point towards increased groundwater levels: (i) we detect a positive trend break in average groundwater levels when the adjudication's pumping restrictions began for most users, (ii) we detect an RD jump in groundwater well drilling for open access parcels beginning at that same moment, consistent with increased groundwater under adjudication that spills over into open access areas, and (iii) we document that prices for groundwater rights have been consistently positive, which our theory shows is a sufficient condition for increased groundwater levels under adjudication relative to open access. The second limitation of our RD approach is that we cannot apply it to urban land parcels because they obtain water from municipal water systems, not local groundwater pumping. We extend our theory to show how data on aggregate urban water allocation and consumption combine to produce a back-of-the-envelope aggregate net benefit of $72-131 million (in 2015 dollars) for urban users. Altogether, the aggregate net benefit to agricultural and urban parcels of the groundwater market is $512-571 million. In contrast, the initial setup cost of the groundwater market was $40 million (in 2015 dollars) (Figueroa, 2001).

This paper contributes to a recent literature using quasi-experimental techniques to understand the consequences of environmental markets. Studies of air pollution and greenhouse gas markets typically examine only regulatory costs (Petrick and Wagner, 2014; Calel and Dechezleprêtre, 2016; Meng, 2017; Calel, 2020) or benefits (Fowlie, Holland and Mansur, 2012; Deschenes, Greenstone and Shapiro, 2017; Hernandez-Cortes and Meng, 2020), rarely both. A larger literature exists for fisheries, reflecting the many instances of market-based management in that domain. These papers have found that rights-based management tends to reduce effort (Hsueh, 2017; Costello and Grainger, 2018; Isaksen and Richter, 2018), distribute effort more evenly across time (Birkenbach, Kaczan and Smith, 2017); and increase resource levels (Costello, Gaines and Lynham, 2008), efficiency (Grafton et al., 2011), and revenues (Scheld, Anderson and Uchida, 2012).[7] For groundwater in particular, Drysdale and Hendricks (2018) and McLaughlin (2020) find reduced water use and higher groundwater

[7] In another quasi-experimental study, Kroetz, Sanchirico and Lew (2015) examine how fishing permit prices diverge following the imposition of trading restrictions.

levels, respectively, following the introduction of a water market. These outcomes, however, do not fully capture current and future net benefits of an environmental market. In our setting, the value of groundwater access is bundled together with the value of a land parcel. As such, we are able to follow the Ricardian tradition by studying land prices that capture the current and future net benefit of a groundwater market.

Another related literature in development economics and economic history employs quasi-experimental approaches to study the consequences of stronger property rights for land, through, for example, more secure land title (Besley, 1995; Besley and Burgess, 2000; Banerjee, Gertler and Ghatak, 2002; Field, 2007; Galiani and Schargrodsky, 2010), lower enforcement costs (Hornbeck, 2010; Libecap and Lueck, 2011), and enhanced access rights (Iwanowsky, 2019). In these settings, land - the resource of interest - was privatized to a certain degree prior to treatment. A test of the consequences of *introducing* property rights requires a resource that was initially held in common. Our setting satisfies this requirement.[8]

Finally, our study informs the increasing need for groundwater management, particularly under anthropogenic climate change. For California, groundwater pumping - which historically provides half of the state's fresh water - has long been unsustainably extracted, with recent consequences especially acute during a prolonged drought (California Dept. of Water Res., 2015). In response, California passed the Sustainable Groundwater Management Act (SGMA), an unprecedented law requiring users of overextracted aquifers to adopt stringent management plans. Groundwater markets are considered a key policy instrument under SGMA (Aladjem and Sunding, 2015; Babbitt and Brozovic, 2017; Green Nylen and Doremus, 2017).[9]

The paper is structured as follows: Section 2 provides background on the Mojave aquifer and its spatially-incomplete market for groundwater rights. Section 3 introduces a dynamic model of groundwater extraction under open access and incomplete groundwater market regimes, which informs our empirical strategy in Section 4. Section 5 details data sources. Section 6 presents our main RD results, robustness checks, and heterogeneity analyses. Section 7 quantifies the aggregate net benefit for agricultural and urban users and presents further evidence that the market has increased groundwater levels. Section 8 concludes.

[8]Note that in our setting landowners have rights to land, but groundwater use is still initially under open access.

[9]Surface water trading has also received renewed interest. Hagerty (2019) demonstrates potentially large gains from surface water trading in California. Rafey (2020) quantifies the gains from trade from observed surface water trading in southeastern Australia.

2 Background

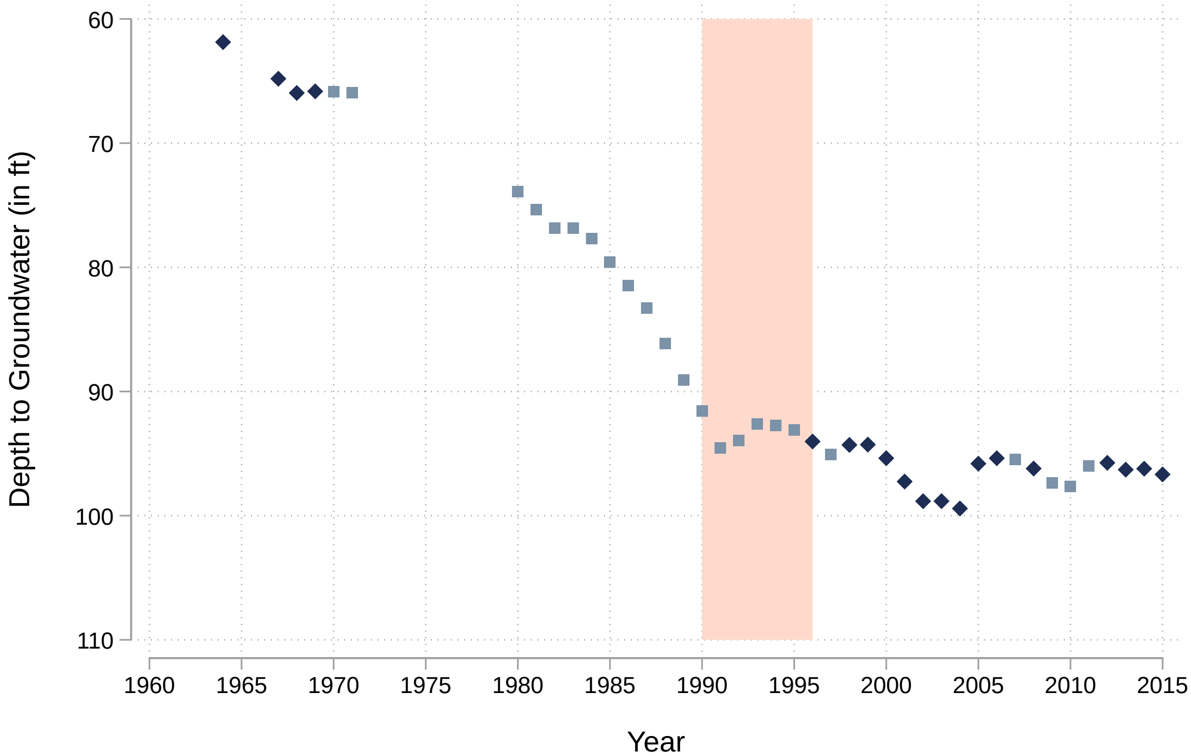
The Mojave Desert, located northeast of Los Angeles in southern California's San Bernardino County, is the driest desert in North America, receiving on average less than two inches of rainfall annually. Yet, farmers in the Mojave Desert have historically produced alfalfa, pistachios, and stone fruits, all highly water-intensive crops. This production is possible, in part, because beneath this desert lies one of California's ten largest groundwater resources, which has historically been extracted for agricultural use under open access conditions.[10]

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. From 1966 to 1976, there was an initial, but failed, attempt on the part of the regional water regulator, the Mojave Water Agency, to allocate water rights through a system known as "adjudication." Discussions about adjudication continued throughout the 1970s and 1980s, culminating in a new adjudication lawsuit in 1990. In 1993, an agreement comprising 75% of groundwater users was reached. In 1996, the local court sanctioned an agreement that applied to nearly all users.

Adjudication has two components. First, water users received individual, perpetual annual groundwater pumping rights defined as their proportion of average annual pumping during the 1986-1990 base period. To stabilize groundwater levels, the aggregate annual allowable pumping across the aquifer ramps down over time. Each year, a perpetual right holder is able to pump an amount equal to their right, scaled back proportionally by the degree of aggregate rampdown. Second, users can buy or sell "paper" groundwater rights, either through annual leases or transfers of perpetual rights. These are paper rights in the sense that users do not transfer physical water. Instead, they exchange pumping rights with any other user, agricultural or urban, who also overlies the groundwater resource. Transfer of rights to users not overlying the resource would require physically transporting pumped water outside the basin and is prohibited. The resulting water market enables users to reap any allocative efficiency gains arising from the sale of rights to other users. This is an im-

[10] Ostrom (2008) defines an open access resource as "a common-pool resource that anybody can enter and/or harvest." This definition accords with use of the Mojave aquifer prior to adjudication because, in principle, anybody could have pumped water from it. In practice, use was limited to overlying landowners because of the high cost of pumping from locations that do not overlie the aquifer. For overlying agricultural users, California law requires groundwater use to be "reasonable and beneficial," but these criteria allowed de facto open access conditions as they have historically allowed unrestricted irrigation in arid regions. However, as detailed below, urban users did have lower priority groundwater access prior to adjudication. While this restriction for urban users means the overall regime prior to adjudication does not exactly match a textbook definition of pure open access, we think open access is a reasonable approximation for the overall regime governing groundwater use prior to adjudication.

Figure 1: Depth to groundwater before and after adjudication



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 squares 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 the U.S. Geological Survey (USGS).

portant change from the prior open access regime, in which users do not own pumping rights and, thus, can only pump water for own use.[11]

Adjudication also brought an added benefit to urban groundwater users. Whereas agricultural landowners extracted under unrestricted open access prior to adjudication and thus were presumably at a private optimum, urban users were previously restricted as they had "junior," or lower priority access, to groundwater which only entitled them to water in excess of agricultural demands. By redefining groundwater rights and introducing the ability to trade, adjudication elevated the rights of cities to be on par with agricultural rights, thus lifting restrictions and allowing for expanded pumping.

[11]In other settings, there may be a less formal arrangement involving local management of groundwater resources by a limited group of users, typically referred to as Groundwater Management Districts (GMDs) (Edwards, 2016). Local resource management is common in fisheries, referred to as territorial user rights fisheries (TURFs), and the subject of a large theoretical and empirical literature (Janmaat, 2005; Sampson and Sanchirico, 2019).

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. Second, in addition to the prohibition on physical water transfers out of the basin, limits are also placed on water right trading across space and time. Landowners can only trade groundwater rights with overlying landowners or municipalities within the same subarea of the groundwater resource. Depending on how much these subareas are hydraulically connected, inefficiencies may arise from having separate groundwater markets. Likewise, water rights can only be banked one year ahead and cannot be borrowed from the future, which limits intertemporal smoothing of water consumption.

The most notable feature of the Mojave adjudication that deviates from an ideal groundwater market is that rights were not assigned over the entire spatial extent of the groundwater resource. Figure 2 illustrates the spatial boundary of the adjudication system (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 simply as the Mojave aquifer.[12] Observe that the spatial footprint of the adjudication system and Mojave aquifer areas do not perfectly overlap, so that some areas overlying the aquifer fall under adjudication (i.e., blue areas within the purple and red box) while others remain under open access (i.e., blue areas outside the purple and red box).

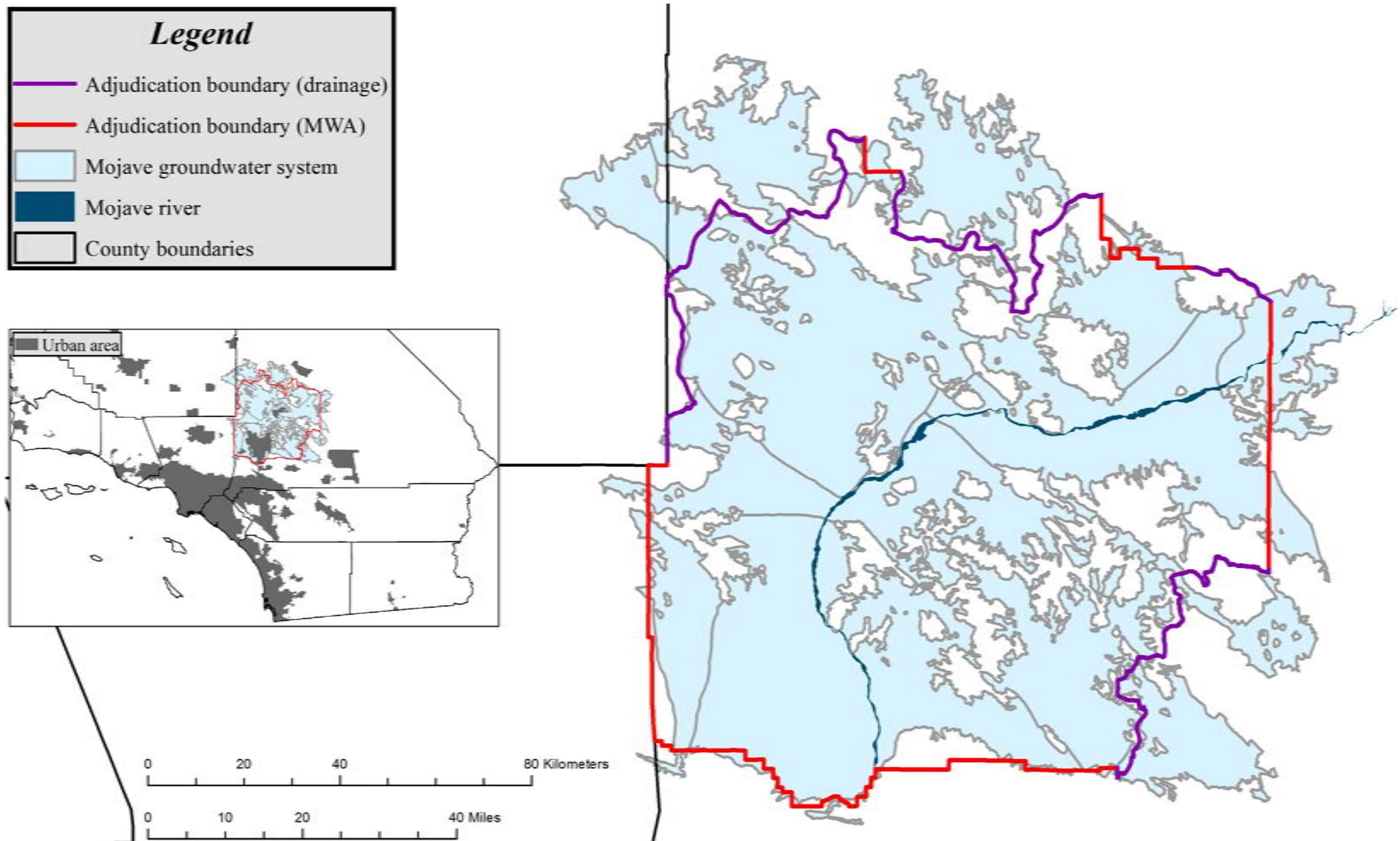
It is important to clarify how the adjudication boundary was drawn. Specifically, it is the spatial intersection of two regions: the jurisdictional area of the pre-existing Mojave Water Agency (shown by red line segments) and the physical surface drainage area of the Mojave River (shown by purple line segments). The straight-line boundaries of the Mojave Water Agency (MWA), formed in 1960 with largely unchanged boundaries since then, are based on the regular grid lines imposed by the Public Land Survey System from the 18th century and thus likely unrelated to subsurface groundwater characteristics. Likewise, the drainage extent of the Mojave River, which is determined by surface topographical features, is also plausibly exogenous to groundwater characteristics.[13]

A spatially-incomplete groundwater market, coupled with knowledge of how its boundary

[12]The key to defining the spatial extent of the relevant groundwater resource is hydraulic connectivity such that extraction in one location can affect the water table in other locations. The blue area in Figure 2 shows the hydraulically connected groundwater resources in the study area, as confirmed by hydrologists at the Mojave Water Agency. State and federal agencies may define multiple administrative "basins" in the region that need not be hydraulically independent. For example, the blue area in Figure 2 consists of several basins defined by California's Department of Water Resources that are largely hydraulically connected.

[13]As robustness checks, we test whether potentially relevant surface topographical features vary smoothly across the boundary. We also examine whether parcels near these two boundary definitions exhibit different RD estimates.

Figure 2: Groundwater market and aquifer 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 groundwater market 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.

was drawn, provides an opportunity to apply a spatial RD design. Before we do so, it is instructive to explore what existing data indicate regarding the net benefit of the Mojave adjudication system. Figure 1 shows that groundwater levels indeed began to stabilize in the 1990s. However, stabilized water levels alone do not imply positive net benefits for landowners under adjudication since pumping restrictions may be costly and transaction costs large. Furthermore, as our theory will show, stabilized water levels are also consistent with continued open access conditions that had yet to reach a steady state prior to adjudication. Trends in agricultural activity are also inconclusive. Figure B.1 shows that agricultural revenue in the Mojave Desert declined after adjudication was finalized. However, agricultural revenue does not capture possible gains from the reallocation of water to other sectors (e.g., urban water use), and thus does not provide a clear indication that adjudication benefited landowners.

Alternatively, one can follow the Ricardian tradition and examine land prices. This is possible in our data setting because the value of groundwater access in San Bernardino County is bundled together with the value of a land parcel. As such, land prices reflect the present discounted value of rental streams from both land and water assets.[14] For open-access parcels, land prices capture the value of unrestricted groundwater pumping for own use. For parcels under adjudication, land prices reflect the cost of restricted groundwater pumping, as well as the benefits of a higher groundwater level and the potential gains from trading 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 model of dynamic groundwater extraction for the Mojave aquifer. Recognizing that the Mojave adjudication regime deviates in practice along several dimensions 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 using spatially-incomplete groundwater rights.[15] 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 dynamics under counterfactual and factual regimes for the period after adjudication is introduced. In the first (counterfactual)

[14] Land prices, however, do not capture the one-time sunk costs of setting up the adjudication system.

[15] An optimal policy will always do at least as well as open access. To be useful for empirical testing, our model must leave open the question of whether spatially-incomplete tradeable groundwater rights yield net benefits.

regime, we model land price dynamics had open access conditions continued for all parcels over the aquifer. In the second (factual) regime, we model land price dynamics following the introduction of adjudication's system of spatially-incomplete tradeable groundwater rights.[16]

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, adjudication imposes the cost of restricted pumping but also generates benefits from a higher water table and the ability to trade groundwater rights. Next, we demonstrate that a spatial RD estimator comparing parcels under adjudication and open access at the adjudication 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 adjudication. Finally, because water table levels are lower at the boundary than in the interior of the adjudication area, the RD estimator is also a lower bound on the estimand in the interior.

Throughout this section, we focus on agricultural parcels for which groundwater is "appurtenant," or tied, to the overlying land surface. This implies that water access is determined by *local* groundwater levels, which facilities our spatial RD design in Section 4. In contrast, urban parcels receive piped water from municipal water systems whose groundwater access is determined *regionally* and thus cannot be examined with a spatial RD approach. We return to a discussion of net benefits for urban parcels in Section 7.1.

3.1 Setup

There are N identical agricultural landowners, each of whom has a land parcel that overlies $1/N$ of the area of 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 tradeable groundwater rights, as we discuss below.

[16] A comparison of land prices under the two regimes is valid only if the initial groundwater level is the same in both cases, implying that our theory must necessarily be dynamic in order to characterize adjustments to the steady states under open access and incomplete tradeable rights.

3.2 Full open access

Under full open access, profit-maximizing landowners ignore any effects of their pumping on the water table,[17] 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:

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

where R is natural recharge and $Nw^a(h(t))$ is aggregate pumping.[18] Consistent with Figure 1, we assume that the aquifer is out of steady state initially and that aggregate pumping $Nw^a(h_0)$ 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. A steady state is reached when pumping is equal to recharge.[19] 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. Thus, the full open access land price is

[17] Our open access model is a limiting case of 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.

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

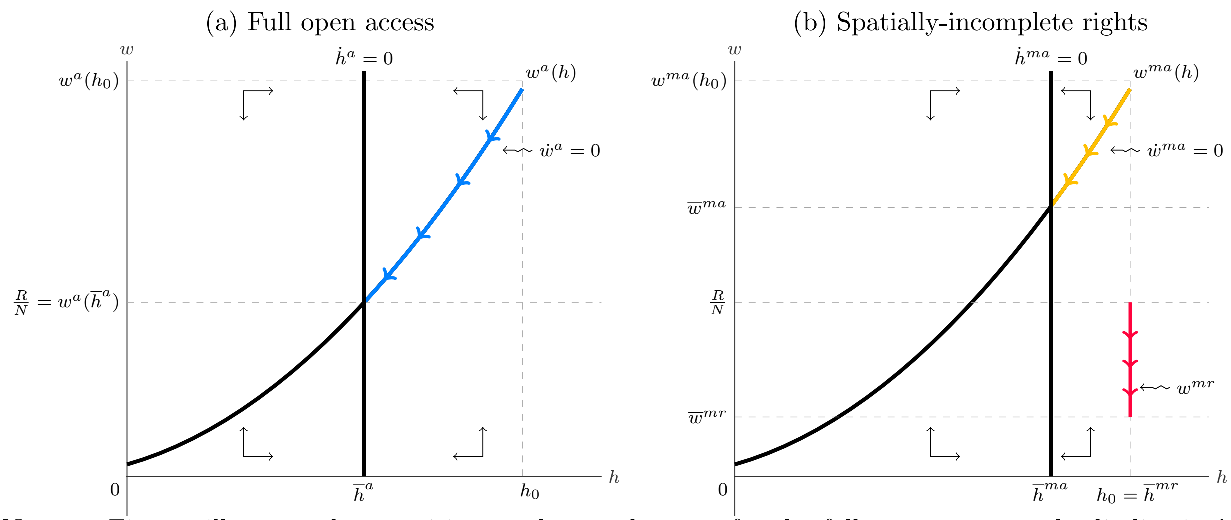
[19] To ensure the steady state occurs at a strictly positive value of h, we assume $w^a(0) < R/N$. This assumption is justified for the Mojave aquifer given evidence of extremely deep aquifers in the region that go far beyond the depth of existing wells (Kang and Jackson, 2016; Perrone and Jasechko, 2019).

given by:

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

where δ is the discount rate and the time interval covers both the transition period and the steady state.

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



NOTES: Figures illustrate the transition to the steady state for the full open access and adjudication's incomplete groundwater 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 adjudication 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 groundwater 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 $w = \bar{w}^{mr}$.

3.3 Spatially-incomplete groundwater 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.[20]

We examine this 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 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 (indicated by 'mr' where 'm' denotes the incomplete, or mixed, regime and 'r' indicates users with rights) hold rights to an endowment of water w^e, whereas open access users (indicated by 'ma') are unconstrained. Open access users continue to solve the profit maximization problem in 1, however, rights holders now solve:

$$\max_{w} \pi(w,h) \qquad s.t. \quad w \leq w^e \tag{4}$$

Assuming $w > 0$, the solution to equation (4) satisfies the first-order condition $\frac{\partial \pi}{\partial w} = \lambda^{mr}$ where λ^{mr} is the shadow value on the constraint. The complementary slackness condition is $\lambda^{mr}(w - w^e) = 0$, which says that at the optimum either the constraint binds or the shadow value of water equals zero (or both). The solution to equation (4) is denoted w^{mr} and defined as the *post-trading* volume of water pumped by landowners in the adjudication area and applied to their land. For now, we assume that the endowments w^e are the same for all landowners in the adjudication area, which implies no trading among agricultural users.[21] We will relax this assumption below. Given the intent to prevent further groundwater drawdown under open access, the constraint in equation (4) binds and, thus, $w^{mr} = w^e$ for all rights holders.

To simplify the analysis, we focus on two representative users, one within the adjudication 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):[22]

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

$$\dot{h}^{mr} = (1-\alpha) R + \theta(h^{ma} - h^{mr}) - (1-\alpha) N w^{mr} \tag{6}$$

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

[21]Because landowners are identical in all respects, shadow values are equal at the initial endowment and there are no gains from trade.

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

where it is assumed that recharge occurs uniformly throughout the aquifer.[23] 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 adjudication 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:

$$\dot{h}^{mr} = (1 - \alpha)R + \theta(h^{ma}(t) - \bar{h}^{mr}) - (1 - \alpha)Nw^{mr}(t) = 0 \tag{7}$$

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

$$\dot{h}^{ma} = \alpha R + \theta(\bar{h}^{mr} - h^{ma}) - \alpha N w^a(h^{ma}) = \alpha R - \alpha N w^a(h_0) \tag{8}$$

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.[24] 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 7. Solving for $w^{mr}(t)$ in equation 7 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 adjudication 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 7 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 5 and substituting $\bar{h}^{mr}$, we define the following relationship between steady-state water table heights:

$$\bar{h}^{mr} = \bar{h}^{ma} + \frac{\alpha}{\theta}(Nw^a(\bar{h}^{ma}) - R) \tag{9}$$

The assumption in footnote 24 implies that for any stabilization target for the adjudication

[23] The assumption of uniform recharge can be relaxed without changing the key insights from our theory.

[24] An additional assumption is needed to guarantee that a unique value of h^{ma} solves $\dot{h}^{ma} = \alpha R + \theta(\bar{h}^{mr} - h^{ma}) - \alpha N w^a(h^{ma}) = 0$, 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 adjudication area is found by substituting $\bar{h}^{mr}$ in equation (9) into equation (6) and setting $\dot{h}^{mr} = 0$, yielding:

$$R - \alpha N w^a(\bar{h}^{ma}) - (1-\alpha)N\bar{w}^{mr} = 0 \tag{10}$$

Substituting $\bar{h}^{ma} = q(\bar{h}^{mr})$ and rearranging equation (10), we obtain:

$$\bar{w}^{mr}(\bar{h}^{mr}) = \frac{R - \alpha N w^a(q(\bar{h}^{mr}))}{(1-\alpha)N} \tag{11}$$

For a given stabilization target $\bar{h}^{mr}$, equation (11) gives the steady-state pumping limit $\bar{w}^{mr} = \bar{w}^{mr}(\bar{h}^{mr})$ that needs to be imposed on landowners within the adjudication area. The steady states are depicted in panel (b) of Figure 3.[25] 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 $t \geq 0$.

Water trading and land prices. Tradeable property rights allow right holders to exchange water with other agricultural users or with urban users. If there are heterogeneous endowments, incentives for trading are created.[26] In particular, at the initial endowments, differences among landowners in the shadow values of water λ^{mr} imply gains from trade. If p^w is the unit price of water supported by a competitive water market, then landowners for whom $\lambda^{mr} < p^w$ ($\lambda^{mr} \geq p^w$) will be sellers (buyers) of water. When gains from trade are exhausted, $\lambda^{mr} = p^w$ for all landowners and all landowners use the same amount of water w^{mr}. Thus, a landowner with a given endowment w^e makes net purchases from other agricultural users and urban areas equal to $w^{mr} - w^e$.[27]

Under incomplete property rights, the land price for a given owner in the adjudication area is:

$$V^{mr} = \int_0^\infty [\pi(w^{mr}(s), \bar{h}^{mr}) - p^w(s)(w^{mr}(s) - w^e(s))]e^{-\delta s}ds \tag{12}$$

Equation (12) captures temporary annual leases as well as transfers of perpetual groundwater rights. If a landowner sells her perpetual water rights to an urban user at a future time t, $w^{mr}(s) = 0$ for $s \geq t$ and the proceeds from the sale, $\int_t^\infty p^w(s)w^e(s)e^{-\delta(s-t)}ds$, are capitalized

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

[26] In practice, other sources of heterogeneity, such as differences in production technologies or depths to groundwater, can also generate trading if endowments are homogenous.

[27] Landowners under the Mojave adjudication are allowed to buy and sell pumping rights (i.e., "paper trades") but not physical amounts of water. Assuming no banking or borrowing, which approximates the Mohave institution, the amount of water bought or sold by a landowner in each period, $w^{mr} - w^e$, must equal the amount applied to their parcel w^{mr} net of their endowment w^e.

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

$$V^{ma} = \int_0^\infty \pi(w^{ma}(s), h^{ma}(s)) e^{-\delta s} ds \tag{13}$$

We made the simplifying assumption, above, 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 adjudication to the open access area. At the boundary of the two areas, the water table height is the same for parcels under the adjudication and open access areas. 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 compare land values between 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.1-A.5. 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 5, we write:

$$\dot{h}^{ma} - \dot{h}^a = \theta(\bar{h}^{mr} - h) + (1 - \alpha)(Nw^a(h) - R) \tag{14}$$

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 spatially-incomplete nature of groundwater 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 whether the RD estimate varies over time.

4.1 Causal estimand

We are interested in whether the Mojave adjudication regime led to net benefits for landowners relative to a full open access counterfactual. For the population of parcels under adjudication, this is the difference in potential outcomes V^{mr} (see equation (12)) and V^a (see equation (3)). Our estimand of interest is the population average treatment effect:

$$\beta = \underbrace{\mathbb{E}_i[V_i^{mr} - V_i^a]}_{\lesseqgtr 0} \tag{15}$$

β is the average net benefit of adjudication relative to the full open access counterfactual. By Proposition 1(a), β is of unknown sign. The reason is that relative to a full open access regime, parcels under adjudication benefit from a higher water table and the ability to trade groundwater rights, but also bear the cost of restricted pumping. Unfortunately, β cannot be directly estimated since V_i^{mr} and V_i^a 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 boundary of the Mojave adjudication regime. Define d_i as parcel i's distance to the adjudication boundary. d_i is normalized so that a parcel is under adjudication 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:

$$\begin{aligned}\hat{\beta}^{RD} &= \underset{d_i \downarrow 0}{\mathbb{E}}\left[V_i^{mr}\right] - \underset{d_i \uparrow 0}{\mathbb{E}}\left[V_i^{ma}\right] \\ &= \underbrace{\underset{i:d_i=0}{\mathbb{E}}\left[V_i^{mr} - V_i^{ma}\right]}_{\lesseqgtr 0}\end{aligned} \tag{16}$$

where the first equality defines our spatial RD estimator at the adjudication boundary. The second equality uses the RD identifying assumption that expected land price under open access is continuous at the boundary, $d_i = 0$.[28] 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 effect of the water table, the remaining opposing influences of gains from groundwater 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 β? There are both internal and external validity considerations. Turning first to internal validity, let us denote the local β for parcels at the boundary as $\beta_{i:d_i=0}$. The difference between $\beta_{i:d_i=0}$ and $\hat{\beta}^{RD}$ is:

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

which is weakly positive by Proposition 1(c). The RD estimator serves as a weak lower bound for the treatment effect at the boundary because it omits the benefit of a higher water table.[29] This lower bound argument can also be interpreted from the perspective of spillover effects. As our theory shows, in a spatially-incomplete groundwater rights regime, water from the adjudicated area spills into the open access area, raising land prices for remaining open access parcels. Because this spillover benefit to open access parcels under adjudication would not occur under a full open access regime, the RD estimator produces a lower value than our estimand.[30]

[28] Specifically, following Hahn, Todd and Van der Klaauw (2001), the identifying assumption states that $\mathbb{E}\left[V_i^{ma}\right]$ is continuous in d_i at $d_i = 0$.

[29] Furthermore, it can be shown that an estimand defined as the average difference in land value between a spatially incomplete groundwater rights and open access regimes will be lower than that for a spatially complete groundwater rights regime. This is because there are no groundwater spillovers to open access areas when rights are complete. Thus our RD estimate is also a weak lower bound on the net benefit of a spatially complete groundwater rights regime.

[30] Using the same argument, Section 7.2 shows RD evidence of groundwater well drilling in open access

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 adjudication area away from the boundary. If other land parcel characteristics are uncorrelated with distance to the 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 adjudication 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 informs the various components of our spatial RD estimate. Specifically, using equations (12) and (13) and further allowing heterogeneity in water use (w_i^{mr}) and endowments (w_i^e) for adjudicated parcels, and in water use (w_i^{ma}) for open access parcels, we can explicitly decompose $\hat{\beta}^{RD}$ into the following components (see Appendix A.6 for details):

$$\hat{\beta}^{RD} = \underbrace{\mathop{\mathbb{E}}_{i:d_i=0}\left[\int_0^\infty [\pi(w_i^e(s), h_i(s)) - \pi(w_i^{ma}(s), h_i(s))]e^{-\delta s}ds\right]}_{\leq 0 \text{ restriction cost}} + \underbrace{\mathop{\mathbb{E}}_{i:d_i=0}\left[\int_0^\infty [\pi(w_i^{mr}(s), h_i(s)) - \pi(w_i^e(s), h_i(s)) - p^w(s)(w_i^{mr}(s) - w_i^e(s))]e^{-\delta s}ds\right]}_{\geq 0 \text{ gains from trade}} \quad (17)$$

$\hat{\beta}^{RD}$ is positive when the gains from groundwater rights trading offset the cost of restricted pumping.[31] In particular, for our RD sample of agricultural parcels, gains from trade would increase in parts of the aquifer with, among other features, expanding urban areas, whose demand for water drives up groundwater rights prices, allowing agricultural parcels to be net sellers of rights.

Finally, Section 3 defines land prices at the start of the program, when $t = 0$ or in 1997. In this case, $\hat{\beta}^{RD}$ indicates whether landowners received a positive stream of discounted net benefits when the adjudication system was finalized. One may also be interested in whether continuation of the regime since 1997 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, we use land prices for later periods to estimate an average RD effect over time, as well as separate RD effects across different time periods.

areas near the boundary following the introduction of adjudication, consistent with increased groundwater under adjudication that spills over into open access areas.

[31] For simplicity, our theory in Section 3 ignores the small annual fee paid by landowners to administer the adjudication regime, set at around \$5 per acre-foot. Such fees provide another reason for why $\hat{\beta}^{RD}$ serves as a lower bound.

5 Data

Based on Section 3, the ideal outcome variable is parcel price, which bundles together the present discounted value of a parcel's land and water assets. Two measures for parcel price are available in San Bernardino County: sales value and assessed value. Unfortunately, sales records in San Bernardino are not required to include adjudicated water rights when such rights are jointly transferred with a land parcel, nor are they required to indicate whether or not a sale includes groundwater rights. This limitation rules out the use of sales data for our analysis. By contrast, land assessments in San Bernardino include the value of adjudicated water rights held on a parcel.[32] For our primary dataset, we use 2015 data on a parcel's assessed land value, size, location, and most recent year it was sold, provided to us by the San Bernardino County Assessor. Additionally, we webscraped a panel of annual assessed land values from 1976 to 2014 (but missing 1977) from an online data portal maintained by San Bernardino County. These data, however, do not include parcel covariates (such as size and year of most recent sales) and are thus used only in examining how RD effects evolve over time.

In years when a parcel is not transacted, land assessors determine the value of groundwater rights using market information from comparable sales. While this determination does not follow a prescribed, mechanistic formula,[33] it is potentially subject to errors that arise in determining which sales are comparable. A unique feature of assessed land values in California helps to mitigate this problem. Since 1978, Proposition 13 has limited property tax increases across California by capping the annual appreciation rate of assessed land value at 2% following a property sale. Strong housing demand in southern California over recent decades means that this 2% limit has regularly constrained increases in assessed value. This implies that, in any given year, the assessed land value of a previously transacted parcel likely captures its market price at the time of last sale, with a 2% annual adjustment. Using our panel dataset of land values, we calculate that between 1997 and 2015, Proposition 13's 2% annual cap was binding for 91% of parcel-year observations in our sample.

There are three consequences of Proposition 13 that are germane to our analysis. First, Proposition 13, when binding, removes assessor discretion from the calculation of assessed land values, reducing unobserved assessment error. Second, for parcels whose most recent transaction year equals the year of assessment, assessed land value equals sales value, a

[32]Specifically, San Bernardino County requires the land assessor to be in contact with the Mojave Water Agency regarding water rights ownership and transfers. The assessor, however, does not separately report the value of water rights, only the total value of water and land assets.

[33]See Sections 501 and 542 of the California Assessor's Handbook. Available here: http://www.boe.ca.gov/proptaxes/ahcont.htm

sample restriction that we apply as a robustness check. Third, when Proposition 13 binds (and there is no jump in year of last sale at the boundary), an RD estimate based on 2015 assessed values will reflect the average treatment effect over a period of years, rather than just the 2015 treatment effect. For example, if the sample includes parcels last sold since 1997, we obtain the average treatment effect over the 1997-2015 period.

We impose several sample restrictions on our primary dataset. First, we restrict our sample to land parcels that were most recently transacted since 1997, after adjudication was confirmed by the county court and thus applied to all parcels within the boundary. Next, our RD design requires land parcels with access to *local* groundwater underlying the parcel. This requires excluding parcels that do not overlie the aquifer. We further exclude urban parcels because their water comes from municipal water systems, not local groundwater pumping. As such, the value of urban land parcels does not reflect local groundwater access.

We collect data from various additional sources. The USGS digital elevation map provides parcel-level average slope and aspect (compass direction).[34] California's Department of Water Resources's well completion reports provide a parcel-level measure of proximity to a private groundwater well and are used to examine the timing of well drilling around the adjudication boundary.[35] USGS monitoring well data is used to examine trend breaks in average Mojave groundwater levels. Lastly, we collect data on groundwater rights endowments, trading volumes and prices from the Mojave Water Agency for various additional analyses.[36]

Table C.1 shows summary statistics for variables in our primary dataset. It includes parcels near the adjudication boundary used in our RD estimation as well as more distant parcels.

6 Results

This section presents our main RD result, robustness checks, and heterogeneity analyses.

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

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

[36] Available here: http://www.mojavewater.org/annual_report.html and http://www.mojavewater.org/water_transfer_reports.html

6.1 Specification

To estimate our RD coefficient, $\hat{\beta}^{RD}$, from Section 4.2, we follow Hahn, Todd and Van der 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 adjudication boundary. $R_i = \mathbf{1}\{d_i \geq 0\}$ is an indicator variable equaling 1 when parcel i is in the adjudication area and 0 otherwise. $f(d_i)$ is a flexible local polynomial function that is fully 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, $\mathbb{X}_i$, detailed below. For our baseline specification, standard errors are clustered at the zip code level to allow for arbitrary forms of heteroscedasticity and spatial autocorrelation among 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 consider alternative bandwidths, error structures (including a zip code-level wild bootstrap procedure), and other estimation choices.

6.2 Covariate smoothness

To assess the validity of our RD estimator, we begin by examining whether relevant covariates exhibit discontinuities at the adjudication boundary. In particular, our set of covariates indirectly tests our identifying assumption and informs how we interpret our RD effect on land values.

Our RD identifying assumption, introduced in Section 4.2, requires that land prices under open access be continuous at the adjudication boundary. In some places, however, the boundary is defined according to the surface water drainage area of the Mojave River. Because the boundaries of a drainage area typically corresponds to a local elevation peak, surface topological features may vary systematically across the boundary. For example, the slope of the land may change at the boundary. Likewise, the aspect of the land, or its compass direction and thus sunlight exposure, may also vary systematically at the boundary.[37] Both slope and aspect can influence a parcel's land value. Our identifying assumption also implies

[37]We thank Jeff Vincent for this insight.

that groundwater levels be continuous at the boundary, which data limitations unfortunately prevent us from directly testing. Instead, we examine whether the presence of a privately-drilled groundwater well within one mile of a parcel, which we view as an imperfect proxy for groundwater availability and possibly irrigation, jumps at the boundary.[38]

We also examine covariates that inform the interpretation of our main RD effect on land values. Proposition 13 limits the annual growth rate of assessed land value at 2% in years after a parcel's sale. If Proposition 13 binds for all sample land parcels, then showing there is no jump in the year of last sale implies that an RD estimator applied to 2015 assessed land values captures the time-averaged RD effect since 1997. In our case, where Proposition 13 binds in 91% of cases, our RD estimate still has a time-averaged RD effect interpretation provided there is no jump in the percentage change in land value since last sale.[39] Finally, to ensure that our RD effect is not capturing differences in land value due to different parcel sizes, we also examine whether there is a discontinuity in land parcel size across the boundary.

Table 1 shows $\hat{\beta}^{RD}$ for each covariate, displayed across columns. Specifically, we estimate separate versions of equation (18), where each covariate in $\mathbb{X}_i$ serves as the dependent variable. Each model uses a local linear function for $f(d_i)$ and excludes other covariates as regressors. We do not detect statistically precise RD effects across these six covariates. In particular, absence of a discontinuity in the last year of sale and in the percentage change in land value since that year shown in columns 4 and 5 imply that our RD estimate on 2015 assessed land value reflects the average RD effect across the 1997-2015 period.

[38]Monitoring wells, which are specifically designed to measure groundwater levels, are spatially sparse in this part of California. For example, the calculation for average groundwater level in 2015 shown in Figure 1 was based on only nine monitoring wells. Spatial interpolations with such a small number of point measurements would generate imputed maps of groundwater levels that likely spatially vary more smoothly than the actual groundwater table, and thus would be uninformative of groundwater levels at the boundary. Alternatively, California's Department of Water Resources well completion reports document privately-drilled wells, which are far more spatially dense than monitoring wells. However, depth to well water for privately-drilled wells varies with well characteristics and may not correspond to the true groundwater level. Furthermore, depth to well water is only recorded at the moment of initial drilling and not during the period when we observe land values. While we cannot use the well completion reports to measure groundwater levels, we use these data to determine whether a parcel is within one mile of a privately drilled well, which serves as a proxy measure for groundwater availability and possibly the presence of irrigation. We note, however, that the use of distance to construct this measure will necessarily impose some spatial continuity.

[39]Formally, for parcel i, denote log land value in 2015 as $lnV_{i,2015}$ and log land value in the year of its last sale, $2015 - \tau_i$, as $lnV_{i,2015-\tau_i}$, where τ_i is years since last sale. If we further define r_i as the average annual land value growth rate between years $2015 - \tau_i$ and 2015, we can write

$$lnV_{i,2015} = lnV_{i,2015-\tau_i} + r_i\tau_i$$

If Proposition 13 always binds, $r_i = 0.02$ for all i, and the time-averaged effect interpretation of our main RD estimate on log land value requires only continuity in τ_i at the boundary. If Proposition 13 does not always bind, a time-averaged effect interpretation requires that the percentage change in land value since last sale, $r_i\tau_i$, is continuous at the boundary.

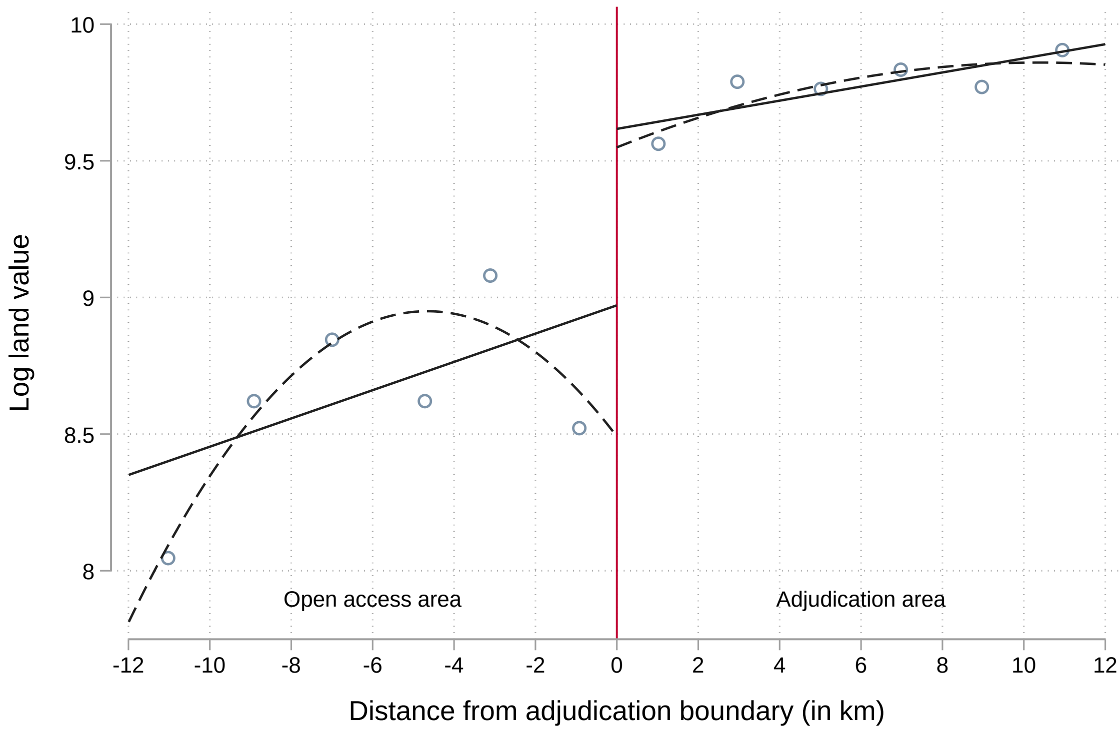
Table 1: Examining covariate smoothness

	(1) Slope	(2) Aspect	(3) Near well?	(4) Last sales year	(5) Pct. change since last sales	(6) Size
$\hat{\beta}^{RD}$	1.699	-2.309	-0.036	-1.175	38.008	10.074
	(1.292)	(25.991)	(0.101)	(0.885)	(80.009)	(7.525)
Mean covariate value	1.614	169.638	0.818	2007.421	179.386	15.422
Observations	3060	3060	3060	3060	3047	3060
Zip codes	27	27	27	27	27	27

NOTES: Estimates of β^{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. Column 1 is average slope measured in degrees relative to level surface. Column 2 is average aspect 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 the most recent year in which the parcel was sold. Column 5 examines the a parcel's percentage change in value since its last sale. Column 6 examines parcel size in acres. Mean control value is the mean covariate value for open access parcels within 2km of the boundary. Standard errors clustered at the zip code level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Figure B.2 plots binned averaged covariate values as a function of distance to the boundary to visualize the magnitudes of the RD effects in Table 1 relative to covariate means in the open access area near the boundary. The only covariate whose noisy RD effect may have meaningful magnitude is parcel slope. A potential discontinuity in slope is consistent with the surface water drainage basin defining a portion of the boundary as land slopes need not be equal at the dividing line between two basins. However, the sign and magnitude of this jump in parcel slope should mitigate identification concerns. Prior hedonic studies find measures of greater slope tend to lower agricultural land values, possibly through increased risk of soil erosion (Palmquist and Danielson, 1989; Schlenker, Hanemann and Fisher, 2005) but that the effect, when measured in degrees, tends to be small (Bigelow et al., 2017).[40] Thus, an RD effect on slope of 1.7 degrees implies that our RD estimate is biased downwards but that the magnitude of this bias is likely small. In a robustness check, we include land slope and other covariates as controls in our RD estimate on land values.

Figure 4: Graphical RD effect



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

6.3 Main RD estimate and robustness checks

We first present our main RD result graphically. Figure 4 plots log land value, our main outcome of interest, against distance to the adjudication boundary, d_i. Log land value is shown as local averages for the average distance within 2 km-wide bins (circles) as well as separate linear (solid line) and quadratic (dashed line) fits on distance over the unbinned data on each side of the boundary. Two features of Figure 4 are worth noting. First, there is a clear jump in land values at the discontinuity. Second, we find that land values are generally increasing from left to right in Figure 4. This is consistent with our theoretical prediction that groundwater levels rise as one moves from the open access area into the interior of the adjudication area. We conduct a continuity test provided by Cattaneo, Jansson and Ma (2019), an alternative to the McCrary (2008) procedure that avoids prebinning data, and do

[40] Palmquist and Danielson (1989); Schlenker, Hanemann and Fisher (2005) use proxy measures for land slope, whereas we measure slope by degrees. Using the estimate from Bigelow et al. (2017), a 1.7 degree increase in slope lowers agricultural land value by a statistically imprecise 1.7%. By contrast, our benchmark RD effect on land values is 250%.

not detect a discontinuity in the density of the distance variable at the threshold.[41]

Table 2: Main RD results

	(1)	(2)	(3)	(4)
	Outcome is log land value			
$\hat{\beta}^{RD}$	1.264**	1.384**	1.259***	1.424**
	(0.539)	(0.643)	(0.478)	(0.663)
Percentage effect (%)	254	299	252	315
Polynomial order	1	2	1	1
Covariates	No	No	Yes	No
Last sales year	1997-2015	1997-2015	1997-2015	2015
Bandwidth	2.774	4.715	3.125	3.073
Observations	3060	5341	3535	206
Zip codes	28	30	28	24

Notes: Estimates of β^{RD} from equation (18) with log land value as outcome. Column 1 uses a local linear function for $f(d_i)$, excludes covariates, and includes all parcels that were last sold between 1997-2015. Column 2 uses a local quadratic function for $f(d_i)$. Column 3 includes 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 as covariates. Column 4 restricts sample to only parcels last sold in 2015. 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 in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

We now turn to estimates of β^{RD} from equation (18), shown in Table 2. For our benchmark model, column 1 uses a local linear function for $f(d_i)$, excludes covariates, and includes all parcels that was last sold in the period 1997-2015. The statistically precise RD estimate of 1.264 translates to a 254% increase in land value.[42] With mean land value for open access parcels within 2 km of the boundary at \$14,300, this implies a land value increase of \$36,300 (in 2015 dollars). To independently verify the magnitude of this effect, we compare this

[41] We further note that traditional RD sorting concerns are lessened in our context. First, land parcels are fixed in space. Second, although there could be unobserved preference heterogeneity among landowners (e.g., some landowners may strongly prefer parcels with secure rights to water), competition in the land market implies that the value of an individual parcel's attributes is determined by the aggregate distribution of preferences across the market and not by individual preferences of that parcel's buyer and seller (Rosen, 1974).

[42] This local RD estimate corresponds visually to the RD jump for the global quadratic model and the binned outcome averages in Figure 4, both of which better account for local values around the discontinuity than the global linear model in Figure 4. The 95% confidence interval for the percentage increase in land value at the boundary is $[23\%, 918\%]$.

average land value increase to the average value of perpetual groundwater rights held by landowners in our RD sample, which equation (17) indicates is an upper bound on our RD estimate. In 2015, this value was \$148,700.[43]

Column 2 models $f(d_i)$ using a local quadratic model. To address remaining concerns about potentially large, though imprecise, jumps in the covariates examined in Table 1, column 3 augments our benchmark specification by including these covariates.[44] Lastly, despite Proposition 13, it may still be the case that the assessed value of a parcel transacted in an earlier year captures errors made by the land assessor. To isolate parcels whose assessed value equal sales value, column 4 restricts our sample to parcels transacted in 2015. All three robustness checks detect positive and statistically significant RD effects that are similar in magnitude to our benchmark result in column 1.

Table 3: Robustness: alternative bandwidths

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Outcome is log land value						
$\hat{\beta}^{RD}$	1.264**	1.459***	1.144***	0.864**	1.210**	1.328***	1.078***
	(0.539)	(0.261)	(0.301)	(0.349)	(0.583)	(0.494)	(0.411)
Bandwidth	2.774	1.000	1.500	2.000	4.000	5.000	6.000
Observations	3060	1054	1571	2110	4545	5606	6566
Zip codes	28	23	25	26	27	27	29

NOTES: Estimates of β^{RD} from equation (18) with log land value as outcome. All models use a local linear model for $f(d_i)$, exclude 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 in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

We next consider several additional robustness checks to the baseline result in column 1 of Table 2. Table 3 presents RD estimates using bandwidths smaller than one-half and larger than twice that of the baseline MSE-optimal bandwidth, showing also the number of

[43]Specifically, from equation (17), note that a component of our RD estimate is the average net present discounted value of endowed groundwater rights, which is weakly positive and weakly larger than the RD estimate: $\mathbb{E}_{i:d_i=0}[\int_0^\infty p^w(s)w_i^e(s)e^{-\delta s}ds] \geq \hat{\beta}^{RD}$. In practice, water users are granted perpetual rights, w_i^e, which are scaled each year s by the aquifer-wide rampdown rate ω such that $w_i^e(t) = w_i^e e^{-\omega t}$. Using data from the Mojave Water Agency, we calculate this value as the product of the number of perpetual groundwater rights a sample landowner holds, w_i^e, and the traded price of that perpetual right, equaling $\int_0^\infty p^w(s)e^{-(\omega+\delta)s}ds$.

[44]Column 3 of Table 2 includes all covariates shown in Table 1 except for the percentage change in land value since last sales because that variable is constructed using assessed 2015 land value, our outcome of interest in Table 2.

parcels at different bandwidths around the boundary. Our RD result is not sensitive to these different bandwidth sizes.

Table C.2 considers alternative variance estimators. Our main RD sample uses zip code clustered standard errors with 28 zip codes. To address potential issues with having few clusters (Cameron, Gelbach and Miller, 2008), column 2 conducts a zip code-level wild bootstrap procedure specific for RD designs following He and Bartalotti (2020). This has little influence on the precision of our RD estimate. We further show in columns 3-5 that our RD result is insensitive to whether variance estimation is undertaken using zip code-level clustering, nearest neighbor matching, or both. Column 7 shows that our RD result also holds when applying a local randomization method that allows for exact inference in finite samples, but requires the additional assumption that potential outcomes are non-random (Cattaneo, Frandsen and Titiunik, 2015; Cattaneo, Titiunik and Vazquez-Bare, 2016).

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 RD estimate is relatively stable across these estimation choices.

Table 4: Placebo boundary tests

	(1)	(2)	(3)	(4)	(5)	(6)
	Outcome is log land value					
$\hat{\beta}^{RD}$	-0.212	-0.094	-0.003	-0.231	0.072	-0.100
	(0.452)	(0.554)	(0.842)	(0.337)	(0.233)	(0.304)
Dist. to true boundary km	-9	-6	-3	3	6	9
Bandwidth	2.273	2.410	6.171	3.746	3.231	3.490
Observations	218	449	4170	6584	6352	6516
Zip codes	10	22	23	33	31	32

NOTES: Estimates of β^{RD} from equation (18) with log land value as outcome. All models use a local linear model for $f(d_i)$, exclude 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. Columns use placebo boundaries set 9, 6, and 3 kilometers within the open access (i.e., $d_i < 0$) and adjudication areas (i.e., $d_i \geq 0$). Standard errors clustered at the zip code level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Finally, Table 4 conducts placebo tests by estimating RD effects using alternative locations for the boundary. Because there is no actual spatial discontinuity between adjudication and open access regimes across these placebo boundaries, we should not detect any RD effects. For models in columns 1-3, we create false boundaries that are 9, 6, and 3 kilometers, respectively, within the open access area relative to the real boundary. In columns 4-6, we create similarly spaced false boundaries within the adjudication area. We do not detect RD effects using any of these false boundaries.

6.4 Heterogeneity

We now turn to heterogeneity analyses, across time and space. Our main RD estimate using 2015 assessed land values pools land parcels that were most recently transacted within the 1997-2015 period. The presence of Proposition 13 together with columns 5 and 6 of Table 1 showing no boundary discontinuity in the last year of sale and change in land value since last sale, suggest that our main RD estimate reflects the average RD effect over the 1997-2015 period, rather than the effect for only 2015. A natural question, then, is whether the net benefit of adjudication has changed since the program was introduced, which Proposition 1(e) indicates is ambiguously signed. Another related question is: what is the magnitude of the RD effect before 1997?

Table 5: Heterogeneity across time

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Outcome is log land value							
$\hat{\beta}^{RD}$	0.632	0.664	0.884	1.937**	1.703*	1.860***	1.471**	1.546**
	(0.567)	(0.407)	(0.913)	(0.937)	(0.926)	(0.651)	(0.730)	(0.653)
Sample period	76-79	80-84	85-89	90-94	95-99	00-04	05-09	10-14
Bandwidth	2.632	1.529	2.380	2.511	2.053	2.274	2.024	3.048
Observations	537	864	660	554	261	474	368	561
Zip codes	20	21	20	19	20	19	20	20

NOTES: Estimates of β^{RD} from equation (18) with log land value as outcome from a panel of assessed land values between 1976-2014 (missing 1977). Each model estimated over 5-year intervals. All models use a local linear model for $f(d_i)$, exclude 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. Standard errors clustered at the zip code level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

To shed light on these questions, we turn to our panel of annual assessed land values covering the 1976-2014 period. Table 5 reports RD estimates from equation (18) estimated separately across five-year periods, with coefficients also plotted in Figure B.3.[45] Three

[45] We are interested in the time-evolution of land values since 1976. However, because of Proposition 13, land values of parcels not sold in a given assessment year is likely to capture its value during the year of last sale and not the value during the year of assessment. Including parcels sold prior to the assessment year would result in an artificially-smoothed RD estimate over time. Unlike our main dataset of 2015 land values obtained from the land assessor, we are unable to explicitly drop parcels from our webscraped panel dataset

results from Table 5 are worth noting. First, the RD estimate has changed very little since the introduction of adjudication.[46] That our estimates remain positive across time suggests that the continuation of adjudication has been economically justified. Second, we detect a statistically precise RD effect in the early 1990s. Because a subset of users already faced adjudication starting in 1993, these effects reflect a combination of implemented and anticipated RD effects. Third, as columns 1-3 show, in the 1976-1989 period before the adjudication process began, the RD effect was one-third to one-half the size of the post-adjudication RD effect and not statistically significant (see Figure B.4 for the graphical RD presentation). We do not necessarily expect RD effects prior to 1990 to be precise zeros as there was an earlier failed attempt at adjudication during 1966-1976 and discussions over future adjudication continued throughout the 1970s and 1980s. Because those earlier proposals also foresaw management by the Mojave Water Agency, whose spatial boundaries are largely unchanged since 1960, any anticipated effects from an eventual adjudication could be capitalized in pre-1990 land values. Thus, it is possible that the smaller pre-1990 RD effects detected in columns 1-3 reflect anticipatory beliefs about future adjudication.

Section 4.2 discusses how our spatial RD estimate depends on the market value of water. When this outside value is high, tradeable groundwater rights allow agricultural landowners to gain from selling rights to other users overlying the aquifer. For groundwater in the Mojave, this higher-value use is likely strongest in the more urban southern part of the region (see inset map in Figure 2).

To test whether urban water demand creates larger net benefits, Table 6 examines heterogeneity in the RD coefficient for the southern and northern subareas. Because rights trading can only occur within a particular subarea, one would expect the RD effect to be larger in the more urbanized southern subareas, all else held equal. Column 1 replicates our baseline results. The model in column 2 restricts the sample to parcels in the southern subareas, while only northern subareas parcels are used to produce estimates in column 3. The RD coefficient for the southern subareas is almost six times larger than for the northern subareas, though statistical inference is complicated by the limited number of zip code clusters. As an alternative approach to modeling this heterogeneity, we interact R_i and $f(d_i)$ from our baseline model of equation (18) with a parcel's latitude. Figure B.5 plots how $\hat{\beta}^{RD}$ varies as

that were transacted earlier because this dataset does not explicitly contain information on year of last sale. To address this, the estimating samples in Table 5 attempt to detect parcels sold during the assessment year by including only parcels for which there is an owner change that year and for which Proposition 13's 2% limit does not bind. For further noise reduction, we drop observations for which the land value more than doubled that year.

[46]Following footnote 45, because we need to infer when parcels were sold in our panel dataset, the estimating sample (and thus RD estimates) in columns 5-8 of Table 5 differs from our that of our main RD estimate in Table 2 using 2015 assessed land values for which we observe year of last sales.

Table 6: Heterogeneity across space

	(1)	(2)	(3)	(4)	(5)	(6)
	Outcome is log land value					
$\hat{\beta}^{RD}$	1.264**	1.941**	0.329	1.145	0.121	1.462***
	(0.539)	(0.853)	(0.482)	(0.803)	(0.676)	(0.537)
Area	All	South	North	South	North	Drop along LA
Boundary definition	All	All	All	River basin	River basin	All
Bandwidth	2.774	2.774	2.774	2.774	2.774	2.774
Observations	3060	2260	800	150	467	1772
Zip codes	28	17	14	4	9	28

NOTES: Estimates of β^{RD} from equation (18) with log land value as outcome. All models use a local linear model for $f(d_i)$, exclude 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 boundary is defined by the Mojave River drainage basin. Standard errors clustered at the zip code level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

one moves northward over the aquifer, showing a statistically significant decline. For parcels that are farthest north, the RD effect becomes negative, which is possible when the gain from trading rights is small.[47]

How much does the tradeability of groundwater rights contribute to the net benefit of the Mojave adjudication regime? Columns 1-3 of Table 6 merely show that gains from rights trading contribute to the net benefit, but not by how much. Note also that by controlling for groundwater level differences, our RD approach cannot definitively isolate the gains from groundwater trading. To conduct a back-of-the-envelope calculation, we assume that the benefit of a higher groundwater table can be identified using land value differences farther away from the boundary and that the gains from rights trading in the northern subareas is small. With these assumptions, we calculate that rights trading contributes to at most 59% of the net benefit of the Mojave adjudication regime, though this estimate is highly uncertain.[48]

[47] While the largest RD estimates occur in subareas with more urban parcels, we also observe transaction of rights between agricultural users, as represented by our theory in Section 3. In particular, of all perpetual rights transactions between 1997-2015, 23% were between agricultural and urban users and 77% were between agricultural users. During that same period, of all transactions of annual leases to rights, 48% were between agricultural and urban users, 45% were between agricultural users, and 7% were between urban users.

[48] To obtain 59%, we divide the difference between RD estimates in columns 1 and 3 in Table 6 (i.e., 1.26-.33), which isolates the gains from rights trading, by the difference in average land values at the edge of the support shown in Figure 4 (i.e., 9.93-8.35), which incorporates the water table gradient. This is an upper bound on the contribution of rights trading because gains from trading in the northern subareas, while smaller, are still positive (i.e., the true numerator is smaller) and because the true water table difference is

Table 6 also shows two final robustness checks. The RD effect may be heterogeneous depending on how the boundary is defined. The model in column 4 of Table 6 further restricts the sample of southern subarea parcels to those whose nearest boundary is defined by the spatial extent of the Mojave River drainage basin (shown by purple line segments in Figure 2) and not by the Mojave Water Agency (shown by red line segments in Figure 2). Column 5 uses a similar sample restriction for the northern subareas. Our RD effect does not differ greatly by how the boundary is defined.[49] Finally, column 6 shows that our RD effect is robust to dropping parcels that are in the subarea directly adjacent to Los Angeles County.[50]

7 Aggregate net benefit of adjudication

We now turn to quantifying the aggregate net benefit of adjudication. We first use RD estimates from Section 6 to quantify the aggregate net benefit to agricultural parcels and then provide a back-of-the-envelope calculation for the aggregate net benefit to urban parcels. Both values are potential lower bounds because they hold groundwater levels fixed. To explore whether adjudication led to more groundwater, we present three additional pieces of evidence, all of which imply that Mojave groundwater levels increased as a consequence of adjudication.

likely larger (i.e., the true denominator is larger). Monte Carlo simulations based on estimated uncertainties for each parameter, however, produce a 95% confidence interval of $[-31\%, 172\%]$. This large uncertainty suggests that this back-of-the-envelope calculation should be interpreted with caution.

[49]Figure 2 shows that boundary segments defined by the Mojave River drainage basin (shown by purple line segments) are better represented in the northern parts of the adjudication 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 6 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.

[50]Furthermore, within our RD sample there are no open access parcels that fall under the jurisdiction of a different water agency. This implies that for parcels near the Mojave Water Agency boundary, those that were adjudicated were under Mojave Water Agency jurisdiction while open access parcels were not part of any local water agency. Because the primary benefit of the Mojave Water Agency is groundwater access, we do not anticipate that this institutional difference results in discontinuities in non-adjudication Mojave Water Agency benefits at the boundary. However, because Mojave Water Agency parcels have to pay an annual fee of 16.75 cents per $100 of assessed land value to the Mojave Water Agency for services aside from of adjudication, the presence of this fee may bias our RD estimate downwards. We believe the magnitude of this bias is small as this fee amounts to $23.95 for the average adjudicated land parcel in our sample, which would slightly lower the land value difference across the boundary.

7.1 Quantifying a (lower bound) aggregate net benefit

We first quantify the aggregate net benefit of the Mojave adjudication regime for agricultural parcels. Proposition 1(c) notes that our RD estimate is a lower bound on the local average treatment effect for agricultural parcels at the boundary. If one further assumes that other characteristics are uncorrelated with distance to the boundary, Proposition 1(d) states that the local average treatment effect at the boundary is itself a lower bound for the population average treatment effect across all agricultural parcels. This orthogonality assumption, together with the south-north heterogeneity in the RD coefficient, enables a lower bound calculation for the aggregate net benefit of adjudication across agricultural parcels.

To that end, we multiply the heterogeneous RD effect separately for agricultural parcels in southern (i.e., column 2 of Table 6) and northern (i.e., column 3 of Table 6) subareas with each parcel's land value. We then sum this product across all adjudicated agricultural parcels. This results in a value of $440 million (in 2015 dollars), or a 50% increase in total land value.[51]

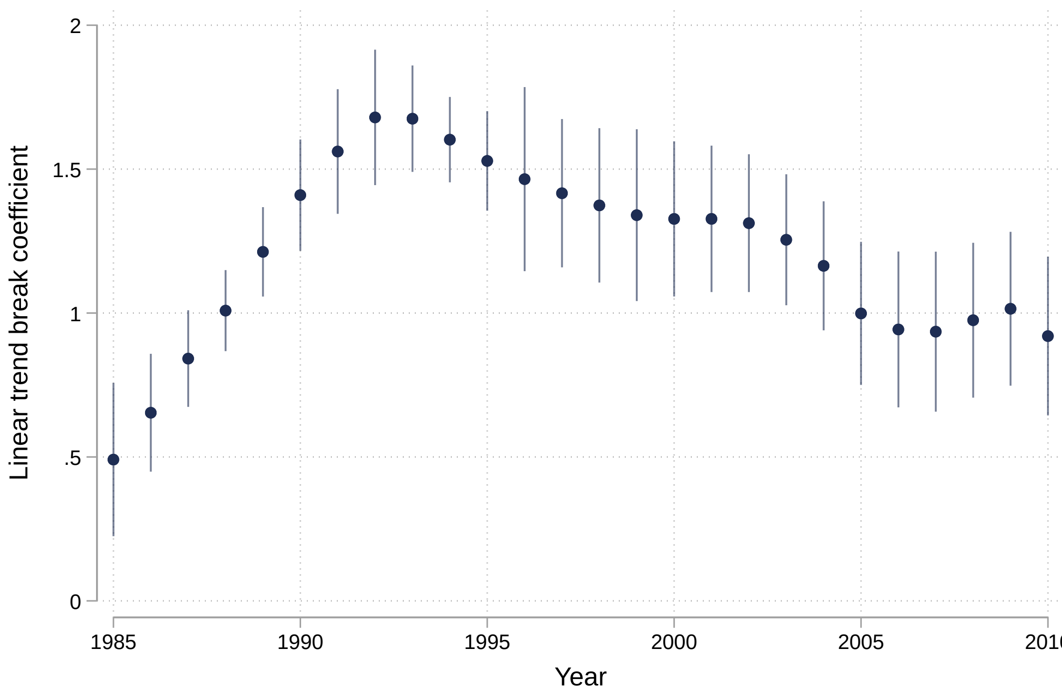
Water access for urban parcels is not tied to underlying groundwater but rather comes from municipal water systems. While this means we are unable to apply our spatial RD estimator to urban parcels, Appendix A.7 details how an extension of our theory along with data on aggregate urban water allocation and trade combine to quantify the aggregate net benefit to urban parcels. Our calculation is based on the following argument: Unlike agricultural parcels, urban parcels held lower priority access to groundwater prior to adjudication and were likely pumping below their private optimum. If, following adjudication, one observed an increase in aggregate urban water consumption, the gain from increased water use must exceed the cost of purchasing groundwater rights from agricultural parcels, implying a positive aggregate urban net benefit. In Appendix A.7, we calculate for a range of demand elasticities found in the literature that adjudication resulted in an aggregate net benefit between $72-131 million (in 2015 dollars) for urban parcels. Altogether, the aggregate net benefit to agricultural and urban parcels of the groundwater market is $512-571 million. By comparison, the initial administrative and legal cost to set up the adjudication system was $40 million (in 2015 dollars) (Figueroa, 2001).

[51] Unlike the 254% average RD sample increase calculated in column 1 of Table 2, this aggregate percentage increase takes into account heterogeneity in RD estimates between northern and southern subareas and the number of parcels and their values in each region. Because there are many more parcels in the northern subareas where the RD effect is lower, the aggregate effect is weighted towards the northern RD effect.

7.2 Did adjudication increase groundwater levels?

The aggregate net benefit estimates in Section 7.1 omit any benefits of a higher groundwater table. If groundwater levels increased under the adjudication, these values are a strict lower bound on the net private and social benefits of the policy. If groundwater levels did not change, then adjudication had no social net benefits but rather only generated private net benefits by enabling a more efficient allocation of groundwater through rights trading. We turn to three pieces of evidence beyond our main RD result to examine whether adjudication increased groundwater levels relative to the open access counterfactual.

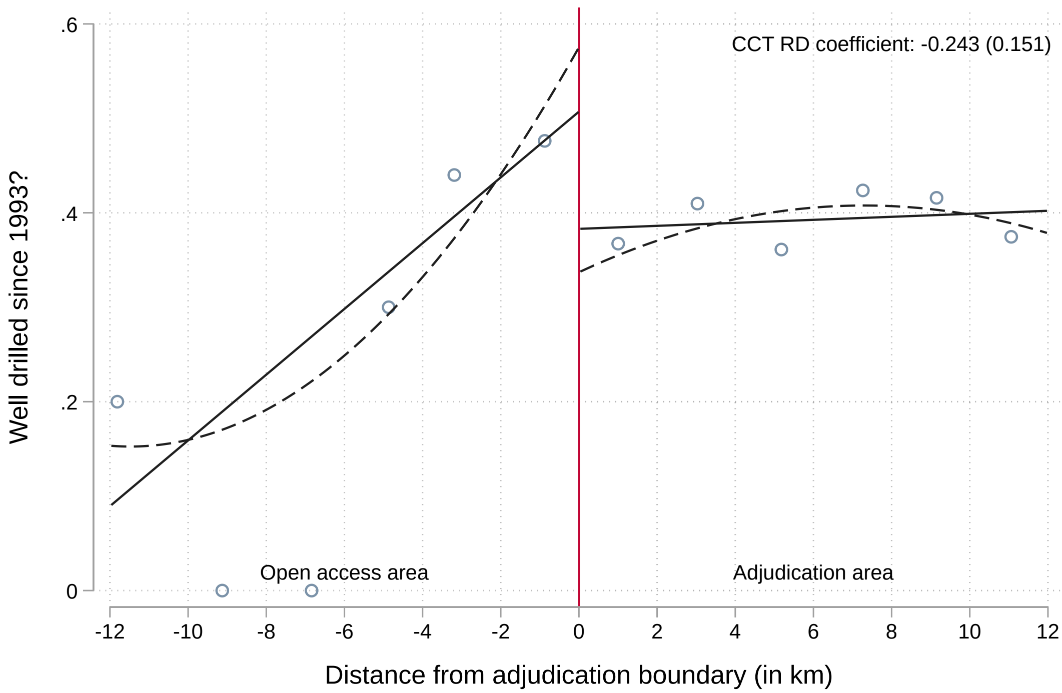
Figure 5: Trend breaks in average Mojave groundwater levels



NOTES: Figure shows the trend break coefficient κ_2 and its 95% confidence interval from the model: $h_t = \kappa_1 t + \kappa_2 t \mathbf{1}\{t \geq \bar{t}\} + \kappa_3 \mathbf{1}\{t \geq \bar{t}\} + \mu_t$, where t is year, h_t is average Mojave groundwater levels (plotted in Figure 1), and μ_t is an error term that is robust to serial correlation and heteroscedasticity with optimal bandwidth following (Newey and West, 1987). $\bar{t}$ is the imposed trend break which varies across years 1985-2010, shown in the x-axis. Sample period is 1980-2015, the years with continuously available average Mojave groundwater levels.

First, we return to the time series of average Mojave groundwater levels depicted in Figure 1, which shows groundwater levels stabilizing in recent decades. To examine the timing of this trend break in groundwater levels, Figure 5 plots trend break coefficients from separate regression models in which the timing of the imposed linear trend break varies across years between 1985 and 2010. We detect the largest trend break in average Mojave groundwater levels around 1993, the year in which 75% of groundwater users first adopted pumping restrictions. One concern with interpreting this trend break as causal evidence is that, as the theory in Section 3.2 details, groundwater levels would have also eventually stabilized had the prior open access regime continued. It is possible that stabilization under open access also would have occurred in 1993.[52]

Figure 6: RD plot on whether a groundwater well was drilled since 1993



NOTES: Vertical axis shows a dummy variable for whether a groundwater well was built since 1993. Horizontal axes shows normalized distance in kilometers, d_i, to adjudication boundary with $d_i \geq 0$ indicating the adjudication area and $d_i < 0$ indicating the open access area. Circles indicate average outcome for the average distance within a 2 km-wide distance bin. Solid (dashed) line shows linear (quadratic) fit over unbinned data separately on each side of the boundary. MSE-optimal RD coefficient with county-clustered standard error shown following Calonico, Cattaneo and Titiunik (2014).

To rule out this possibility, for our second piece of evidence we return to our spatial RD setting and look at the timing of when wells were drilled. If adjudication did not result in more groundwater compared with the open access counterfactual, one would not observe changes in efforts to access water following the introduction of adjudication. Figure 6, which mirrors our main RD plot in Figure 4, examines a dummy variable for whether a groundwater well was drilled during or after 1993, the year when most groundwater users

[52]A second concern may be that the Mojave Water Agency began recharging the aquifer with water imported from California's State Water Project in 1990. While this does not invalidate our RD design, which excludes changes in groundwater levels, it may prohibit one from drawing causal conclusions from the time break analysis in Figure 5. However, as Figure B.6 shows, there is no clear trend break in State Water Project imports in 1993.

first adopted pumping restrictions. On average, there are more wells drilled since 1993 just inside the open access area than just inside the adjudication area. More wells since 1993 on the open access side is consistent with the pumping restrictions imposed by the adjudication increasing groundwater spillovers into the open access area, lowering the cost of pumping, and increasing the returns to drilling a well on unrestricted open access parcels.[53] One concern with this evidence is that the CCT-optimal RD estimate for new wells since 1993 has a p-value of 0.11, just above the conventional threshold for statistical significance.

Our final argument turns to the price of groundwater rights. Figure B.7 plots the average traded prices of perpetual rights and annual leases under the Mojave adjudication regime during the 1997-2015 period, showing consistent trading at positive prices. As discussed in Section 3.3, heterogeneous endowments produce initial differences among landowners in the shadow value of water λ^{mr}. These differences imply gains from trade, which are exhausted when λ^{mr} is equal across all landowners and equal to the competitive price for a water right. Thus, a positive price for water implies a positive shadow value for all landowners and water use w^{mr} that satisfies $\frac{\partial \pi}{\partial w} = \lambda^{mr} = p^w > 0$. The properties of π - concave and single-peaked in w - imply $\frac{\partial \pi}{\partial w} > 0$ if and only if $w^{mr} < w^a$ since w^a satisfies $\frac{\partial \pi}{\partial w} = 0$. The same argument holds for the price of a perpetual groundwater right. In sum, positive water prices are a sufficient condition for the adjudication to have reduced pumping relative to open access and, thereby, increased groundwater levels.

These three additional pieces of evidence all suggest that adjudication resulted in more groundwater than would have occurred under the open access counterfactual. As such, it is likely that adjudication resulted in social benefits by reducing the externality associated with groundwater pumping. Furthermore, this implies that the aggregate net benefit of adjudication calculated in Section 7.1, which omits the benefit from more groundwater, is understated.

8 Conclusion

This paper applies a spatial regression discontinuity design to quantify the net benefit of using an environmental market to manage a groundwater aquifer in southern California. We estimate that agricultural land values on the groundwater market side of the boundary

[53]The only way for more open access wells after adjudication to not increased groundwater levels is if adjudication required adjudicated parcels to pump more than they would have under open access. Under this circumstance, one can construct a scenario whereby groundwater levels are lower in the adjudicated area and higher in the open access area following adjudication such that there is no change in total groundwater compared to full open access. We think this is highly unlikely, particularly since agricultural users were already pumping at their private optimum prior to adjudication such that any mandate to pump more would have led to private losses for all adjudicated users.

are, on average, 250% higher than on the open access side. Using a model of dynamic groundwater extraction, we show that our RD estimate corresponds to a weak lower bound on the net benefit of the program for agricultural parcels. Heterogeneity analyses suggest that a component of these benefits comes from the tradeability of these rights, which enable a more efficient allocation of water away from water-intensive agriculture toward urban use. Furthermore, additional evidence suggests that the groundwater market led to increased groundwater levels.

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 recently passed the Sustainable Groundwater Management Act, an unprecedented policy requiring users of overextracted aquifers to adopt sustainable management plans. While it remains contentious which management tools should be employed, this paper's findings suggest that a market for groundwater rights can lead to substantial net benefits. Users and regulators alike may reference these benefits in future efforts to establish environmental markets for groundwater and common-pool resources more generally.

References

Aeschbach-Hertig, W., and Tom Gleeson. 2012. "Regional strategies for the accelerating global problem of groundwater depletion." *Nature Geoscience*, 5: 853–861.

Aladjem, David, and David Sunding. 2015. "Marketing the Sustainable Groundwater Management Act: Applying economics to solve California's groundwater problems." *Nat. Resources & Env't*, 30: 28.

Babbitt, C., Hall M. Hayden A. Briones A.L.G. Young R., and N. Brozovic. 2017. "Groundwater Trading as a Tool or Implementing California's Sustainable Groundwater Management Act."

Baerenklau, Kenneth A, Kurt A Schwabe, and Ariel Dinar. 2014. "The residential water demand effect of increasing block rate water budgets." *Land Economics*, 90(4): 683–699.

Banerjee, Abhijit V, Paul J Gertler, and Maitreesh Ghatak. 2002. "Empowerment and efficiency: Tenancy reform in West Bengal." *Journal of Political Economy*, 110(2): 239–280.

Besley, Timothy. 1995. "Property Rights and Investment Incentives: Theory and Evidence from Ghana." *Journal of Political Economy*, 103(5): 903–937.

Besley, Timothy, and Robin Burgess. 2000. "Land Reform, Poverty Reduction, and Growth: Evidence from India." *The Quarterly Journal of Economics*, 115(2): 389–430.

Bigelow, Daniel P, Andrew J Plantinga, David J Lewis, and Christian Langpap. 2017. "How does urbanization affect water withdrawals? Insights from an econometric-based landscape simulation." *Land economics*, 93(3): 413–436.

Birkenbach, Anna M, David J Kaczan, and Martin D Smith. 2017. "Catch shares slow the race to fish." *Nature*, 544(7649): 223–226.

Calel, Raphael. 2020. "Adopt or Innovate: Understanding Technological Responses to Cap-and-Trade." *American Economic Journal: Economic Policy*, 12(3): 170–201.

Calel, Raphael, and Antoine Dechezleprêtre. 2016. "Environmental policy and directed technological change: evidence from the European carbon market." *Review of economics and statistics*, 98(1): 173–191.

California Dept. of Water Res. 2015. "California's Groundwater Update 2013: A Compilation of Enhanced Content for California Water Plan Update 2013."

Calonico, Sebastian, Matias D. Cattaneo, and Max H. Farrell. 2019. "Coverage Error Optimal Confidence Intervals for Local Polynomial Regression." *mimeo.*

Calonico, Sebastian, Matias D Cattaneo, and Rocio Titiunik. 2014. "Robust nonparametric confidence intervals for regression-discontinuity designs." *Econometrica*, 82(6): 2295–2326.

Calonico, Sebastian, Matias D. Cattaneo, Max H. Farrell, and Rocío Titiunik. 2019. "Regression Discontinuity Designs Using Covariates." *The Review of Economics and Statistics*, forthcoming.

Cameron, A. Colin, Jonah B. Gelbach, and Douglas L. Miller. 2008. "Bootstrap-Based Improvements for Inference with Clustered Errors." *The Review of Economics and Statistics*, 90(3): 414–427.

Cattaneo, Matias D, Brigham R Frandsen, and Rocio Titiunik. 2015. "Randomization inference in the regression discontinuity design: An application to party advantages in the US Senate." *Journal of Causal Inference*, 3(1): 1–24.

Cattaneo, Matias D., Michael Jansson, and Xinwei Ma. 2019. "Simple Local Polynomial Density Estimators." *Journal of the American Statistical Association*, 0(0): 1–7.

Cattaneo, Matias D, Rocio Titiunik, and Gonzalo Vazquez-Bare. 2016. "Inference in regression discontinuity designs under local randomization." *The Stata Journal*, 16(2): 331–367.

Coase, R. H. 1960. "The Problem of Social Cost." *Journal of Law and Economics*, 3: pp. 1–44.

Coman, Katharine. 1911. "Some Unsettled Problems of Irrigation." *The American Economic Review*, 1(1): 1–19.

Costello, Christopher, and Corbett A Grainger. 2018. "Property rights, regulatory capture, and exploitation of natural resources." *Journal of the Association of Environmental and Resource Economists*, 5(2): 441–479.

Costello, Christopher, Daniel Ovando, Tyler Clavelle, C. Kent Strauss, Ray Hilborn, Michael C. Melnychuk, Trevor A. Branch, Steven D. Gaines, Cody S. Szuwalski, Reniel B. Cabral, Douglas N. Rader, and Amanda Leland. 2016. "Global Fishery Prospects under Contrasting Management Regimes." *Proceedings of the National Academy of Sciences*, 113(18): 5125–5129.

Costello, Christopher, Nicolas Quérou, and Agnes Tomini. 2015. "Partial enclosure of the commons." *Journal of Public Economics*, 121: 69–78.

Costello, Christopher, Steven D. Gaines, and John Lynham. 2008. "Can Catch Shares Prevent Fisheries Collapse?" *Science*, 321(5896): 1678–1681.

Covich, Alan P. 2009. "Emerging Climate Change Impacts on Freshwater Resources: A Perspective on Transformed Watersheds."

Crocker, T. 1966. "The structuring of atmospheric pollution control systems. The economics of air pollution." *The economics of air pollution. New York, WW Norton & Co*, 61–86.

Cropper, Maureen L., and Wallace E. Oates. 1992. "Environmental Economics: A Survey." *Journal of Economic Literature*, 30(2): pp. 675–740.

Dale, John H. 1968. "Pollution, Property, and Prices: An Essay in Policy-Making."

Dalhuisen, Jasper M, Raymond JGM Florax, Henri LF De Groot, and Peter Nijkamp. 2003. "Price and income elasticities of residential water demand: a meta-analysis." *Land economics*, 79(2): 292–308.

Deschenes, Olivier, Michael Greenstone, and Joseph S Shapiro. 2017. "Defensive investments and the demand for air quality: Evidence from the NOx budget program." *American Economic Review*, 107(10): 2958–89.

Drysdale, Krystal M., and Nathan P. Hendricks. 2018. "Adaptation to an irrigation water restriction imposed through local governance." *Journal of Environmental Economics and Management*, 91: 150 – 165.

Edwards, Eric C. 2016. "What lies beneath? Aquifer heterogeneity and the economics of groundwater management." *Journal of the Association of Environmental and Resource Economists*, 3(2): 453–491.

Elliott, Joshua, Delphine Deryng, Christoph Müller, Katja Frieler, Markus Konzmann, Dieter Gerten, Michael Glotter, Martina Flörke, Yoshihide Wada, Neil Best, Stephanie Eisner, Balázs M. Fekete, Christian Folberth, Ian Foster, Simon N. Gosling, Ingjerd Haddeland, Nikolay Khabarov, Fulco Ludwig, Yoshimitsu Masaki, Stefan Olin, Cynthia Rosenzweig, Alex C. Ruane, Yusuke Satoh, Erwin Schmid, Tobias Stacke, Qiuhong Tang, and Dominik Wisser. 2014. "Constraints and potentials of future irrigation water availability on agricultural production under climate change." *Proceedings of the National Academy of Sciences*, 111(9): 3239–3244.

Espey, Molly, James Espey, and W Douglass Shaw. 1997. "Price elasticity of residential demand for water: a meta-analysis." *Water resources research*, 33(6): 1369–1374.

Ferguson, Grant, Jennifer C McIntosh, Debra Perrone, and Scott Jasechko. 2018. "Competition for shrinking window of low salinity groundwater." *Environmental Research Letters*, 13(11): 114013.

Field, Erica. 2007. "Entitled to Work: Urban Property Rights and Labor Supply in Peru." *The Quarterly Journal of Economics*, 122(4): 1561–1602.

Figueroa, Teri. 2001. "Water agreement endangered: Move by Baldy Mesa Water District could lead to costly legal battles." *Desert Dispatch*.

Fowlie, Meredith, Stephen P Holland, and Erin T Mansur. 2012. "What do emissions markets deliver and to whom? Evidence from Southern California's NOx trading program." *American Economic Review*, 102(2): 965–93.

Freeman, Jody, and Charles D Kolstad. 2006. *Moving to markets in environmental regulation: Lessons from twenty years of experience.* Oxford University Press.

Galiani, Sebastian, and Ernesto Schargrodsky. 2010. "Property rights for the poor: Effects of land titling." *Journal of Public Economics*, 94(9): 700 – 729.

Gerardino, Maria Paula, Stephan Litschig, and Dina Pomeranz. 2017. "Can Audits Backfire? Evidence from Public Procurement in Chile." National Bureau of Economic Research Working Paper 23978.

Giordano, Mark. 2009. "Global Groundwater? Issues and Solutions." *Annual Review of Environment and Resources*, 34(1): 153–178.

Gisser, Micha, and David Sanchez. 1980. "Competition versus optimal control in groundwater pumping." *Water Resources Research*, 16(4): 638–642.

Gordon, H Scott. 1954. "The Economic Theory of a Common-Property Resource: The Fishery." *The Journal of Political Economy*, 124–142.

Goulder, Lawrence H. 2013. "Markets for pollution allowances: what are the (new) lessons?" *Journal of Economic Perspectives*, 27(1): 87–102.

Grafton, R. Quentin, Gary Libecap, Samuel McGlennon, Clay Landry, and Bob O'Brien. 2011. "An Integrated Assessment of Water Markets: A Cross-Country Comparison." *Review of Environmental Economics and Policy*, 5(2): 219–239.

Green Nylen, N., Kiparsky M. Archer K. Schnier K., and H. Doremus. 2017. "Trading Sustainably: Critical Considerations for Local Groundwater Markets Under the Sustainable Groundwater Management Act."

Hagerty, Nick. 2019. "Liquid Constrained in California: Estimating the Potential Gains from Water Markets." *mimeo.*

Hahn, Jinyong, Petra Todd, and Wilbert Van der Klaauw. 2001. "Identification and Estimation of Treatment Effects with a Regression-Discontinuity Design." *Econometrica*, 69(1): pp. 201–209.

Hahn, Robert W. 1984. "Market Power and Transferable Property Rights." *The Quarterly Journal of Economics*, 99(4): pp. 753–765.

Hardin, Garrett. 1968. "The Tragedy of the Commons." *Science*, 162(3859): 1243–1248.

He, Yang, and Otavio Bartalotti. 2020. "Wild bootstrap for fuzzy regression discontinuity designs: obtaining robust bias-corrected confidence intervals." *The Econometrics Journal*. utaa002.

Hernandez-Cortes, Danae, and Kyle C Meng. 2020. "Do Environmental Markets Cause Environmental Injustice? Evidence from California's Carbon Market." National Bureau of Economic Research Working Paper 27205.

Holland, Paul W. 1986. "Statistics and Causal Inference." *Journal of the American Statistical Association*, 81(396): 945–960.

Hornbeck, Richard. 2010. "Barbed wire: Property rights and agricultural development." *The Quarterly Journal of Economics*, 125(2): 767–810.

Hsueh, Lily. 2017. "Quasi-Experimental Evidence on the "Rights to Fish": The Effects of Catch Shares on Fishermen's Days at Sea." *Journal of the Association of Environmental and Resource Economists*, 4(2): 407–445.

Isaksen, Elisabeth Thuestad, and Andries Richter. 2018. "Tragedy, property rights, and the commons: investigating the causal relationship from institutions to ecosystem collapse." *Journal of the Association of Environmental and Resource Economics.*

Iwanowsky, Mathias. 2019. "Property Rights, Resources, and Wealth: The Public Grazing Solution in the United States." *mimeo.*

Janmaat, Johannus A. 2005. "Sharing clams: tragedy of an incomplete commons." *Journal of Environmental Economics and Management*, 49(1): 26–51.

Kaffine, Daniel T, and Christopher Costello. 2011. "Unitization of spatially connected renewable resources." *The BE Journal of Economic Analysis & Policy*, 11(1).

Kang, Mary, and Robert B Jackson. 2016. "Salinity of deep groundwater in California: Water quantity, quality, and protection." *Proceedings of the National Academy of Sciences*, 113(28): 7768–7773.

Kroetz, Kailin, James N. Sanchirico, and Daniel K. Lew. 2015. "Efficiency Costs of Social Objectives in Tradable Permit Programs." *Journal of the Association of Environmental and Resource Economists*, 2(3): 339–366.

Libecap, Gary D. 2011. "Institutional Path Dependence in Climate Adaptation: Coman's "Some Unsettled Problems of Irrigation"." *American Economic Review*, 101(1): 64–80.

Libecap, Gary D., and Dean Lueck. 2011. "The Demarcation of Land and the Role of Coordinating Property Institutions." *Journal of Political Economy*, 119(3): 426–467.

Lloyd, William Forster. 1833. *Two Lectures on the Checks to Population.* Oxford University Press.

Malik, Arun S. 1990. "Markets for pollution control when firms are noncompliant." *Journal of Environmental Economics and management*, 18(2): 97–106.

Malueg, David A. 1990. "Welfare consequences of emission credit trading programs." *Journal of Environmental Economics and management*, 18(1): 66–77.

Mangin, Tracey, Miguel Ángel Cisneros-Mata, Jennifer Bone, Christopher Costello, Steven D Gaines, Gavin McDonald, Laura Rodriguez, C Kent Strauss, and Pedro Zapata. 2018. "The cost of management delay: The case for reforming Mexican fisheries sooner rather than later." *Marine Policy*, 88: 1–10.

McCrary, Justin. 2008. "Manipulation of the running variable in the regression discontinuity design: A density test." *Journal of Econometrics*, 142(2): 698–714.

McDonald, Robert I., Pamela Green, Deborah Balk, Balazs M. Fekete, Carmen Revenga, Megan Todd, and Mark Montgomery. 2011. "Urban growth, climate change, and freshwater availability." *Proceedings of the National Academy of Sciences*, 108(15): 6312–6317.

McLaughlin, David. 2020. "Well-defined property rights: Do groundwater adjudications work? Evidence from California." *mimeo.*

Meng, Kyle C. 2017. "Using a free permit rule to forecast the marginal abatement cost of proposed climate policy." *American Economic Review*, 107(3): 748–84.

Montgomery, W. David. 1972. "Markets in Licenses and Efficient Pollution Control Programs." *Journal of Economic Theory*, 5(3): 395 – 418.

Newey, Whitney K., and Kenneth D. West. 1987. "A Simple, Positive Semi-Definite, Heteroskedasticity and Autocorrelation Consistent Covariance Matrix." *Econometrica*, 55(3): 703–708.

Olmstead, Sheila M. 2010. "The economics of managing scarce water resources." *Review of Environmental Economics and Policy*, 4(2): 179–198.

Ostrom, Elinor. 1990. *Governing the commons.* Cambridge university press.

Ostrom, Elinor. 2008. "The challenge of common-pool resources." *Environment: Science and Policy for Sustainable Development*, 50(4): 8–21.

Palmquist, Raymond B., and Leon E. Danielson. 1989. "A Hedonic Study of the Effects of Erosion Control and Drainage on Farmland Values." *American Journal of Agricultural Economics*, 71(1): 55–62.

Perrone, Debra, and Scott Jasechko. 2019. "Deeper well drilling an unsustainable stopgap to groundwater depletion." *Nature Sustainability*, 2(8): 773–782.

Petrick, Sebastian, and Ulrich J Wagner. 2014. "The impact of carbon trading on industry: Evidence from German manufacturing firms." *Available at SSRN 2389800.*

Prudhomme, Christel, Ignazio Giuntoli, Emma L. Robinson, Douglas B. Clark, Nigel W. Arnell, Rutger Dankers, Balázs M. Fekete, Wietse Franssen, Dieter Gerten, Simon N. Gosling, Stefan Hagemann, David M. Hannah, Hyungjun Kim, Yoshimitsu Masaki, Yusuke Satoh, Tobias Stacke, Yoshihide Wada, and Dominik Wisser. 2014. "Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment." *Proceedings of the National Academy of Sciences*, 111(9): 3262–3267.

Rafey, Will. 2020. "Droughts, deluges, and (river) diversions: Valuing market-based water reallocation." *mimeo.*

Richey, Alexandra S., Brian F. Thomas, Min-Hui Lo, John T. Reager, James S. Famiglietti, Katalyn Voss, Sean Swenson, and Matthew Rodell. 2015. "Quantifying renewable groundwater stress with GRACE." *Water Resources Research*, 51(7): 5217–5238.

Rosen, Sherwin. 1974. "Hedonic prices and implicit markets: product differentiation in pure competition." *Journal of Political Economy*, 82(1): 34–55.

Salzman, James, Genevieve Bennett, Nathaniel Carroll, Allie Goldstein, and Michael Jenkins. 2018. "The Global Status and Trends of Payments for Ecosystem Services." *Nature Sustainability*, 1(3): 136–144.

Sampson, Gabriel S, and James N Sanchirico. 2019. "Exploitation of a mobile resource with costly cooperation." *Environmental and Resource Economics*, 73(4): 1135–1163.

Scheld, Andrew M., Christopher M. Anderson, and Hirotsugu Uchida. 2012. "The Economic Effects of Catch Share Management: The Rhode Island Fluke Sector Pilot Program." *Marine Resource Economics*, 27(3): 203–228.

Schlenker, Wolfram, W. Michael Hanemann, and Anthony C. Fisher. 2005. "Will U.S. Agriculture Really Benefit from Global Warming? Accounting for Irrigation in the Hedonic Approach." *American Economic Review*, 95(1): 395–406.

Schmalensee, Richard, and Robert N Stavins. 2017. "The design of environmental markets: What have we learned from experience with cap and trade?" *Oxford Review of Economic Policy*, 33(4): 572–588.

Shertzer, Kyle W, and Michael H Prager. 2006. "Delay in fishery management: diminished yield, longer rebuilding, and increased probability of stock collapse." *ICES Journal of Marine Science*, 64(1): 149–159.

Stavins, Robert N. 1995. "Transaction Costs and Tradeable Permits." *Journal of Environmental Economics and Management*, 29(2): 133–148.

Stavins, Robert N. 2011. "The problem of the commons: still unsettled after 100 years." *American Economic Review*, 101(1): 81–108.

Tietenberg, Tom. 2003. "The Tradable-Permits Approach to Protecting the Commons: Lessons for Climate Change." *Oxford Review of Economic Policy*, 19(3): 400–419.

Vörösmarty, Charles J., Pamela Green, Joseph Salisbury, and Richard B. Lammers. 2000. "Global Water Resources: Vulnerability from Climate Change and Population Growth." *Science*, 289(5477): 284–288.

World Bank Group. 2020. "State and Trends of Carbon Pricing."

Worm, Boris, Ray Hilborn, Julia K. Baum, Trevor A. Branch, Jeremy S. Collie, Christopher Costello, Michael J. Fogarty, Elizabeth A. Fulton, Jeffrey A. Hutchings, Simon Jennings, Olaf P. Jensen, Heike K. Lotze, Pamela M. Mace, Tim R. McClanahan, Cóilín Minto, Stephen R. Palumbi, Ana M. Parma, Daniel Ricard, Andrew A. Rosenberg, Reg Watson, and Dirk Zeller. 2009. "Rebuilding Global Fisheries." *Science*, 325(5940): 578–585.

Appendix – For Online Publication

A Theory appendix

Sections A.1-A.5 derives Proposition 1(a)-1(e). Section A.6 decomposes our main RD effect. Section A.7 details a back-of-the-envelope calculation for the aggregate urban net benefit.

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

Using equations (3) and (12), define

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

where the first term in equation (A.1) is weakly negative because $w^a(t) \geq w^{mr}(t)$ for $t \geq 0$ and $\pi_w > 0$. The second term in equation (A.1) is weakly positive because $\bar{h}^{mr} \geq h^a(t)$ for $t \geq 0$ and $\pi_h > 0$. The third bracketed term in equation (A.1) can have either sign depending on whether the landowner is a net buyer or seller of groundwater rights. $V^{mr} - V^a \gtreqless 0$ follows from summing the terms in equation (A.1).

A.2 Proposition 1(b): $V^{mr} - V^{ma} \gtreqless 0$

Using equations (12) and (13), define

$$
\begin{aligned}
V^{mr} - V^{ma} &= \int_0^\infty [\pi(w^{mr}(s), \bar{h}^{mr}) - p^w(s)(w^{mr}(s) - w^e(s))]e^{-\delta s} ds \\
&\quad - \int_0^\infty \pi(w^{ma}(s), h^{ma}(s)) e^{-\delta s} ds \\
&= \int_0^\infty \Bigg[\underbrace{\pi(w^{mr}(s), \bar{h}^{mr}) - \pi(w^{ma}(s), \bar{h}^{mr})}_{\leq 0} + \underbrace{\pi(w^{ma}(s), \bar{h}^{mr}) - \pi(w^{ma}(s), h^{ma}(s))}_{\geq 0} \\
&\quad - \underbrace{p^w(s)(w^{mr}(s) - w^e(s))}_{\gtreqless 0} \Bigg] e^{-\delta s} ds
\end{aligned}
\tag{A.2}
$$

where the first term in equation (A.2) is weakly negative because $w^{ma} \geq w^{mr}$ for $t \geq 0$ and $\pi_w > 0$. The second term in equation (A.2) is weakly positive because $\bar{h}^{mr} \geq h^{ma}(t)$ for $t \geq 0$ and $\pi_h > 0$. The third bracketed term in equation (A.2) can have either sign depending on whether the landowner is a net buyer or seller of groundwater rights. $V^{mr} - V^{ma} \gtreqless 0$ follows from summing the terms in equation (A.2).

A.3 Proposition 1(c): $(V^{mr}(h^b) - V^a) - (V^{mr}(h^b) - V^{ma}(h^b) \geq 0$

Using equations (3) and (13), define

$$
\begin{aligned}
(V^{mr}(h^b) - V^a) - (V^{mr}(h^b) - V^{ma}(h^b) &= V^{ma}(h^b) - V^a \\
&= \int_0^\infty \left[\pi(w^{ma}(s), h^b(s)) - \pi(w^a(s), h^a(s))\right] e^{-\delta s} ds \\
&= \int_0^\infty \Bigg[\underbrace{\pi(w^{ma}(s), h^b(s)) - \pi(w^a(s), h^b(s))}_{\geq 0} \\
&\quad + \underbrace{\pi(w^a(s), h^b(s)) - \pi(w^a(s), h^a(s))}_{\geq 0}\Bigg] e^{-\delta s} ds \qquad \text{(A.3)}
\end{aligned}
$$

where the first term in equation (A.3) is weakly positive because $w^{ma} \geq w^a$ for $t \geq 0$ and $\pi_w > 0$. The second term in equation (A.3) 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 $\pi_h > 0$.

A.4 Proposition 1(d): $(V^{mr} - V^a) - (V^{mr}(h^b) - V^a) \geq 0$

Using equation (12), define

$$
\begin{aligned}
(V^{mr} - V^a) - (V^{mr}(h^b) - V^a) &= V^{mr} - V^{mr}(h^b) \\
&= \int_0^\infty [\pi(w^{mr}(\bar{h}^{mr}, s), \bar{h}^{mr}) - p^w(s)(w^{mr}(\bar{h}^{mr}, s) - w^e(s))]e^{-\delta s} ds \\
&- \int_0^\infty [\pi(w^{mr}(h^b(s), s), h^b(s)) - p^w(s)(w^{mr}(h^b(s), s) - w^e(s))]e^{-\delta s} ds \\
&= \int_0^\infty \underbrace{[\pi(w^{mr}(\bar{h}^{mr}, s), \bar{h}^{mr}) - \pi(w^{mr}(h^b(s), s), h^b(s))]}_{\geq 0} e^{-\delta s} ds \\
&- \int_0^\infty \underbrace{p^w(s)(w^{mr}(\bar{h}^{mr}, s) - w^{mr}(h^b(s), s))}_{\geq 0} e^{-\delta s} ds \qquad \text{(A.4)}
\end{aligned}
$$

where $w^{mr}(\bar{h}^{mr}, s)$ and $w^{mr}(h^b(s), s)$ are the solutions to (4) given $\bar{h}^{mr}$ and $h^b(s)$, respectively, and a common endowment $w^e(s)$. The two terms in (A.4) are weakly positive because $\bar{h}^{mr} \geq h^b(t)$ for $t \geq 0$, $\pi_h > 0$, $\frac{dw^{mr}}{dh} > 0$ by Cramer's rule, $\pi_w > 0$, and $p^w(s) \geq 0$. To show that the difference in the two terms,

$$\begin{aligned}\Omega_0 = \pi(w^{mr}(\bar{h}^{mr}, s), \bar{h}^{mr}) - \pi(w^{mr}(h^b(s), s), h^b(s)) \\ - p^w(s)(w^{mr}(\bar{h}^{mr}, s) - w^{mr}(h^b(s), s)),\end{aligned} \tag{A.5}$$

is weakly positive, we note that $p^w(s) = \pi_w(w^{mr}(\bar{h}^{mr}, s), \bar{h}^{mr})$, and show that the following expression is weakly positive:

$$\begin{aligned}\Omega_1 = & \underbrace{\frac{\pi(w^{mr}(\bar{h}^{mr}, s), \bar{h}^{mr}) - \pi(w^{mr}(h^b(s), s), \bar{h}^{mr})}{w^{mr}(\bar{h}^{mr}, s) - w^{mr}(h^b(s), s)} - \pi_w(w^{mr}(\bar{h}^{mr}, s), \bar{h}^{mr})}_{\geq 0} \\ & + \underbrace{\frac{\pi(w^{mr}(h^b(s), s), \bar{h}^{mr}) - \pi(w^{mr}(h^b(s), s), h^b(s))}{w^{mr}(\bar{h}^{mr}, s) - w^{mr}(h^b(s), s)}}_{\geq 0}\end{aligned} \tag{A.6}$$

The first term is weakly positive from the concavity of π and the second term is weakly positive because $\bar{h}^{mr} \geq h^b(t)$ for $t \geq 0$, $\pi_h > 0$, and $\frac{dw^{mr}}{dh} > 0$. By inspection, $\Omega_0 \geq 0 \iff \Omega_1 \geq 0$. Therefore, $(V^{mr} - V^a) - (V^{mr}(h^b) - V^a) \geq 0$.

A.5 Proposition 1(e): $\frac{d}{dt}(V^{mr}(h^b) - V^{ma}(h^b)) \gtreqless 0$

Applying Liebnitz's Rule to equations (12) and (13) evaluated at h^b, we obtain

$$\begin{aligned}\frac{d}{dt}(V^{mr}(h^b) - V^{ma}(h^b)) = \delta[V^{mr}(h^b) - V^{ma}(h^b)] \\ + [\pi(w^{ma}(t), h^b(t)) - \pi(w^{mr}(t), h^b(t)) + p^w(t)(w^{mr}(t) - w^e(t))]\end{aligned}$$

The second bracketed term is ambiguously signed. $\pi(w^{ma}(t), h^b(t)) - \pi(w^{mr}(t), h^b(t)) \geq 0$ because $w^{ma}(t) \geq w^{mr}(t)$ for $t \geq 0$ and $\pi_w > 0$. However, $p^w(t)(w^{mr}(t) - w^e(t))$ is unconstrained in sign. The first bracketed term is

$$\begin{aligned}V^{mr}(h^b) - V^{ma}(h^b) = \int_t^{\infty} [\underbrace{\pi(w^{mr}(s), h^b(s)) - \pi(w^{ma}(s), h^b(s))}_{\leq 0}] e^{-\delta(s-t)} ds \\ - \int_t^{\infty} [\underbrace{p^w(s)(w^{mr}(s) - w^e(s))}_{\gtreqless 0}] e^{-\delta(s-t)} ds\end{aligned}$$

This term is ambiguously signed since our model imposes no constraints on the sign of $p^w(s)(w^{mr}(s) - w^e(s))$. Thus, $\frac{d}{dt}(V^{mr}(h^b) - V^{ma}(h^b)) \gtreqless 0$.

A.6 Decomposing $\hat{\beta}^{RD}$

Our RD estimator from equation 16 can be written as

$$\begin{aligned}
\hat{\beta}^{RD} &= \mathop{\mathbb{E}}_{i:d_i=0}\left[V_i^{mr} - V_i^{ma}\right] \\
&= \mathop{\mathbb{E}}_{i:d_i=0}\left[\int_0^\infty [\pi(w_i^{mr}(s), h_i(s)) - p^w(s)(w_i^{mr}(s) - w_i^e(s)) - \pi(w_i^{ma}(s), h_i(s))]e^{-\delta s}ds\right] \\
&= \mathop{\mathbb{E}}_{i:d_i=0}\left[\int_0^\infty [\underbrace{\pi(w_i^e(s), h_i(s)) - \pi(w_i^{ma}(s), h_i(s))}_{\leq 0}]e^{-\delta s}ds\right] \\
&+ \mathop{\mathbb{E}}_{i:d_i=0}\left[\int_0^\infty [\underbrace{\pi(w_i^{mr}(s), h_i(s)) - \pi(w_i^e(s), h_i(s)) - p^w(s)(w_i^{mr}(s) - w_i^e(s))}_{\geq 0}]e^{-\delta s}ds\right]
\end{aligned} \tag{A.7}$$

where the first equality applies equations (12) and (13) for parcels at the boundary. The second equality adds and subtracts profit under initial water endowment for parcels with property rights, or $\pi(w_i^e(s), h_i(s))$. The first bracketed term, which captures the restriction cost, is weakly negative because for $h_i(t)$, $\pi(w, h_i(t))$ is maximized at $w^{ma}(h_i(t))$.

We examine the second bracketed term, reflecting the gains from groundwater permit trading, separately for net permit buyers and sellers, and for each time period, thus dropping the time subscript. Observe that profit maximization under adjudication implies $\pi_w = p^w$. For a net permit buyer with $w_i^{mr} \geq w_i^e$, note that

$$\pi(w_i^{mr}, h_i) - \pi(w_i^e, h_i) - p^w(s)(w_i^{mr} - w_i^e) \geq 0 \iff \frac{\pi(w_i^{mr}, h_i) - \pi(w_i^e, h_i)}{w_i^{mr} - w_i^e} \geq \pi_w(w_i^{mr})$$

This inequality holds because π is concave in w. For a net permit seller, with $w_i^{mr} \leq w_i^e$

$$\pi(w_i^{mr}, h_i) - \pi(w_i^e, h_i) - p^w(s)(w_i^{mr} - w_i^e) \geq 0 \iff \frac{\pi(w_i^{mr}, h_i) - \pi(w_i^e, h_i)}{w_i^{mr} - w_i^e} \leq \pi_w(w_i^{mr})$$

which holds again because π is concave in w.

A.7 Calculating the aggregate net benefit for urban parcels

Water for urban parcels is not extracted on site but rather available through municipal water systems. As such, we are unable to apply our spatial RD approach for adjudicated urban parcels. In this section, we extend our theory to inform a back-of-the-envelope calculation on the aggregate net benefit of adjudication to urban parcels.

To do so, we make two simplifying assumptions. First, as with our RD design on agricultural parcels, we omit increases in groundwater levels as a consequence of adjudication, implying, as with our RD estimate, that this calculation is a weak lower bound on the true effect. Second, we assume that under adjudication the system has reached a steady state where urban pumping, w^*, and the annual price of groundwater, $\bar{p}^w$, are constant over time.

Let $\Pi_w(w)$ be the instantaneous aggregate urban groundwater demand.[54] Unlike agricultural users, who under open access pumped until the marginal value of water is zero, urban users faced constraints on pumping prior to adjudication because they had groundwater access that was "junior" to agricultural users. As a consequence, urban users were likely pumping below their private optimum prior to adjudication. If aggregate urban consumption increases following adjudication, there would be an aggregate urban net benefit provided that the gain from increased water use offsets the cost of purchasing groundwater rights to enable that increased consumption.

Let w^a denotes the steady state pumping under the open access counterfactual. w^e is the steady state groundwater endowment under adjudication. $w^e < w^a$ in order to stabilize groundwater levels. The pumping restriction under adjudication imposes a loss in perpetuity to urban users given by:

$$L = \int_{w^e}^{w^a} \frac{1}{\delta}\Pi_w(w)dw$$

where δ is the discount rate. Adjudication also made it possible for cities to buy and sell water rights. In the case where a city buys perpetual rights to consume more water, its gain is:

$$G = \int_{w^e}^{w^*} \frac{1}{\delta}\Pi_w(w)dw - r\left(w^* - w^e\right)$$

where w^* is the post-trade consumption of water in perpetuity defined by $\Pi_w(w^*) = \bar{p}^w$ and r is the value of a perpetual right defined by $r = \frac{1}{\delta}\Pi_w(w^*)$. If urban users decrease water consumption following adjudication, $w^* < w^a$, then they are unambiguously worse off since

$$G - L = -\int_{w^*}^{w^a} \frac{1}{\delta}\Pi_w(w)dw - r\left(w^* - w^e\right) < 0$$

However, if urban users increase water consumption following adjudication, $w^* > w^a$, the net benefit from adjudication can be negative or positive

$$G - L = \int_{w^a}^{w^*} \frac{1}{\delta}\Pi_w(w)dw - r\left(w^* - w^e\right) \gtreqless 0 \tag{A.8}$$

Table A.1 calculates the aggregate net benefit to urban parcels in 2015. From the Mojave Water Agency, we obtain aggregate endowment of groundwater rights for urban parcels (w^e) and aggregate urban groundwater consumption (w^*) as the sum of endowments and net transfers. For aggregate urban groundwater use under the counterfactual open access regime (w^a), we conservatively assume that aggregate average annual urban groundwater use in 1986-1990, prior to adjudication, would be maintained by 2015 had adjudication not been established.[55] Using a range of instantaneous residential demand elasticities of -0.4 to -0.7

[54]The urban profit function $\Pi(\cdot)$ is analogous to an agricultural user's profits, $\pi(\cdot)$ from Section 3, but differs in that profit is not defined per unit area of land, but rather for the aggregate population of households and businesses served by municipal water systems.

[55]In practice, the true counterfactual w^a should be lower as groundwater levels deplete under open access conditions, implying a larger gain from rights trading.

obtained from the literature (Espey, Espey and Shaw, 1997; Dalhuisen et al., 2003; Olmstead, 2010; Baerenklau, Schwabe and Dinar, 2014), we calculate an aggregate net benefit to urban users of $72-131 million (in 2015 dollars).

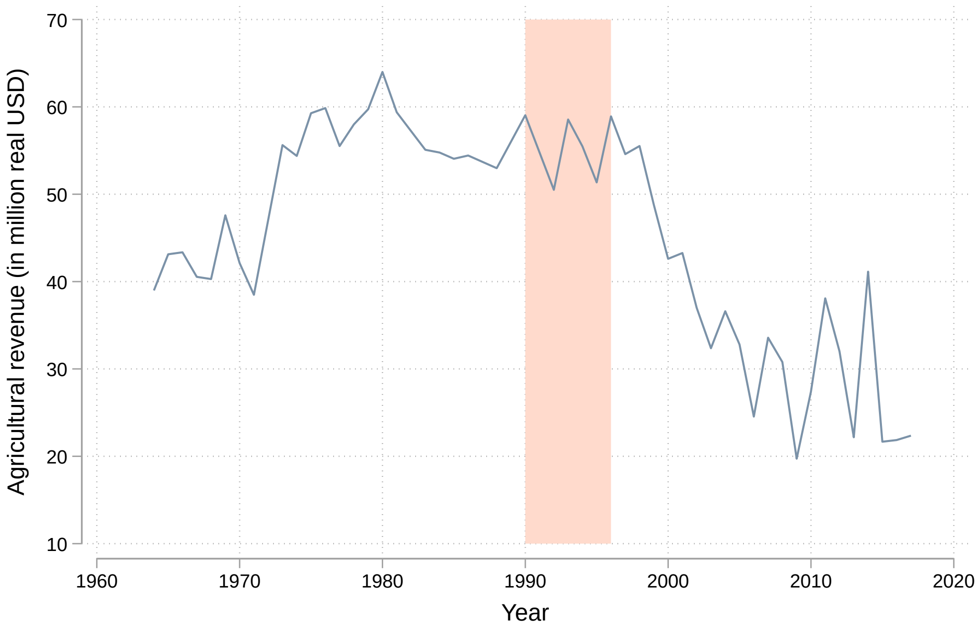
Table A.1: Calculating the aggregate urban net benefit

w^e	w^a	w^*	r	Inst. demand elasticity:		
60191	64327	83927	1725	-0.4	-0.6	-0.7
	Aggregate urban net benefit (in mil. 2015 $USD)					
				71.8	111.3	131.0

NOTES: Aggregate urban endowment of groundwater rights (w^e), groundwater consumption (w^*), and average price of a perpetual right (r) for 2015. Restricted aggregate urban water use under open access counterfactual (w^a) assumed equal to average 1986-1990 aggregate urban groundwater use. Instantaneous elasticities for residential urban demand of -0.4 and -.06 from Espey, Espey and Shaw (1997); Dalhuisen et al. (2003); Olmstead (2010). Elasticity of -0.7 from Baerenklau, Schwabe and Dinar (2014). Discount rate set at $r = 0.02$.

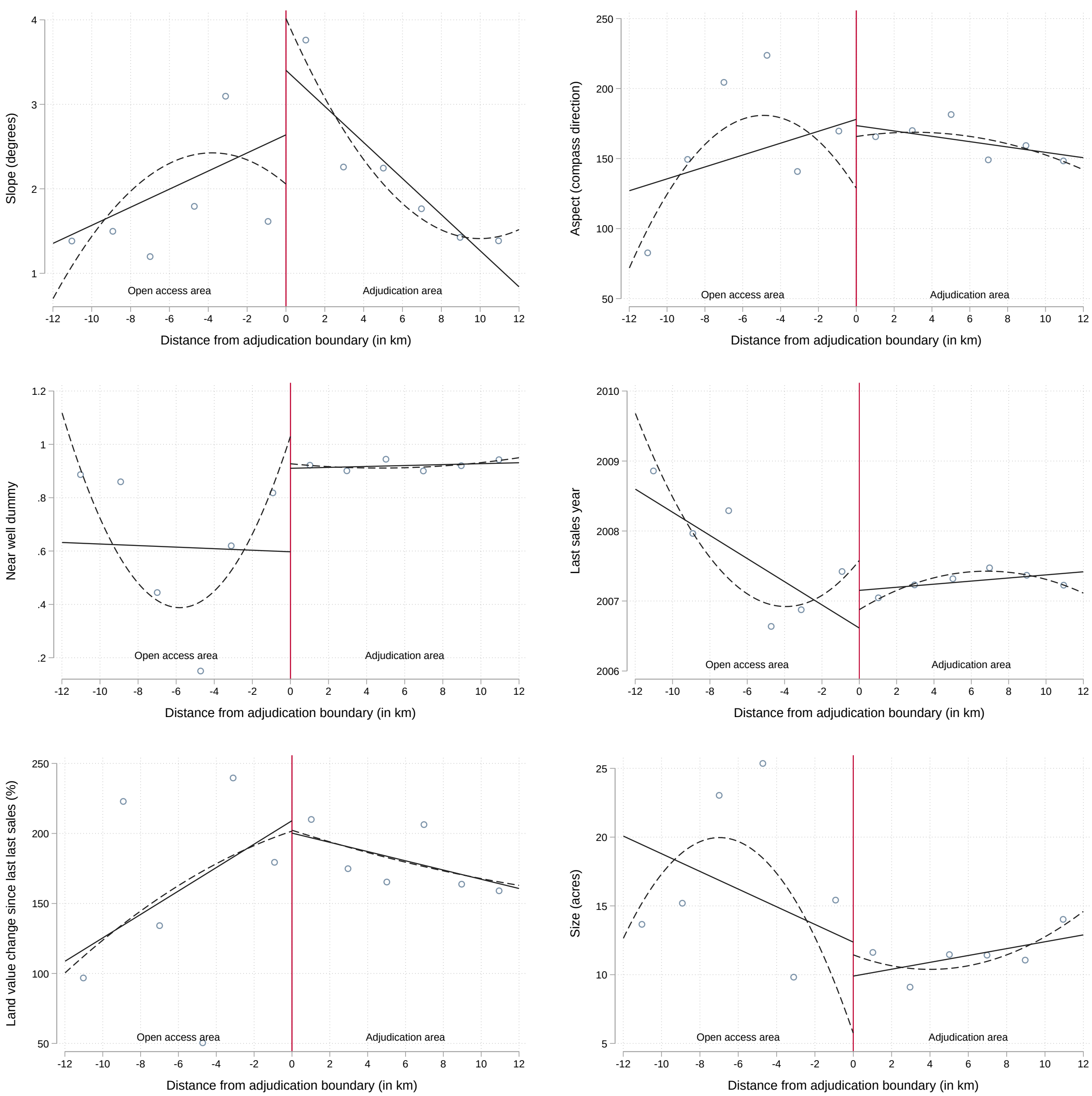
B Appendix Figures

Figure B.1: Agricultural revenue before and after adjudication



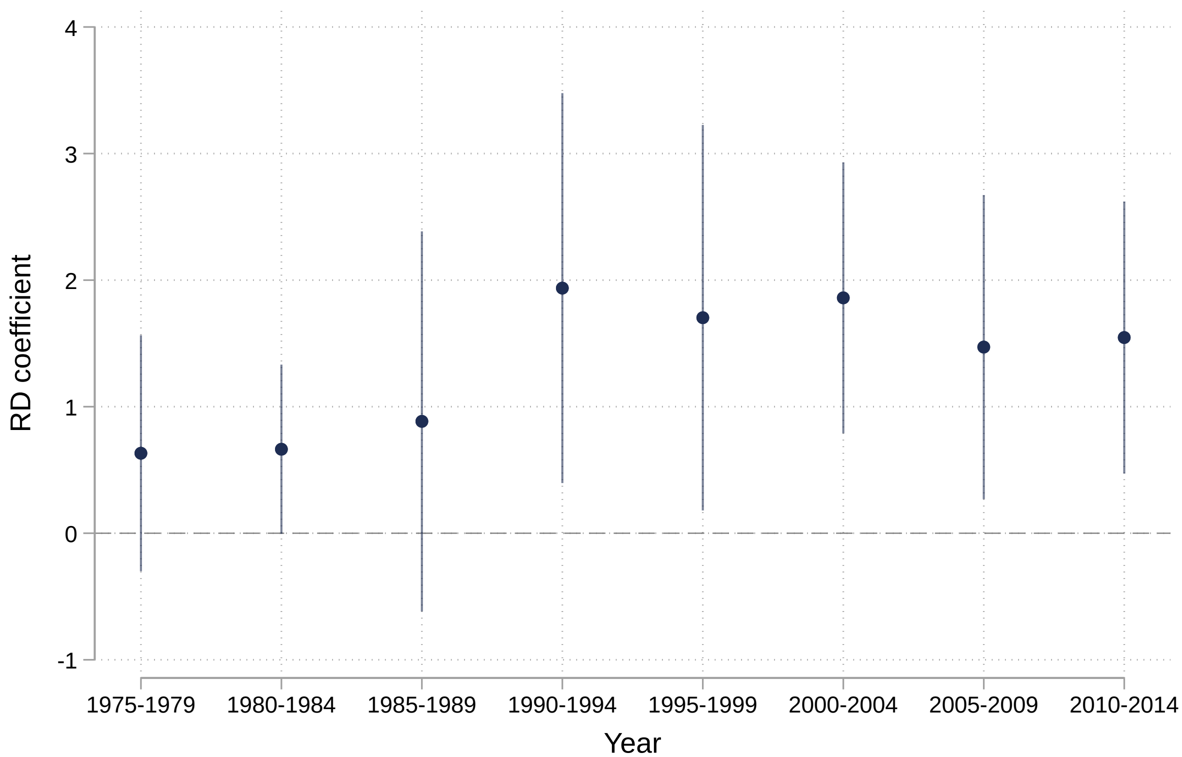
Notes: Plot shows agricultural revenue (in real million USD) for the Mojave Desert from 1960-2017. Data takes the sum of revenue from the North and South Desert regions of San Bernardino county, obtained from the San Bernardino county Annual Crop Reports. Orange-shaded area marks the period from 1990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

Figure B.2: Graphical RD: covariates



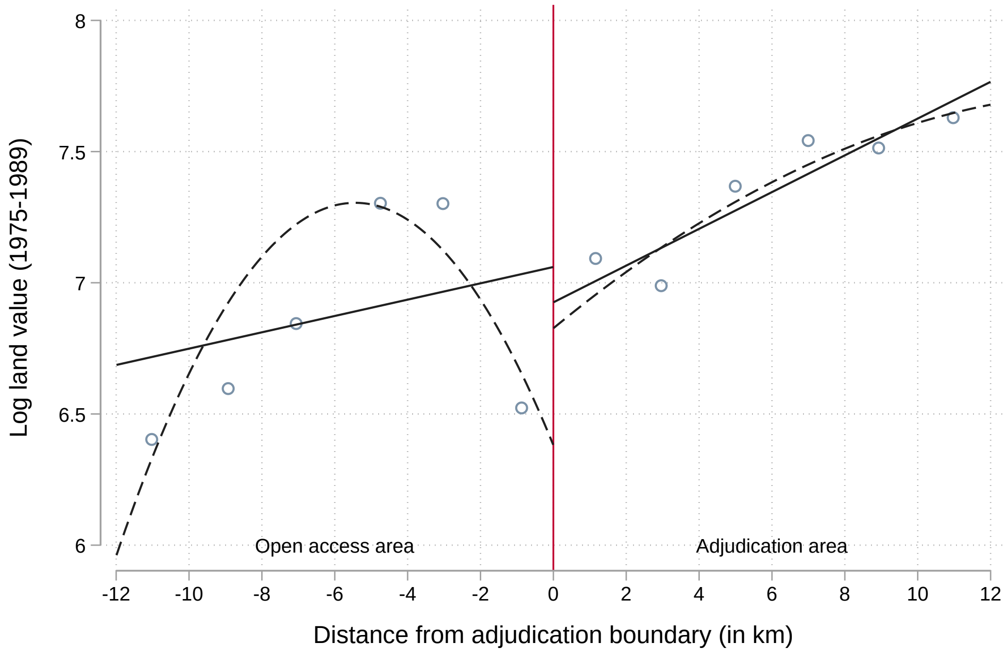
NOTES: Vertical axes shows covariate value. Horizontal axes shows normalized distance in kilometers, d_i, to property rights boundary with $d_i \geq 0$ indicating the adjudication area and $d_i < 0$ indicating the open access area. Circles indicate average covariate values for the average distance within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

Figure B.3: RD effects over time



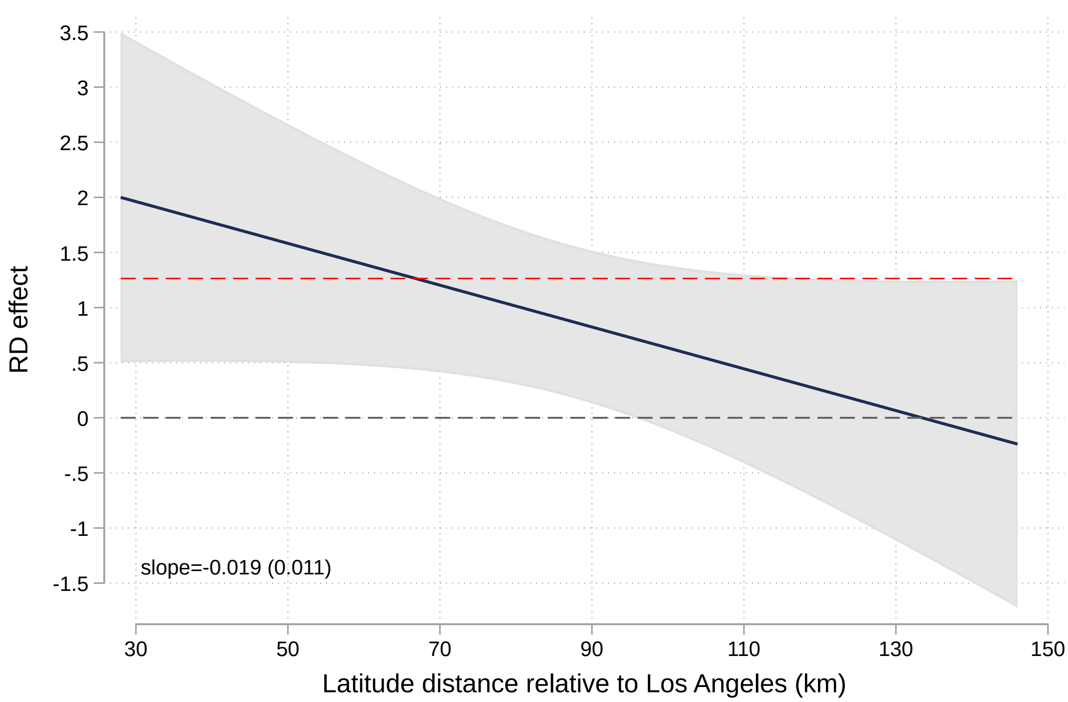
NOTES: Estimates of β^{RD} from equation (18) with log land value as outcome from a panel of assessed land values between 1976-2014, but missing 1977 (see historic land value data details in footnote 45). Estimates correpond to those shown in Table 5. Each model estimated over 5-year intervals. All models use a local linear model for $f(d_i)$, exclude 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. Standard errors clustered at the zip code level in parentheses.

Figure B.4: Graphical RD: land value before adjudication (1975-1989)



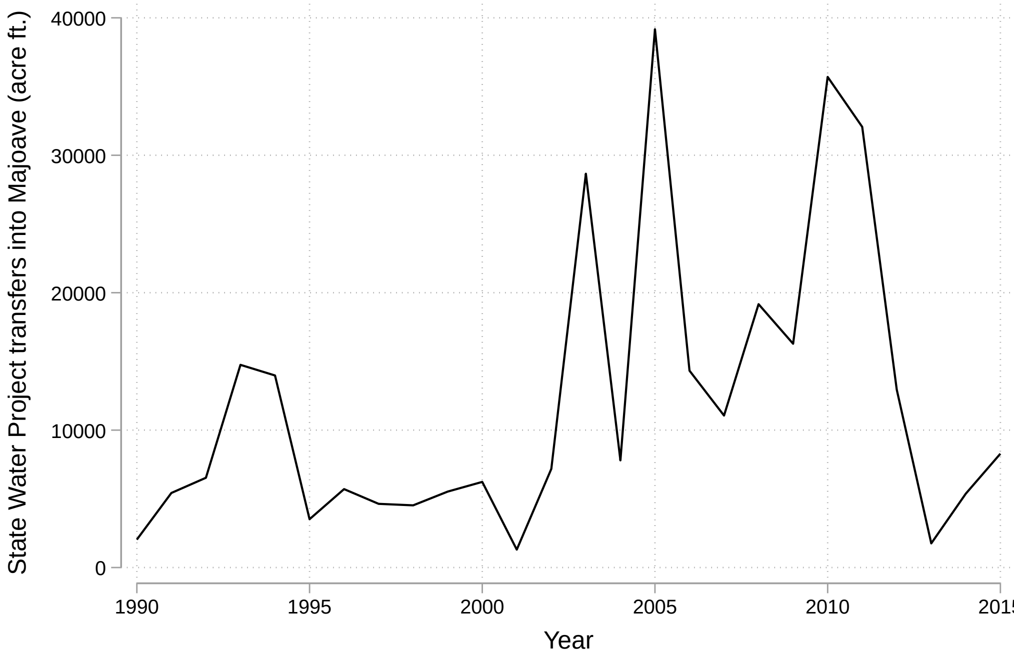
Notes: Vertical axes shows log land value during 1975-1989, the period with available data prior to the initial adjudication lawsuit (see historic land value data details in footnote 45). Horizontal axes shows normalized distance in kilometers, d_i, to property rights boundary with $d_i \geq 0$ indicating property rights area and $d_i < 0$ indicating open access area. Log land value is shown as local averages for the average distance within 2 km-wide bins (circles) as well as separate linear (solid line) and quadratic (dashed line) fits on distance over the unbinned data on each side of the discontinuity.

Figure B.5: Heterogeneity: south to north



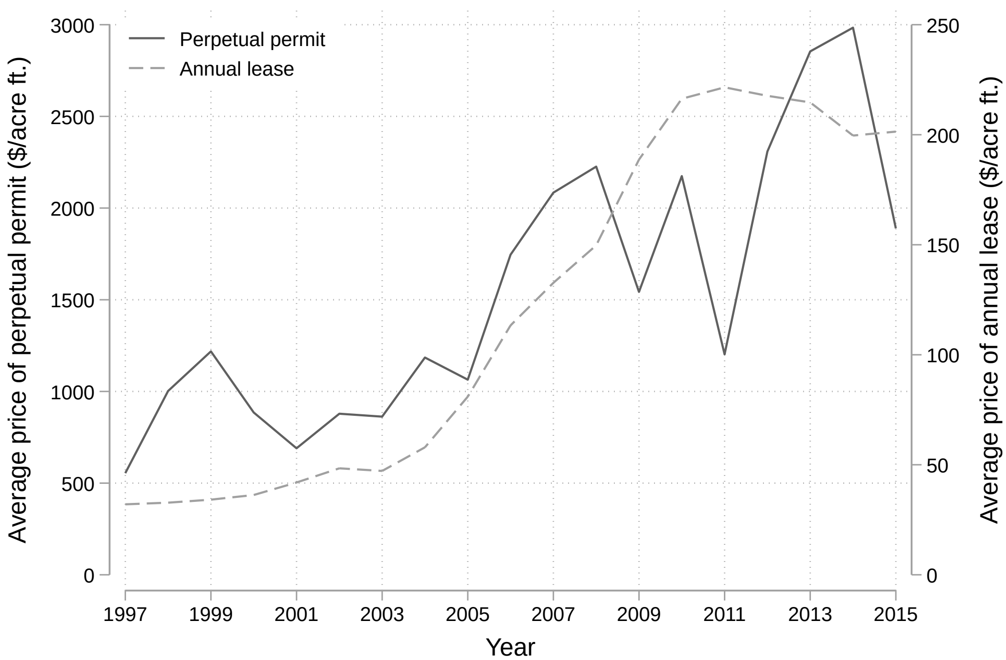
Notes: Plot shows heterogeneity in $\hat{\beta}^{RD}$ as a function of a parcel's latitude, relative to the centroid of Los Angeles. Point estimate and standard error on slope shown. Horizontal red dashed line shows baseline uninteracted RD effect from column 1 of Table 2. 95% confidence intervals shown.

Figure B.6: Annual transfers from the State Water Project into the Mojave Aquifer



Notes: Figure shows annual transfers from the State Water Project to the Mojave Aquifer. Data from the Mojave Water Agency.

Figure B.7: Average price and total trading volume of annual groundwater permits



Notes: Average price of a perpetual permit and annual lease between 1997-2015. Data from the Mojave Water Agency.

C Appendix Tables

Table C.1: Summary statistics

	Obs	Mean	Std dev	p(1)	p(99)
Land value (in 2015 USD)	22462	31983.7	64549.4	612.0	278694.0
Dist. from prop. rights boundary (in km)	22462	12.0	11.0	-14.2	37.6
Avg. slope (in degrees)	22462	1.9	2.7	0.1	15.2
Avg. aspect (in compass direction)	22446	166.4	93.8	12.8	345.0
Dummy whether near 1 mile of well	22462	0.9	0.3	0.0	1.0
Parcel size (in acres)	22462	13.7	39.9	0.2	160.0
Last sales year	22462	2007.2	4.6	1997.0	2015.0
Land value change since last sales (in %)	22430	217.6	3827.6	-84.6	1973.2

NOTES: Number of observations, mean, standard deviation, 1st percentile and 99th percentile of variables in primary dataset (see Section 5). Sample includes land parcels close to the adjudication boundary used in RD estimation and those further away.

Table C.2: Robustness: alternative variance estimators

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Outcome is log land value						
$\hat{\beta}^{RD}$	1.264**	1.300	1.170***	1.144***	1.126***	1.296***	1.161
	(0.539)		(0.155)	(0.157)	(0.157)	(0.437)	{0.000}
	[0.207, 2.320]	[0.442, 2.263]	[0.866, 1.474]	[0.837, 1.451]	[0.819, 1.434]	[0.440, 2.152]	
Std. error/inference	zip code cluster	wild bootstrap zip code cluster	50 NN	100 NN	200 NN	200 NN/ zip code cluster	random- ization
Bandwidth	2.774	2.774	2.748	2.676	2.653	3.417	2.774
Observations	3060	3060	3013	2903	2874	3877	3060

NOTES: Estimates of β^{RD} from equation (18) with log land value as outcome. All models use a local linear model for $f(d_i)$, exclude 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. Column 2 uses a block wild bootstrap procedure at the zip code level following He and Bartalotti (2020). Columns 3, 4, and 5 use a nearest neighbor variance estimator with 50, 100 and 200 minimum nearest neighbors (NN). Column 6 uses a zip code cluster-robust, nearest neighbor variance estimator with 200 minimum nearest neighbors. Column 7 uses local randomization inference following Cattaneo, Frandsen and Titiunik (2015) and Cattaneo, Titiunik and Vazquez-Bare (2016). Standard errors in parentheses; p-values in curly brackets; 95% confidence interval in square brackets. *** 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				
$\hat{\beta}^{RD}$	1.264**	1.246**	0.983*	1.182**	1.210**
	(0.539)	(0.550)	(0.577)	(0.526)	(0.516)
Optimal bandwidth selector	MSE-1	MSE-2	CER-1	CER-2	MSE-1
Kernel	uniform	uniform	uniform	uniform	triangular
Bandwidth	2.774	2.488/5.066	2.319	2.080/4.235	3.330
Observations	3060	5093	2457	4267	3773
Zip codes	28	30	28	30	29

NOTES: Estimates of β^{RD} from equation (18) with log land value as outcome. All models use a local linear model for $f(d_i)$ and exclude covariates. Columns 1-4 uniformly weight 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 in parentheses. *** p<0.01, ** p<0.05, * p<0.1.